Robot-Assisted Rehabilitation of Children with Cerebral Palsy

Devices, Data and Clinical Evidence from Kazakhstan

Authored by

Prashant Kumar Jamwal

Computing and Intelligent Systems

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Front Matter

Title: Robot-Assisted Rehabilitation of Children with Cerebral Palsy: Devices, Data and Clinical Evidence from Kazakhstan

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I thank the children who took part in the program's studies and their families, whose patience and trust made this work possible; the clinical, therapeutic and educational staff of NCCR; and the program's engineering, clinical and educational team.

Conflict of Interest Statement

The author is an inventor of the gait rehabilitation technology described in this book and holds a leadership role in an organization involved in its manufacture. The program received co-financing from Zein Invest LLP.

Preface

Cerebral palsy is the most common cause of physical disability in childhood. Its consequences reach well beyond movement: many children also live with impairments of balance, speech, communication and cognition, and these often matter as much to families as walking does. Rehabilitation for these children is long and labor-intensive, it is unevenly available, and the evidence base for many interventions is still thin. Robotics and artificial intelligence promise to make therapy more intensive, more measurable and more consistent. They also risk adding expensive equipment that has not been tested with the children it is meant to help. I have worked in rehabilitation robotics since 2007, and over those years I have come to think that the second risk deserves as much attention as the first promise.

This book reports what one national program learned while trying to keep that promise without overstating it. Program BR27199433, funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan and co-financed by Zein Invest LLP, brought together engineers from the

School of Engineering and the Center of Excellence in Medical Robotics and Research at Nazarbayev University, clinicians from the University's School of Medicine and from the National Center for Children's Rehabilitation (NCCR) in Astana, and special-education researchers from the Graduate School of Education. NCCR receives roughly 300 children a month, and its willingness to open its therapy rooms to research made it possible to work with children at a scale that is rare in paediatric rehabilitation robotics: 170 children in the social-robot studies, 25 in the perturbation-training trial and 25 in the gait-robot trial.

The program developed or adapted four devices. The Gait Rehabilitation Robot is a hip–knee exoskeleton that walks with the child on a treadmill and measures, through a load cell at each joint, how much of the effort is the child's own. The adaptive body-weight support system, designed by our team, uses a compliant pneumatic drive to unload the child by a prescribed and individually chosen amount. The Robotic Perturbation Trainer is a cable-driven robot that pulls briefly and unpredictably at the pelvis during walking, so that children can practise recovering their balance in a safe setting; its final version can perturb in all three planes. The fourth device is QTrobot, a commercial social robot that we taught to speak Kazakh as well as Russian and for which we wrote bilingual therapy scripts for communication, cognition and social skills. Alongside the devices, the program built two software platforms: GARAS, which turns the gait robot's sensor data into a Gait Recovery Index and rule-based therapy recommendations, and the NCCR Rehabilitation Platform, which brings clinical and sensor data together for documentation and research.

The book is organised in four parts. Part I sets out the clinical problem, the international state of the art and the methodology of the program. Part II describes each device in turn: its rationale, design, control and safety architecture, and the protocols by which it is used. Part III describes the software through which the devices produce data and indices for clinicians. Part IV presents the clinical evidence gathered so far, discusses what it does and does not show, and considers the route from laboratory prototype to registered medical device and routine service.

Throughout, I have tried to keep apart three kinds of material that are easily confused in a field driven by technology: what has been published after peer review, what is still under review or in preparation, and what is still pending. Each chapter states the status of the results it reports. Several studies described here are pilot or feasibility studies with small samples; I present them as such, and I show, with sample-size calculations based on our own pilots, how much larger a confirmatory trial would need to be. Where an analysis method is demonstrated before trial data are available, the demonstration is labelled as such at the point of use.

One point needs to be stated plainly. At the time of writing, the randomised trial of the Gait Rehabilitation Robot, registered as ACTRN12626001203347, and the perturbation-training trial are still in progress. Enrolment for the gait trial began in September 2026, and robot-assisted sessions began in October 2026 after the final ethics conditions for the device had been met. The results of these two trials are therefore pending, and this book describes their designs and analysis plans rather than their outcomes. I would rather publish an honest account of a program in progress than a premature claim of benefit.

The book is written for researchers and graduate students in rehabilitation engineering, for clinicians and therapists who work with children with neurological disabilities, and for those who plan and fund rehabilitation services, particularly in Central Asia. I hope it does justice to the children and families who gave their time to this work.

Prashant Kumar Jamwal Astana, October 2026

List of Abbreviations

Abbreviation	Meaning
6MWT	Six-minute walk test
10MWT	10-metre walk test
AFO	Ankle-foot orthosis
ANZCTR	Australian New Zealand Clinical Trials Registry
BBS	Berg Balance Scale
BRI	Balance Recovery Index
BWS	Body-weight support
CEMRR	Center of Excellence in Medical Robotics and Research
CFCS	Communication Function Classification System
CoP	Centre of pressure
CP	Cerebral palsy
CV	Coefficient of variation
EMG / sEMG	Electromyography / surface electromyography
FSIQ	Full-Scale Intelligence Quotient
GARAS	Gait analysis and rehabilitation recommendation system
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
GRI	Gait Recovery Index
IMU	Inertial measurement unit
IREC	Institutional Research Ethics Committee (Nazarbayev University)
ISSAI	Institute of Smart Systems and Artificial Intelligence (Nazarbayev University)
MACS	Manual Ability Classification System
MCID	Minimal clinically important difference
MDC	Minimal detectable change
MRTK	Mixed Reality Toolkit
MSHE	Ministry of Science and Higher Education of the Republic of Kazakhstan
NCCR	National Center for Children's Rehabilitation, Astana
NU	Nazarbayev University
NURA	Nazarbayev University Research Administration
PTF	Patient Torque Fraction
RAGT	Robot-assisted gait training
RCT	Randomised controlled trial
RPT	Robotic Perturbation Trainer
SAR	Socially assistive robot
SHAP	SHapley Additive exPlanations
SI	Symmetry index
TRL	Technology readiness level
TTS	Text-to-speech

Abbreviation	Meaning
TUG / TUGT	Timed Up and Go test
URP	Universal Render Pipeline (Unity)
VR	Virtual reality
WISC-V	Wechsler Intelligence Scale for Children, Fifth Edition

Prashant Kumar Jamwal

Part I. Background and Rationale

Chapter 1. Cerebral Palsy: Clinical Picture and Rehabilitation Needs

Abstract. This chapter sets out the clinical and epidemiological background against which the robotic and data-driven rehabilitation program described in this book was designed. It reviews how cerebral palsy (CP) has been defined and redefined, what is currently understood about its aetiology and neurobiology, and how children are classified by motor type, topography and functional level using the Gross Motor Function Classification System (GMFCS), the Manual Ability Classification System (MACS) and the Communication Function Classification System (CFCS). Prevalence estimates reported in the literature used by the program are compared, and the principal domains of impairment that the program targets are described: walking and gross motor function, postural control and balance, speech and communication, and cognition and socio-emotional functioning. The chapter then summarises the principles and evidence base of conventional, therapist-delivered rehabilitation and identifies its structural limitations, including dependence on scarce specialist time, difficulty in sustaining practice intensity and motivation, and a historical emphasis on motor outcomes. Finally, it describes the rehabilitation context in Kazakhstan and the role of the National Center for Children's Rehabilitation (NCCR) in Astana, where the program's clinical work took place, and derives from this background a set of rehabilitation needs that motivate the devices and software described in later chapters.

Keywords: cerebral palsy; definition; aetiology; classification; GMFCS; MACS; CFCS; epidemiology; gait; balance; communication; cognition; paediatric rehabilitation; Kazakhstan

1.1 Introduction and Scope

Cerebral palsy is the term used for a lifelong condition that begins with an injury to, or abnormal development of, the immature brain and that manifests primarily as a disorder of movement and posture. It is, in most series, the most common cause of physical disability in childhood, and it is increasingly recognised as a condition whose consequences extend well beyond the motor system into communication, cognition, behaviour and social participation [1–3]. Because the underlying lesion does not progress while the child continues to grow and develop, the clinical picture is dynamic: musculoskeletal deformities, secondary complications and functional limitations change over time, and so do the goals of rehabilitation [4, 5].

The program reported in this monograph was funded under grant BR27199433 (2024–2026) of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan and conducted at Nazarbayev University in partnership with the National Center for Children's Rehabilitation (NCCR) in Astana. Its devices and software address four broad areas of need: walking, balance, communication and cognition. This first chapter explains why these areas were chosen. It does not attempt a comprehensive clinical textbook account of CP; rather, it assembles the evidence that the program's investigators drew upon when they framed their research questions, and it highlights the points at which conventional rehabilitation leaves gaps that technology may plausibly help to fill. Readers with an engineering background will find here the clinical vocabulary used throughout the book, while clinical readers will find a statement of the assumptions on which the engineering work was based.

1.2 Definition and Conceptual Evolution

The modern definition of CP emerged from an international consensus process reported in 2007, which characterised CP as a set of lifelong disorders affecting the development of movement and posture,

limiting the child's activities, and arising from non-progressive disturbances of the brain during fetal life or infancy [6]. Several elements of this definition deserve emphasis because they have direct consequences for rehabilitation engineering. First, CP is described as a *group* of disorders rather than a single disease; the term is an umbrella for clinically heterogeneous presentations that share a developmental origin and a predominantly motor phenotype [7, 8]. Second, the disorders are *permanent*, meaning that rehabilitation aims to maximise function and participation within the constraints of a persisting impairment rather than to cure the underlying lesion. Third, the lesion is *non-progressive*, but its musculoskeletal and functional expression is not static, because the child's body and nervous system continue to develop around it [4].

The 2007 consensus also emphasised that the motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication and behaviour, by epilepsy and by secondary musculoskeletal problems [4, 6]. More recent syntheses have pushed this broader view further. An updated description of CP published in 2026 and a comprehensive 2025 review both frame CP as a neurodevelopmental condition in which motor impairment is the defining but not the only feature, and in which the associated impairments may be as important for a child's daily life as the motor disorder itself [1, 2]. Studies of language, social cognition and executive function have similarly argued that outcome research in CP must look beyond motor endpoints [9].

This conceptual shift matters for the present program. A rehabilitation strategy that addresses only walking would serve only part of the needs that families and clinicians identify. The decision to combine gait and balance devices with a socially assistive robot for communication and cognition, described in Chapter 3, follows directly from this broader understanding of what CP is.

1.3 Aetiology, Risk Factors and Pathophysiology

1.3.1 Timing and mechanisms of injury

The causes of CP are diverse and, in many individual cases, remain uncertain. Reviews of aetiology have stressed that CP usually results from the interaction of several factors acting over a period of time rather than from a single event, and that a substantial proportion of injuries originate before birth [10]. The brain disturbances that give rise to CP occur before the nervous system has matured, typically in the prenatal or perinatal period or in early infancy [4, 5]. Intracerebral haemorrhage and periventricular leukomalacia, a pattern of white-matter injury adjacent to the lateral ventricles, are among the lesion types most frequently described in children born preterm [4, 11].

At the cellular level, hypoxia–ischaemia, inflammation, oxidative stress and disrupted maturation of neurons and oligodendrocytes have been implicated. These processes can produce white-matter injury, necrosis and impaired myelination, which in turn disrupt the transmission of both motor and sensory signals [5, 11]. The anatomical substrates of the resulting deficits include the corticospinal tract, the basal ganglia and the cerebellum, but thalamocortical and other sensory projections are also affected, which helps to explain why children with CP often have difficulty processing proprioceptive, tactile and visual information [5].

1.3.2 Risk factors

Established risk factors include maternal infection, multiple gestation, prematurity and low birth weight [4, 5]. The relationship between gestational age and the prevalence, type and severity of CP has been examined in meta-analytic work, which underlines that preterm and term-born children tend to present with different lesion patterns and clinical subtypes [12]. For the purposes of this book, the relevance of these risk factors is mainly indirect: they shape the case mix seen in a national rehabilitation centre and

therefore the range of motor and non-motor profiles that devices must accommodate. Data from Kazakhstan are limited. A retrospective case–control study of 150 children with CP and 150 matched controls in Almaty reported neonatal hyperbilirubinaemia, head and cervical-spine injury and severe infection with sepsis as frequent postnatal findings in the CP group, while cautioning that, given the retrospective design, these associations should be regarded as hypotheses for prospective study [92]. No risk-factor data specific to the NCCR population were available to the program.

1.3.3 Consequences beyond the motor system

Because the developing brain is injured before sensory, motor and associative networks are fully established, the effects of the lesion are rarely confined to motor control. Disturbances of sensory integration and of brain connectivity have been linked to difficulties with attention, memory, language, speech development and social cognition [5]. At the same time, the developing brain retains considerable capacity for plastic reorganisation, and functional neuroimaging studies have reported changes in brain activity accompanying gains in motor skill after gross motor interventions in children with diplegic CP [13]. This combination of widespread impairment and preserved plasticity is the biological rationale for intensive, repetitive and engaging therapy, which is the central idea behind the robotic interventions described in Part II of this book.

1.4 Classification

Classification in CP serves several purposes: it communicates the clinical picture concisely, it allows outcomes to be compared across studies and registries, and it guides the selection of interventions. A scoping review of CP registries worldwide has documented considerable variation in which variables registries record, which complicates international comparison [14]. Three complementary axes are commonly used: the predominant motor type, the topographical distribution of involvement, and the level of everyday functional ability.

1.4.1 Motor type and topography

By predominant motor syndrome, CP is commonly divided into spastic, dyskinetic and ataxic forms, with spastic presentations further described by topography as hemiplegia (one side of the body), diplegia (predominantly the lower limbs) or quadriplegia/tetraplegia (all four limbs) [6, 15]. Dyskinetic CP is characterised by involuntary and fluctuating movements, including dystonia and choreoathetosis, which disturb coordination and postural stability [16, 17]. Spastic diplegia primarily affects the lower body and is associated with stiffness of the lower-limb musculature and difficulty in walking; its gait has been classified into recognisable sagittal-plane patterns, namely true equinus, jump gait, apparent equinus and crouch gait, each of which is linked to specific management options [82, 83]. The International Classification of Diseases, 10th Revision (ICD-10), codes these subtypes as G80.0 (spastic quadriplegic), G80.1 (spastic diplegic), G80.2 (spastic hemiplegic) and G80.3 (dyskinetic) CP, and the program's clinical studies recorded diagnoses using these codes [18, 19].

It is worth noting at the outset how these subtypes were represented in the program's own cohorts, because this distribution shapes the generalisability of the evidence reported in Part IV. In the largest social-robot study conducted at NCCR, which enrolled 32 children in the intervention group, spastic diplegia (G80.1) was the most frequent diagnosis, followed by spastic hemiplegia (G80.2) and dyskinetic CP (G80.3), with a single child with spastic tetraplegia (G80.0) [18]. The exploratory body-weight support study included children with spastic hemiplegia, spastic diplegia and dyskinetic CP [19], and the two adolescents in the published perturbation-training study had spastic diplegic and spastic dyskinetic presentations, respectively [20].

1.4.2 Functional classification systems

Motor type and topography describe *where* and *how* the motor system is affected, but they say little about what a child can actually do. Functional classification systems fill this gap. Three five-level ordinal systems are now standard in clinical practice and research: the GMFCS for self-initiated gross motor function, particularly sitting and walking; the MACS for the ability to handle objects in daily activities; and the CFCS for everyday communication performance [15, 21]. The GMFCS was introduced by Palisano and colleagues in 1997 [84] and later expanded and revised (GMFCS-E&R) to add an age band for youth aged 12 to 18 years [85]; the MACS was developed and validated by Eliasson and colleagues [86], and the CFCS by Hidecker and colleagues [87]. Table 1.1 summarises the scope of each system as it is used in this book.

Table 1.1. Functional classification systems used to characterise children with cerebral palsy in this book.

System	Domain classified	Levels	Use in the program
Gross Motor Function Classification System (GMFCS)	Self-initiated gross motor function, emphasising sitting, standing and walking	I (least limited) to V (most limited)	Eligibility for gait, balance and body-weight support studies; recorded on pre-assessment forms
Manual Ability Classification System (MACS)	Handling of objects in everyday activities	I to V	Reported in the literature reviewed; not systematically available in NCCR records for the social-robot cohorts
Communication Function Classification System (CFCS)	Everyday communication performance with familiar and unfamiliar partners	I to V	Recommended for future social-robot studies; not systematically available in NCCR records for the cohorts analysed to date

Sources: GMFCS [84, 85]; MACS [86]; CFCS [87]. Sources for the "use in the program" column: gait and balance eligibility criteria [19, 20]; availability of classification data in clinical records [22, 23].

1.4.3 Classification in practice and in the program

In the motor studies of the program, GMFCS level was used as a principal eligibility criterion. The exploratory body-weight support study, for example, enrolled children at GMFCS levels I and II [19], and the perturbation-training protocol accepted children at levels I to III, excluding levels IV and V [20]. These restrictions reflect the practical requirement that a child be able to step on a treadmill, with or without support, and to report pain or discomfort.

By contrast, the social-robot studies conducted at NCCR found that standardised functional classifications, particularly the MACS and the CFCS and formal dysarthria severity ratings, were frequently not documented in the centre's clinical records [22, 23]. The authors of these studies identified this as a limitation and recommended that future work collect GMFCS and CFCS levels systematically at baseline so that individual response patterns can be interpreted against established functional profiles [23]. The international literature makes the same point from the opposite direction: a scoping review of socially assistive robotics in CP found that children at GMFCS and MACS levels IV and V were underrepresented in published studies [15]. Systematic functional classification therefore emerges as both a clinical-documentation need and a research-design need, and it is addressed in the program's data acquisition platform described in Chapter 9.

1.5 Epidemiology

Estimates of the prevalence of CP vary with the populations studied, the period of birth, the case definition and the method of ascertainment. Table 1.2 collects the estimates cited across the source documents of this program. They are broadly consistent in placing prevalence at roughly two to three per 1,000 live births, with a systematic analysis of global data reporting a range of 1.6 to 3.4 per 1,000 [24].

Table 1.2. Prevalence estimates of cerebral palsy reported in the literature used by the program.

Estimate	Population or scope	Reference
1.6–3.4 per 1,000 live births	Global systematic analysis	[24]
Approximately 2–3 per 1,000 live births	Worldwide (narrative review)	[25]
Approximately 2–4 per 1,000 live births	European surveillance and meta-analytic data	[12, 26, 27]
More than 17 million people affected	Global estimate of people living with CP	[4, 28]

For the purposes of this book, the exact figure matters less than its implications. Even at the lower bound of these estimates, CP affects a substantial number of children in any national population, and because it is lifelong, the cumulative demand for rehabilitation services is large. No population-based surveillance estimate of CP prevalence or incidence for Kazakhstan, comparable to those in Table 1.2, has been published. Administrative and registration data nevertheless indicate the scale of need. Official government information reported that in 2018 more than 80,000 children in Kazakhstan were registered as disabled and that more than 30,000 children received medical rehabilitation, of whom more than 5,000 had CP [93]; a press report from the same period, citing registration data, gave 16,768 children with CP on the register [94]. A Kazakh study, drawing on press sources, reported that the registered prevalence of CP rose from 44.6 to 73.6 per 100,000 population between 2006 and 2015 [92]; because these figures derive from registration rather than population surveillance, they cannot be compared directly with the per-live-birth estimates above. More recently, the Ministry of Health reported that children with disabilities make up 1.6% of all children in the country and that diseases of the nervous system are now the leading cause of childhood disability [95].

The age at which CP is diagnosed is also epidemiologically important because it determines when rehabilitation can begin. Advances in early diagnosis have made it possible to identify many infants at high risk of CP well before the traditional age of diagnosis, enabling earlier intervention [29]. Nevertheless, a scoping review of referral practices found that the age at referral for diagnosis and rehabilitation services remains variable [30]. The program's own studies enrolled children aged approximately 5 to 18 years, reflecting the populations attending NCCR rather than infants in early-intervention services.

1.6 Motor Impairment and Walking

1.6.1 Neuromuscular contributors to gait dysfunction

Walking is, for many children and adolescents with CP and their families, a priority rehabilitation goal, and maintaining or improving walking ability is a central aim of physical therapy [19, 31]. In spastic CP, the neuromuscular contributors to gait dysfunction include muscle weakness, shortened muscle–tendon units, spasticity and impaired selective motor control; importantly, the relative contribution of each of these varies from one child to another [32]. Impaired selective voluntary motor control, the reduced ability to activate muscles in isolation from obligatory synergistic patterns, has received particular attention because it is associated with gait deviations and may limit the response to strength-

based training. A systematic review of training methods that might improve selective voluntary motor control in children with spastic CP identified a range of candidate approaches but limited high-quality evidence [33].

The heterogeneity of these contributors is a recurring theme of this book. If two children at the same GMFCS level walk poorly for different reasons, a single standard therapy prescription is unlikely to be optimal for both. This observation motivated the program's interest in individualised parameter selection, for example in the choice of body-weight support level (Chapter 5), and in instrumented, multidimensional gait analysis (Chapter 8).

1.6.2 Clinical gait patterns

Clinicians describe gait in CP using a set of recognisable patterns. The program's pre-assessment form for paediatric exoskeleton training at NCCR asks the assessing therapist to record, among other features, whether the child walks independently or with an aid, and whether toe-walking on the affected side, foot dragging, hip hiking, circumduction, crouched gait, scissor gait or reduced arm swing are present [34]. In hemiplegic presentations, the form notes that the affected side typically shows a shorter step length, which is the main asymmetry that robot-assisted training aims to reduce. These observational categories are not precise measurements, but they provide a shared clinical language that the instrumented measures described in Chapter 8 are intended to quantify. In the literature, such observations have been organised into classifications of sagittal gait patterns in spastic hemiplegia and diplegia, based on kinematic data, that relate each pattern to the underlying muscle–tendon pathology and to treatment options [82, 83].

1.6.3 Fatigue, endurance and secondary musculoskeletal change

Walking in CP is energetically costly, and fatigue is a recognised and limiting problem among young people with the condition [35]. A dedicated self-assessment instrument for fatigue impact and severity has been developed for youth and young adults with CP [36]. Fatigue has practical consequences for rehabilitation: it constrains the duration and intensity of training sessions and can confound the interpretation of repeated performance tests. Several of the program's studies encountered this directly, for example when declines in six-minute walk distance after a short training period were judged to be potentially influenced by testing fatigue and by the cumulative demands of inpatient rehabilitation [19].

Although the brain lesion is non-progressive, secondary complications, particularly musculoskeletal deformities, can worsen over time if not adequately managed [4, 5]. In adulthood, people with CP experience a higher prevalence of several chronic conditions than the general population [37], and balance has been linked to deterioration of walking in adults with spastic bilateral CP [38]. These findings reinforce the importance of establishing durable walking ability and postural control during childhood and adolescence.

1.7 Postural Control and Balance

Postural control, the ability to maintain and recover balance, depends on the coordinated integration of vestibular, visual and proprioceptive information with appropriate motor responses. Impairment in any of these systems reduces stability and functional performance [39]. In CP, deficits of postural control are common across severity levels and are particularly pronounced in spastic diplegic and dyskinetic presentations [38, 40, 41]. Children with spastic CP may show characteristic impairments of trunk control [40], and experimental work comparing children with CP and typically developing children has shown that the capacity to adapt to changing balance threats is reduced in CP [41].

Two aspects of balance are relevant to the design of rehabilitation devices. *Anticipatory* (proactive) control prepares the body for predictable disturbances, such as those produced by one's own movement, whereas *reactive* control responds to unexpected perturbations. Conventional balance exercises tend to emphasise the former and often fail to challenge the balance system with realistic, unpredictable perturbations of the kind encountered in daily life [20, 39]. This gap provides the rationale for perturbation-based balance training, reviewed in Chapter 2 and implemented in the program's Robotic Perturbation Trainer (Chapter 6).

Clinical assessment of balance in children typically relies on functional scales and timed tests. The program used the Berg Balance Scale in its perturbation study and the Paediatric Berg Balance Scale and Timed Up and Go (TUG) test in its gait trial (Chapter 3). The usefulness of such scales for differentiating specific types of balance deficit has, however, been questioned [39], and the minimal clinically important differences of several balance measures have not been established for children with CP, which complicates the interpretation of small changes [20]. The Paediatric Balance Scale was developed as a modification of the Berg Balance Scale for school-age children with mild to moderate motor impairment, and its reliability was examined in that population [88]; the reliability and validity of the TUG test have been investigated in typically developing children and in children with CP [89].

1.8 Speech, Language and Communication

Communication difficulties are among the most common accompanying impairments in CP. A Swedish population-based study reported that more than one in two children with CP had speech problems [42], and depending on the definition and assessment method used, the reported proportion of children with motor speech disorders ranges from approximately 33% to 63% [43]. The same review noted that speech assessment in this population is poorly standardised, which limits comparison between studies [43].

The most characteristic speech disorder in CP is dysarthria, a motor speech disorder arising from impaired control of the muscles of respiration, phonation, resonance and articulation. Communication disorders in CP are frequently linked with dysarthria, articulation impairment and limited motor control of the speech organs, which together make verbal communication difficult [15]. Reduced intelligibility is not merely a cosmetic problem: children whose speech is harder to understand participate less in communication and in daily life [44], and speech and communication limitations are associated with broader social and educational outcomes [45]. Access to augmentative and alternative communication and other assistive technology is therefore an important part of care for children with communication limitations [46].

Interventions for motor speech disorders in CP include intensive voice treatment and systems-based approaches. A systematic review of motor speech interventions for children with CP found a developing but still limited evidence base [47]. Intensive voice treatment adapted from the Lee Silverman Voice Treatment approach has been studied in children with spastic CP and dysarthria [48], and a secondary analysis of the Speech Systems Approach has examined its effect on intelligibility [49]. Measuring change in speech is itself a methodological challenge. Acoustic analysis of fundamental frequency, formants, intensity and duration has long been used to characterise dysarthric speech objectively [50], whereas the functional standard for intelligibility is an identification task in which blinded listeners record the words they hear [51].

For the languages spoken by children at NCCR, the measurement infrastructure is particularly thin. Kazakh child speech resources are almost absent, the first dedicated Kazakh child speech corpus having been published only recently for speech-technology purposes [52]. For Russian, standardised assessment tools for child speech and language exist but are limited in number, and none is specific to CP or

dysarthria [53]. These gaps shaped both the design of the program's social-robot interventions, which were delivered in Kazakh and Russian, and the outcome measures it explored, including the acoustic and blinded-listener protocol reported in Chapter 11.

1.9 Cognition, Learning and Socio-emotional Functioning

1.9.1 Cognitive profiles

Cognitive impairment is common in CP but highly variable. Children with CP, including those without intellectual disability, often show difficulties with attention, working memory, processing speed and reasoning [54, 55]. Reduced processing speed and attention-related symptoms [56] and problems with executive functions such as working memory, sustained attention and inhibitory control [57] have been reported. Cognitive functioning in dyskinetic CP has been specifically studied in relation to motor function, communication and epilepsy [58]. Estimates of the proportion of children with CP who have an intellectual disability vary with case ascertainment and assessment method. A systematic review that distilled prognostic messages for families reported that about one in two children with CP has an intellectual disability [90], and a population-based register study found intellectual disability in 45% of children whose intellectual status was known [91]; lower figures, of around 30%, are also quoted in the social-robotics literature [15]. Whatever the precise figure, a substantial minority of children with CP, and possibly half, have an intellectual disability.

1.9.2 The assessment problem

Accurate assessment of cognition in children with CP is difficult. Standard instruments such as the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V), and the Wechsler Preschool and Primary Scale of Intelligence were developed primarily for children with typical motor function, and many subtests require fine motor responses, sustained physical effort or rapid verbal output [59–61]. Children with CP may therefore perform below their actual cognitive capacity. Motor-free short forms and adapted administration procedures have been proposed [59, 60], but systematic reviews have shown that the psychometric properties of cognitive assessments in children with motor impairment are often inadequate [61]. A Norwegian national cohort study found that children with more severe motor, communication or visual impairments were the least likely to receive a cognitive assessment at all [62], and follow-up programs for CP have tended to concentrate on physical functioning, with cognitive ability often assumed rather than evaluated [63].

This mismatch between cognitive capacity and measurable performance is not only a diagnostic problem but also a rehabilitation problem. A child whose comprehension, memory or reasoning is underestimated may be offered tasks that are insufficiently challenging, while a child whose difficulties go unrecognised may be offered tasks that are too demanding. Interventions with a measurable impact on cognitive functions in CP have been reviewed systematically [64], but the evidence base remains much smaller than that for motor interventions. This gap motivated one strand of the program's work: using structured, repeated interaction with a socially assistive robot as a context in which cognitive behaviour can be *observed* under reduced motor and verbal demands, rather than formally tested (Chapter 11).

1.9.3 Social, emotional and behavioural functioning

Children with CP may experience difficulties in social cognition, peer relationships and emotional regulation. A randomised controlled trial exploring social cognition in children with CP found relationships with executive functions [65], and a scoping review of socio-emotional development in young children with CP highlighted difficulties in establishing peer contacts and in expressing negative emotions [66]. Higher rates of conduct difficulties, anxiety and attention-deficit/hyperactivity disorder

symptoms have been reported than in the general child population [55, 67]. These findings support rehabilitation approaches that are socially engaging and that attend to motivation and emotional climate, not only to task performance.

1.10 Participation, Quality of Life and Transition to Adulthood

The consequences of motor, communicative and cognitive impairment converge on participation, the involvement of the child in life situations at home, at school and in the community. Children and young people with CP face restrictions in leisure participation [68], and preschool and school-age predictors of community participation have been examined longitudinally [69]. Participation restrictions persist into adolescence [70]. In adulthood, employment has been associated with manual ability in a population-based study [71], and a 13-year follow-up study documented the long-term relationships between quality of life, participation and functional status [72]. A qualitative systematic review of children's and young people's own perspectives on living with CP underscored the importance they attach to social and everyday activities rather than to impairment-level change alone [73].

The International Classification of Functioning, Disability and Health (ICF) provides the conceptual framework within which these levels of functioning, from body structures and functions through activities to participation, are linked. ICF core sets for children and youth with CP have been developed and are being implemented internationally [28]. The widely used "F-words" framework (function, family, fitness, fun, friends and future) translates the ICF into a child- and family-centred language for goal setting [74]. Both frameworks are relevant to this book because they caution against evaluating robotic rehabilitation solely by changes in gait parameters or test scores; the ultimate question is whether a child's participation and quality of life improve.

1.11 Conventional Rehabilitation: Principles, Evidence and Limits

1.11.1 Principles

Contemporary rehabilitation for children with CP is goal-directed, family-centred and multidisciplinary. An international clinical practice guideline on interventions to improve physical function recommends that interventions be based on goals selected by the child and family, that therapy involve active, whole-task practice, and that the choice of intervention take into account the child's age, functional ability, preferences and rehabilitation context [31]. Systematic syntheses of the evidence have graded a wide range of interventions according to the strength of supporting evidence, offering clinicians a "traffic-light" summary of what works, what probably works and what should be discontinued [70].

A common thread in effective motor interventions is the principle that improvement depends on intensive, repetitive, task-specific practice that is meaningful to the child. The capacity of the developing brain for functional reorganisation, documented in studies of gross motor interventions [13], provides the neurobiological justification for this principle. In practice, however, the intensity of practice that can be delivered is constrained by therapist time, by the child's fatigue and motivation, and by the organisation of services.

1.11.2 Gait training and its evidence

Task-specific walking practice can be delivered overground or on a treadmill, and on a treadmill it can be combined with partial body-weight support or with robotic assistance of the legs. A Cochrane review of mechanically assisted walking training in children with CP concluded that such training may produce small improvements in walking speed compared with no walking training, but that it had not been shown to be consistently superior to an equivalent dose of overground walking practice [75]. This finding is

important for the interpretation of the program's results. It implies that the value of robotic or mechanically assisted gait training lies not in any intrinsic superiority of the machine, but in what the machine makes possible: higher practice doses, safer training for children who cannot practise independently, more consistent movement patterns and objective measurement. Chapter 2 examines the robotic gait-training literature in more detail.

1.11.3 Measuring meaningful change

Rehabilitation outcomes in CP are commonly measured with standardised instruments such as the Gross Motor Function Measure (GMFM), the six-minute walk test (6MWT), the 10-metre walk test (10MWT) and the TUG test. A key interpretive question is how large a change must be before it is considered real and clinically meaningful. Distribution-based estimates of the minimal clinically important difference for gross motor function and for gait endurance have been reported for children with motor impairment; for the 6MWT in children with CP at GMFCS levels I and II, these estimates range widely depending on the method used [76]. For several other measures commonly used in the program, including the 10MWT, the TUG and the Berg Balance Scale, minimal clinically important differences for paediatric CP have not been established [20]. This limitation is acknowledged repeatedly in the results chapters of this book, where small individual changes are reported descriptively rather than classified as clinically meaningful.

1.11.4 Limitations of conventional, therapist-delivered rehabilitation

Several structural limitations of conventional rehabilitation emerge from the literature reviewed above and from the experience of the program's clinical partners.

The first is *dependence on specialist time*. Traditional rehabilitation for children with CP is predominantly therapist-driven [18, 23]. Manual gait training, in particular, is physically demanding for therapists, which limits the number of steps a child can practise in a session. The scarcity of qualified specialists, including speech-language pathologists, is especially acute in underserved and remote regions [15].

The second is *dose and consistency*. Because practice intensity is limited by staff availability and by the physical demands of assisting a child, the dose of task-specific practice delivered in routine care may fall below what the motor-learning literature suggests is necessary. Variation between therapists and between sessions also makes it difficult to standardise and document what was delivered.

The third is *engagement and motivation*. Repetitive practice is effective only if the child participates actively, and sustaining engagement over many sessions is difficult, particularly for younger children and those with attention or communication difficulties. Technology-mediated approaches, including socially assistive robots, have been proposed in part because they can provide engaging and repeatable practice without the fatigue that affects human therapists [15].

The fourth is a *historical emphasis on motor outcomes*. Traditional approaches have been criticised for giving limited attention to the communicative, cognitive and social dimensions of development, even though these are equally critical for participation in education and community life [23, 70, 74]. Follow-up programs have likewise tended to focus on physical functioning [63].

The fifth is *measurement*. Clinical outcome measures are typically administered at only a few time points, are subject to ceiling and floor effects and practice effects, and capture limited aspects of performance. Instrumented measurement during therapy itself, which robotic devices make feasible, offers the possibility of richer, session-by-session documentation of change.

None of these limitations implies that conventional therapy is ineffective; the evidence reviewed above shows that many conventional interventions are effective. Rather, they define the specific points at which technology may add value as a complement to, not a replacement for, human therapists. This complementary role is emphasised throughout this book and is consistent with the conclusions of the robotics and social-robotics literature reviewed in Chapter 2 [15, 77, 78].

1.12 The Kazakhstan Context and the National Center for Children's Rehabilitation

1.12.1 Access to rehabilitation services

The program was conducted in the Republic of Kazakhstan, a large country with a dispersed population and significant differences in service provision between urban and rural areas. According to UNICEF, only 28.6% of children with a registered disability in Kazakhstan were covered by specialised social services, and access to rehabilitation in rural areas is further constrained by economic and infrastructural barriers [23, 79]. These systemic limitations make it both challenging and important to investigate scalable, technology-mediated approaches that could extend access to structured therapy.

Paediatric medical rehabilitation in Kazakhstan is delivered through a network of specialised centres and hospital departments. Official information published in 2019 described 12 children's medical rehabilitation centres, three at republican and nine at regional level, with 1,273 beds, together with 39 rehabilitation departments in hospitals with 1,384 beds; children with CP are entitled to republican-level rehabilitation at least once a year [93]. In the same period, the director of the national rehabilitation centre reported that about 5,700 children passed through republican centres each year and that instructors worked with 15 to 20 children per day [94]. These figures illustrate both the scale of the state system and the pressure on specialist time discussed in Section 1.11.4.

The literature on socially assistive robotics also highlights the near absence of research from Central Asia. Reviews and studies by the program's investigators found that published SAR studies for children with CP originate predominantly from Western Europe, North America and East Asia, and that no SAR outcome studies had previously been reported from Central Asian rehabilitation settings [15, 18, 23].

1.12.2 The National Center for Children's Rehabilitation

The clinical site for the program was the National Center for Children's Rehabilitation (NCCR) in Astana, a specialist facility providing rehabilitation services to children with disabilities [80]. The centre provides consultation and rehabilitation through a multidisciplinary team that includes paediatric neurologists, physiotherapists, occupational therapists, speech therapists, psychologists and special-needs teachers, and it integrates medical, psychological, pedagogical and social approaches to rehabilitation [23]. According to program records, NCCR receives approximately 300 children each month (author communication), a throughput that made it feasible to recruit children into several study strands within the program period, while the centre continues to face constraints on access to specialised therapists and technology-based interventions [18].

Children typically attend NCCR for scheduled rehabilitation stays as part of an annual program; in the body-weight support study, for example, participants received approximately one month of multidisciplinary rehabilitation during their stay [19]. The standard programs are individually prescribed and, depending on the child's needs, typically combine kinesiotherapy and physiotherapy, hydrokinesiotherapy, therapeutic massage, speech and language therapy, occupational therapy, and psychological and pedagogical support; some children also receive device-based motor rehabilitation

such as robotic gait training [81]. The centre has a history of incorporating structured neurorehabilitation methods, including reflex locomotion therapy, into the complex rehabilitation of neurological paediatric patients [80].

This organisational model has two consequences for research design that recur throughout the book. First, children enrolled in the program's studies continued to receive their usual multidisciplinary care, so the effects of any single intervention must be interpreted against a background of concurrent therapy. Second, the length of a child's stay at the centre limits the number of sessions that can be delivered within a single admission, which constrains intervention dose and follow-up.

1.12.3 Linguistic and cultural context

Kazakhstan is linguistically diverse, and both Kazakh and Russian serve as clinical languages at NCCR [18]. In the program's social-robot cohorts, the majority of children were Kazakh-speaking, with a substantial Russian-speaking minority [18, 23]. Most commercially available social-robot platforms are optimised for English or major European languages, so bilingual delivery required substantial adaptation, including Kazakh speech synthesis and culturally familiar content [18]. The scarcity of standardised speech, language and cognitive assessment tools in Kazakh and of CP-specific tools in Russian [52, 53] is a further feature of this context that affects both clinical practice and research.

1.12.4 Clinical documentation

A final contextual factor concerns clinical documentation. As noted in Section 1.4.3, standardised functional classifications and formal dysarthria ratings were often unavailable in the clinical records of the children enrolled in the program's social-robot studies [22, 23]. Clinical records at NCCR are predominantly in Russian and include Kazakh personal names, which creates specific challenges for de-identification and structured data extraction. These challenges informed the design of the program's data acquisition and processing platform, described in Chapter 9. Within the program, the team has also prepared a manuscript describing a rule-based pipeline for de-identifying mixed-script, Russian-language paediatric clinical documents containing Kazakh personal names and for extracting structured variables such as GMFCS and MACS levels from them.

1.13 From Clinical Needs to Program Design

The background reviewed in this chapter can be condensed into a set of rehabilitation needs that the program sought to address. Table 1.3 links each need to its clinical rationale and to the program component that responds to it. The table is intended as a map for the rest of the book rather than as a claim that each need was fully met; the evidence for each component is presented, with its limitations, in Part IV.

Table 1.3. Rehabilitation needs identified from the clinical background and the corresponding program components.

Need	Clinical rationale (this chapter)	Program response	Chapter
High-dose, task-specific walking practice that is safe for children who cannot practise independently	Walking is a priority goal; practice intensity is limited by therapist time (Sections 1.6, 1.11)	Gait Rehabilitation Robot (paediatric gait exoskeleton) on a treadmill with body-weight support	4
Individualised setting of training parameters	Heterogeneous contributors to gait dysfunction (Section 1.6.1)	Adaptive body-weight support system with	5

Need	Clinical rationale (this chapter)	Program response	Chapter
		multidomain selection of unloading level	
Training of reactive balance under realistic perturbations	Postural control deficits; conventional therapy rarely challenges reactive balance (Section 1.7)	Robotic Perturbation Trainer	6
Engaging, repeatable communication and cognition practice in the child's language	High prevalence of speech, language and cognitive difficulties; scarce specialists; bilingual context (Sections 1.8, 1.9, 1.12)	QTrobot socially assistive robot delivering Kazakh- and Russian-language modules	7
Objective, session-by-session measurement of gait	Limited sensitivity and frequency of clinical tests (Section 1.11.3)	GARAS gait analysis and rehabilitation recommendation software	8
Systematic, de-identified clinical and sensor data	Incomplete functional classification in records; multilingual documentation (Sections 1.4.3, 1.12.4)	NCCR Rehabilitation Platform for data acquisition and processing	9

1.14 Summary

Cerebral palsy is a heterogeneous, lifelong neurodevelopmental condition defined by disorders of movement and posture arising from non-progressive disturbances of the developing brain, but accompanied in many children by impairments of balance, speech, communication, cognition and socio-emotional functioning. Its etiology is multifactorial and its pathophysiology affects sensory as well as motor networks, while the developing brain retains a capacity for plastic change that underpins intensive, repetitive therapy. Children are described by motor type and topography and, functionally, by the GMFCS, MACS and CFCS, although in the program's clinical setting these functional classifications were not always recorded. Prevalence is approximately two to three per 1,000 live births internationally; no population-based surveillance estimate exists for Kazakhstan, although official data show that several thousand children with CP receive medical rehabilitation each year.

Conventional, goal-directed rehabilitation is supported by a substantial evidence base, but it is constrained by therapist availability, by the difficulty of delivering and documenting high practice doses, by the challenge of sustaining engagement, by an historical focus on motor outcomes and by the limited sensitivity of periodic clinical tests. In Kazakhstan, these constraints are compounded by limited coverage of specialised services, especially in rural areas, and by a bilingual Kazakh–Russian context for which few standardised tools exist. The NCCR in Astana, the program's clinical partner, offers multidisciplinary inpatient rehabilitation within which new technologies can be evaluated alongside usual care. These needs define the rationale for the devices and software presented in this book, and Chapter 2 now examines the international state of the art in the technologies the program adopted.

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Chapter 2. Robotics and AI in Paediatric Rehabilitation: State of the Art

Abstract. This chapter reviews the international state of the art in the technologies adopted by the program: robot-assisted gait training with treadmill-based exoskeletons, body-weight support (BWS), perturbation-based balance training, socially assistive robots (SARs), and instrumented gait analysis supported by artificial intelligence (AI). For each technology, the chapter explains the underlying rationale, summarises the clinical evidence available in children with cerebral palsy (CP), and identifies the limitations of that evidence. The review shows that robot-assisted gait training can deliver intensive, repeatable stepping practice, but that its advantages over dose-matched conventional training are inconsistent and that the choice of training parameters such as speed and unloading remains largely empirical. Perturbation-based training has a strong rationale and growing evidence in adult neurological populations, but paediatric implementations have been limited in perturbation direction and in the simultaneous measurement of muscle activity. SARs are consistently reported to be feasible and engaging for children with CP, yet the evidence base is dominated by small, short, single-language studies with heterogeneous outcomes. Instrumented sensing and machine learning offer objective, frequent measurement, but validated paediatric pipelines that translate sensor data into clinically interpretable indices are scarce. The chapter closes with a structured statement of the research gaps that the program set out to address.

Keywords: rehabilitation robotics; exoskeleton; robot-assisted gait training; body-weight support; perturbation-based balance training; socially assistive robots; QTrobot; instrumented gait analysis; machine learning; cerebral palsy

2.1 Introduction

Chapter 1 identified a set of rehabilitation needs in CP that conventional, therapist-delivered care struggles to meet: the delivery of high doses of task-specific practice, the individualisation of training parameters, the training of reactive balance, sustained engagement in communication and cognitive practice, and objective, frequent measurement of change. Rehabilitation technology has been proposed as a means of addressing each of these needs. Early reviews of robot-assisted and computer-enhanced therapies for children with CP described both the promise of these technologies and the practical challenges of implementing them in clinical services [1]. From the perspective of locomotor neurorehabilitation more generally, the clinical application of robotics has been framed in terms of its capacity to provide intensive, repetitive and well-controlled training, while emphasising that devices must be matched to the patient's impairments and integrated into a broader therapeutic program [2].

Since those early reviews, the field has diversified considerably. Systematic and scoping reviews now address robotic systems for the physiotherapy treatment of children with CP [3, 4], robotic exoskeletons for gait rehabilitation in CP [5], robotics for gait and balance with biomechanical implications [6], intelligent robotics in paediatric cooperative neurorehabilitation [7], and the use of robots with children with disabilities more broadly [8, 9]. Reviews of usability have considered the perspectives of both patients and healthcare professionals on robotic and virtual-reality devices in neuromotor rehabilitation [10]. In parallel, socially assistive robotics has emerged as a distinct field concerned with assistance through social interaction rather than physical contact [11, 12].

This chapter does not attempt to duplicate these reviews. Instead, it focuses on the specific technologies the program adopted, and for each it asks three questions: What is the rationale? What does the evidence

in children with CP show? What remains unknown? The final section draws these threads together into a statement of research gaps.

2.2 Robot-Assisted Gait Training

2.2.1 Rationale and device classes

Robot-assisted gait training (RAGT) uses powered devices to guide or assist the legs through a stepping pattern, usually while the patient walks on a treadmill with partial body-weight support. Its rationale follows from the principles summarised in Chapter 1: motor learning depends on repetitive, task-specific practice, and a robot can deliver many more steps per session than a therapist assisting the legs manually, with a more consistent kinematic pattern and with continuous recording of joint angles and forces.

Gait-training robots are commonly grouped into two broad classes. *Exoskeleton-type* devices have joints aligned with the patient's hip and knee (and sometimes ankle) and apply torques directly to the limb segments, typically while the patient is suspended over a treadmill. *End-effector* devices instead move the feet along a prescribed trajectory, with the proximal joints left free. Wearable exoskeletons for overground walking form a third, more recent category. The treadmill-based exoskeleton class is exemplified by the Lokomat, which originated as a driven gait orthosis for people with paraplegia [137] and whose paediatric version has been evaluated in children with CP [138]. End-effector devices include the mechanised Gait Trainer [139] and the G-EO system, which extends end-effector training to floor walking and stair climbing [140]. Wearable and mobile paediatric systems include a powered knee exoskeleton designed to treat crouch gait in children with CP [141] and the CPWalker platform, which combines a robotic walker with a lower-limb exoskeleton for overground training [142].

A recent systematic review by members of the program team examined robotic exoskeletons for gait rehabilitation specifically in CP [5]. Following PRISMA guidelines, it analysed 30 lower-limb exoskeletons reported in 57 papers published between 2010 and 2024, assessing each device's design, rehabilitation interface, technological features, user experience and clinical effectiveness. The review identified a growing tendency to adapt exoskeleton functions to the individual user, supporting more personalised rehabilitation, but found a lack of long-term evaluations and of evidence on whether therapeutic benefits are sustained. It also emphasised usability, calling for user-friendly designs that encourage prolonged engagement and adherence to therapy [5].

2.2.2 Clinical evidence in children with CP

The clinical evidence for RAGT in CP is growing but remains mixed. A systematic review with meta-analysis comparing robot-assisted gait therapy with conventional therapy or treadmill training in children with CP found advantages for robotic therapy in some outcomes, including walking speed and walking distance, but these advantages were not consistent across all outcomes or comparators [13]. The Cochrane review of mechanically assisted walking training, discussed in Chapter 1, reached a similar overall conclusion: mechanically assisted walking may yield small gains in walking speed compared with no walking training, but it has not been shown to outperform an equivalent dose of overground walking practice [14].

Individual trials illustrate both the potential and the variability of response. In a randomised controlled trial of a robotic-assisted gait training program for ambulatory children with CP, no significant between-group advantage in spatiotemporal gait parameters was found for robotic compared with conventional body-weight-supported treadmill training, and baseline motor function influenced the change in gait parameters [15]. In children with unilateral CP, a course of ten 20-minute robotic sessions was reported to produce greater improvements in walking speed and six-minute walk distance than conventional care,

together with changes in cerebral connectivity [16]. A study of patient-specific factors in bilateral spastic CP associated functional improvement after robotic gait training with disability severity and treatment exposure, albeit in a cohort with a broad age and functional range [17]. Work using muscle-synergy analysis has asked whether changes in neuromuscular coordination can explain the motor gains seen after robotic training in children with CP [18].

The question of *dose and parameter selection* has received comparatively little attention. A randomised study of training intensity in RAGT for children with CP compared different combinations of walking speed and BWS (higher speed with lower BWS, lower speed with higher BWS, and intermediate settings) and found that these combinations improved different functional domains, leading the investigators to recommend that training intensity be adjusted to the child's goals [19]. Because speed and BWS were manipulated together, however, that study could not isolate the effect of either parameter [19, 20]. This limitation is directly relevant to the program's work on individualised BWS selection (Section 2.3 and Chapter 5).

Taken together, these studies suggest that RAGT is safe and can improve walking in some children, that the response is heterogeneous and influenced by baseline function, and that the advantage over well-dosed conventional training is uncertain. They also suggest that the most promising role for robotics may lie in enabling higher, better-documented and better-individualised doses of practice rather than in the robot's guidance per se.

2.2.3 Control strategies: from position control to assist-as-needed

The earliest treadmill-based gait-training robots, such as the driven gait orthosis from which the Lokomat developed, were largely position-controlled, imposing a fixed reference trajectory on the limbs [137]. A concern with this approach is that it may encourage passive participation, since the robot moves the legs regardless of the patient's effort. Subsequent research therefore shifted towards interaction control strategies that modulate assistance according to the patient's contribution.

The program's device lineage reflects this shift. Earlier work by members of the team developed an intrinsically compliant robotic gait training orthosis and investigated several control strategies for robotic orthoses of this kind, including adaptive impedance control [21], robust nonlinear control [22], general control of a robotic orthosis for gait rehabilitation [23] and assist-as-needed control, in which robotic assistance is reduced as the patient's own contribution increases [24]. More recent work has addressed the design and analysis of a multi-degree-of-freedom compliant gait rehabilitation robot [25], nonlinear model predictive control of a self-aligning compliant gait rehabilitation robot [26], and the design and transparency assessment of a gait rehabilitation robot with biomimetic knee joints [27]. Transparency, the extent to which a robot can follow the patient's movement without imposing resistive forces, is an important property for assist-as-needed operation because it determines how faithfully the patient's own effort can be expressed and measured. These earlier projects provide the technical background for the program's Gait Rehabilitation Robot described in Chapter 4; they were not outputs of the present grant.

A related development in the wider exoskeleton field is *human-in-the-loop optimisation*, in which assistance parameters are tuned in real time on the basis of a physiological or performance objective measured from the user, for example to minimise metabolic cost during walking [28]. Such approaches typically use Bayesian optimisation, which is designed to find the optimum of an expensive, noisy and unknown function in as few evaluations as possible [29, 30]. Although human-in-the-loop optimisation has been developed mainly in adults, its logic is directly relevant to the individualisation of training parameters in children with CP.

2.2.4 Open questions for paediatric gait robots

Several questions remain open. First, paediatric devices must accommodate a wide range of body sizes and growth, which complicates mechanical design and alignment of robot and anatomical joint axes. Second, children with CP differ widely in spasticity, contracture and selective motor control (Chapter 1), so a controller tuned for one child may be inappropriate for another. Third, most clinical studies report outcomes only before and after a training block, so little is known about the trajectory of change during training. Fourth, although robots record rich data during every session, these data are rarely translated into clinically interpretable indices that therapists can use to adjust therapy. The program's Gait Rehabilitation Robot and its gait analysis software (Chapters 4 and 8) were designed with these questions in mind.

2.3 Body-Weight Support

2.3.1 Rationale

Body-weight support (BWS) partially unloads the lower limbs, usually by means of a harness connected to an overhead suspension system, so that a child who cannot bear full weight or maintain balance can nevertheless practise stepping on a treadmill. It is used both on its own, as partial body-weight-supported treadmill training, and as an integral component of most robotic gait trainers. Early work reported that body-weight-supported treadmill training improved the regularity of stepping kinematics in children with CP [31].

2.3.2 Effects of the unloading level

The magnitude of unloading is not a neutral setting. Experimental studies show that changing the level of BWS alters the mechanical and neuromuscular demands of walking. In children with CP, progressively increasing BWS reduced the activation of several muscles involved in supporting body weight, including the gluteal muscles and vastus lateralis, while the complexity of muscle synergies remained largely unchanged; greater unloading thus reduced antigravity demand without necessarily improving motor-control organisation [32]. In children with unilateral CP, immediate neural and biomechanical responses differed across 0%, 20% and 40% BWS, with limited changes in muscle-synergy measures but condition-specific changes in measures of gait deviation [33]. Related work has examined how walking speed influences gait asymmetry and variability in children with CP [34] and how acute responses to locomotor tasks differ according to the pattern of gait asymmetry in hemiplegic CP [35].

These findings carry two implications. First, there is little basis for assuming that a single unloading percentage is optimal for every child. Second, an unloading level that improves one gait characteristic may not improve others, so selection on the basis of a single variable may overlook competing effects on symmetry, variability, loading and centre-of-pressure behaviour [20]. The evidence that BWS-assisted walking is not consistently superior to dose-matched overground practice [14] further suggests that the level of support should be treated as an adjustable training parameter rather than assumed to be beneficial in proportion to its magnitude.

2.3.3 Selecting the level of support

Despite this evidence, objective methods for choosing a participant-specific BWS level remain scarce. Existing studies have mainly characterised responses to a few BWS conditions rather than formalising how a condition should be selected [20]. Selecting among several tested conditions on the basis of multiple gait characteristics is, in methodological terms, a multi-criteria decision problem. Established

tools for such problems include composite indicators with explicit normalisation, weighting and aggregation choices, whose robustness can be assessed by uncertainty and sensitivity analysis [36, 37], and ranking methods such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [38]. Bootstrap resampling provides a general means of quantifying the stability of such selections [39]. Alternatively, as noted in Section 2.2.3, the relationship between unloading and gait quality can be modelled as a continuous function and its optimum located by response-surface modelling or Bayesian optimisation [29, 30]. Chapter 5 describes how the program applied a multidomain, within-participant selection framework of this kind and how it plans to extend it.

Engineering considerations also matter. BWS systems differ in whether they provide static or dynamic unloading, in how accurately they maintain the target force during the vertical oscillations of walking, and in how they are integrated with treadmills and robots. In practice, the unloading actually delivered to the child may differ from the commanded value because of harness losses and trunk movement, a discrepancy that the program's data-collection protocols explicitly sought to measure using instrumented insoles [40]. The size of this discrepancy depends on the design of the support system. In a laboratory comparison, passive counterweight systems showed mean unloading errors of up to 5.3 kg and static systems with a fixed suspension length errors of about 11 kg during treadmill walking, whereas a mechatronic system combining a passive spring with closed-loop force control kept the mean error below 1 kg and could also deliver time-varying unloading profiles [143]. Static and dynamic BWS are therefore not interchangeable, and the achieved, rather than the commanded, unloading should be reported.

2.4 Perturbation-Based Balance Training

2.4.1 Principles

Perturbation-based balance training (PBT) exposes a person to repeated, controlled and often unexpected disturbances of balance during standing or walking, with the aim of improving reactive balance control, the ability to maintain or regain stability after a perturbation [41]. Its rationale rests on the observation, introduced in Chapter 1, that conventional balance therapy seldom challenges the balance system with realistic, unpredictable disturbances [42, 43]. A review of the principles, mechanisms and clinical implementation of PBT has described how repeated exposure to perturbations can drive both rapid within-session adaptation and longer-term improvements in reactive responses [41].

2.4.2 Evidence in adult neurological populations

Most of the clinical evidence for PBT comes from adult populations. A systematic review and meta-analysis found perturbation-based training to be effective in improving balance in patients with stroke [44]. In Parkinson's disease, a systematic review reported benefits for postural control and gait [45], and an experimental study showed that people with Parkinson's disease adapted their stability during repeated perturbed walking [46]. PBT has also been studied in post-operative individuals with degenerative cervical myelopathy [47] and in healthy older adults, in whom acute effects on cognitive performance were explored [48]. In people with cerebellar ataxia, repeated waist-pull perturbations during treadmill walking were shown to exploit residual motor-learning capacity and to improve gait stability [49].

2.4.3 Perturbation training in children with CP

In paediatric CP, perturbation-based and balance-challenging interventions have been explored using a variety of mechanical arrangements and planes of motion. An early pilot study examined the effect of balance training on the muscle activity used to recover stability in children with CP [50]. A feasibility

study delivered perturbation-based training on compliant surfaces to improve balance in children with CP [51]. During treadmill walking, gradually increasing the perturbation load was found to produce longer retention of locomotor adaptation in children with CP than an abrupt increase [52]. Using a cable-driven Tethered Pelvic Assist Device, timed frontal-plane pelvic moments during overground walking altered pelvic motion not only in the frontal plane but also in the sagittal and transverse planes, while increasing activation of the gluteus medius, a muscle central to pelvic stability [53].

Cable-driven parallel mechanisms are well suited to applying controlled forces to the pelvis because they are lightweight, have a large workspace and can be integrated around a treadmill. Their design requires attention to workspace and to the condition that all cables remain in tension, since a slack cable cannot transmit force [54].

2.4.4 Gaps

The program's review of this literature concluded that existing implementations were often restricted to particular perturbation directions, to stationary conditions or to non-standardised delivery mechanisms, and that the application of controlled transverse-plane perturbations during walking, together with simultaneous measurement of muscle activation, had been insufficiently described [43]. In addition, almost all paediatric studies are small feasibility studies, and the minimal clinically important differences for many balance outcomes in children with CP have not been established, which limits the interpretation of change [43, 55]. These gaps motivated the design of the program's Robotic Perturbation Trainer, described in Chapter 6.

2.5 Socially Assistive Robots

2.5.1 Concept

Socially assistive robots are designed to help users through social interaction, such as speech, gesture, facial expression and contingent feedback, rather than through physical contact [11]. They typically take humanoid or animal-like forms, and their defining feature is the capacity for interpersonal engagement [12, 56]. Surveys of social-robot design trace the evolution of these platforms over several decades [57]. In rehabilitation, SARs are proposed to offer consistent, engaging and fatigue-free support that can deliver highly repeatable interventions without the limitations of human fatigue or emotional strain [58].

2.5.2 Evidence from other paediatric and clinical populations

The largest body of SAR evidence comes from children with autism spectrum disorder (ASD). A systematic review and meta-analysis of 40 studies, 17 of them randomised controlled trials, found that robot-mediated interventions improved social functioning in children on the autism spectrum, with a small-to-moderate pooled effect (Hedges' $g = 0.35$, 95% CI 0.09 to 0.61); younger children appeared to benefit more, and the RCTs were short, with a mean of nine sessions [59, 60]. A landmark home-based study extended a SAR protocol to approximately 30 daily sessions and reported improved joint attention in children with ASD [61]. Reviews have also examined whether robots are ready to deliver autism interventions [62] and how efficacy findings translate from the laboratory to real-world settings [63]. Of particular relevance to this book, children with ASD were found to direct more sustained attention towards QTrobot than towards a human partner and to show fewer repetitive and stereotyped behaviours during robot interaction [64].

Beyond ASD, SARs have been studied in education [65], as mental-health interventions for children [66], in social anxiety [67], in dementia, where a meta-analysis assessed feasibility, acceptability and effects on cognition and quality of life [68], in stroke rehabilitation, where patients and caregivers

reported their acceptance, needs and concerns [69], and in mild cognitive impairment, where they may support cognitive stimulation and social mediation [70]. Reviews of robotic rehabilitation for cognitive training [71] and of cognitive robots in developmental disorders [72] provide further context.

2.5.3 Socially assistive robots for children with CP

Interest in SARs specifically for children with CP has grown over the past decade. An early review described the emergence of socially assistive robotics in CP rehabilitation [73], and a meta-analysis published in 2021 synthesised the available studies [74]. To map the field comprehensively, the program's investigators conducted a scoping review following the PRISMA-ScR framework, searching six databases for studies published between 2015 and 2025 that used a social robot in cognitive, speech, communication or engagement-focused rehabilitation of children aged 18 years or younger with CP [58]. This review, published in the *Journal of NeuroEngineering and Rehabilitation*, is summarised here because it framed the program's social-robot research agenda.

Twenty studies met the inclusion criteria. They originated from 13 countries, predominantly in Western Europe and North America, with contributions from Latin America and Asia, and none from Central Asia [58]. The studies addressed six principal outcome domains: speech production, language comprehension and expression, attention and memory, social communication and pragmatics, symbolic play, and motor function combined with social interaction. Humanoid robots dominated, and the NAO platform was the most frequently used, although animal-like and non-anthropomorphic devices were also represented [58].

Several individual studies illustrate the range of applications. A semi-autonomous, animal-like SAR designed to elicit communication, motor skills, emotion and visual regard in young children with complex CP produced higher and more stable engagement over time than a switch-adapted toy [75]. A 16-session intervention with a NAO robot for a child with dyskinetic CP sustained motivation for walking practice, with functional gains documented by goal attainment scaling [76]. A robot-mediated free-play intervention improved playfulness in children with severe motor limitations [77]. The NAOTherapist platform has been used for upper-limb rehabilitation in a longitudinal study with paediatric patients [78] and, in a gamified form, for intensive therapies in neurorehabilitation [79], supported by a three-layer planning architecture for autonomous control of therapy sessions [80]. A general-purpose social robot was adapted for paediatric rehabilitation through in situ design with clinicians [81]. Engagement dynamics in a non-verbal communication game for CP have been personalised algorithmically [82], and home-based engagement and adherence have been explored with the REHAB-PAL system [83]. Speech-oriented applications include a robotic assistant for speech therapy [84], the humanoid MARKO, which enabled children to follow instructions and sustain short dialogues [85, 86], and automatic speech recognition fine-tuned on Japanese and English dysarthric speech [87]. Robotic coaching of motor function in CP was explored early by Fridin and Belokopytov [88], and a scoping review has examined robot-assisted therapy for upper-limb impairment in CP [89]. Robot-assisted therapy has also been framed as a complementary and alternative approach in CP rehabilitation [90], and a recent Russian-language study examined the potential for improving speech function in children with CP using robotic devices and biofeedback [91].

Across studies, children accepted SARs readily, often perceiving them as companions or play partners, and parents and clinicians reported high satisfaction, increased adherence and reduced therapist workload [58]. The scoping review nevertheless identified important limitations. Most studies included fewer than 20 participants; few extended over multiple weeks or included follow-up, leaving the durability and transfer of gains largely unknown; outcome measures were heterogeneous, preventing aggregation; children at GMFCS and MACS levels IV–V were underrepresented; and speech-language

interventions were almost always delivered in a single language, with little exploration of multilingual deployment [58]. Technical progress in dysarthric and multilingual speech recognition had not yet been integrated into clinical trials [58]. A later analysis by the program team observed that none of the 20 studies measured speech itself using instrumental acoustic analysis or blinded listener judgements of intelligibility [92].

The review concluded that SARs are best understood as complements to, rather than replacements for, therapists: by automating repetitive demonstrations, structuring practice and maintaining engagement, they may free clinicians to concentrate on more complex, individualised work, which is particularly relevant where access to specialists such as speech-language pathologists is limited [58]. Cost, technical infrastructure and the need for professional training remain barriers to wider adoption [58].

2.5.4 The QTrobot platform

Because QTrobot is the social robot used throughout the program, its characteristics are summarised here; its adaptation for Kazakh and Russian is described in Chapter 7. QTrobot is a child-sized humanoid robot developed by LuxAI S.A. (Luxembourg) for research, teaching and therapeutic use with children [93]; the program used the AI@Edge model [95]. Its face is a digital display on which animated emotional expressions, such as happiness, sadness and surprise, are rendered, and its upper body has twelve degrees of freedom for arm and head gestures [60]. For perception it carries a three-dimensional depth camera for vision and gesture recognition and an array of microphones for voice capture, and it produces speech through onboard text-to-speech synthesis [60, 94]. Its software architecture supports both autonomous execution of scripted behaviours and teleoperation, allowing a supervising therapist to trigger behaviours in real time, and in therapeutic configurations a child-facing tablet presents task content while a second tablet allows the therapist to select and pace scripts [60, 94, 95].

The design of QTrobot emphasises simplicity and predictability, with the aim of reducing the social-processing demands that can overwhelm children with developmental difficulties [60]. The first empirical study with the platform, in fifteen children with ASD, found more sustained attention towards the robot than towards a human partner and fewer repetitive and stereotyped behaviours [64], and later work has extended its use to social-skills groups, emotion-recognition training and structured therapeutic protocols in several countries [96]. Almost all published QTrobot intervention studies, however, have involved children with ASD rather than children with CP, have been brief and have been conducted in laboratory rather than clinical settings [60]. Before the program began, therefore, there was no published evidence on the use of QTrobot with children with CP in a routine rehabilitation setting, and none in Kazakh or Russian.

2.5.5 Language, culture and storytelling

Language adaptation is a concrete implementation challenge for SARs. Most commercially available platforms are optimised for English or major European languages, and their use in multilingual or minority-language settings requires substantial customisation [60]. Social robots have been proposed as cultural brokers that can mediate between children of different linguistic backgrounds and support translanguaging pedagogy [97], and robots have been used for second-language tutoring with preschool children [98]. A review of interactive scenarios for speech and language therapy with social robots [99] and a study of SARs in speech-language therapy for children with language impairments [100] provide models for therapeutic content. Storytelling with robots has been studied as a vehicle for language development in preschool children [101], including in a long-term study of rapport, social emulation and language learning with a peer-like robot [102], and a storytelling robot was proposed for paediatric rehabilitation as early as 2000 [103]. Case studies of robot-assisted speech therapy for children with

language disorders [104] and studies of preschool children's engagement with a social robot during literacy activities [105] add further evidence.

Two further factors shape child–robot interaction. Developmental stage and individual characteristics strongly influence how children respond to robots [106], and parental involvement in robot-mediated interventions has been systematically reviewed across European and Asian contexts [107]. Both factors are relevant to the bilingual, family-attended sessions conducted at NCCR, which are described in Chapters 7 and 11.

2.5.6 Measuring engagement and outcome

Engagement is central to SAR research but difficult to measure. Engagement is commonly conceptualised as having behavioural, emotional and cognitive components that are related but distinct [108], of which only the behavioural component is directly observable [109]. A scoping review of 286 studies of children's engagement in early childhood settings found that almost two-thirds provided no clear definition of engagement and that many used single-use scales without reliability evidence [110]. In child–robot interaction, engagement has been evaluated through behavioural coding of gaze, gesture, vocalisation and task participation [111].

Most SAR studies have relied on pre–post comparisons, which cannot reveal how change unfolds over sessions. Multi-session observational studies with the Kaspar robot illustrate the alternative: one study documented 111 individual sessions with seven children over ten weeks and found session-level improvements in communication, imitation and attention that were not uniform across children [112], and another highlighted a "disposition-of-the-day" effect whereby children's states varied substantially between sessions [113]. Developmental science offers methods suited to such data, including the microgenetic method for studying change through dense repeated observation [114] and growth-curve modelling of individual trajectories [115].

Automated measurement is an active research area. Deep-learning approaches for detecting user engagement in human–robot interaction have been reviewed [116]; real-time attention classifiers [117], robot-based screening technologies [118] and supervised models of engagement in long-term in-home SAR interventions [119] have been developed, mainly for children with ASD; and engagement has been recognised automatically from facial expressions in educational settings [120]. Direct comparisons between robots and other digital media are rare. In ASD, stakeholders accepted both a robot-assisted and a tablet-based social training scenario, with the tablet often preferred because of its familiarity and ease of use [121], whereas in parent–toddler play the physical presence of a robot was associated with more non-verbal communication and greater enjoyment than a tablet [122]. No such comparison had been reported in children with CP before the program's own exploratory study (Chapter 11). A systematic review of mobile applications for people with CP and their caregivers rated most of the included studies at moderate or serious risk of bias [123].

2.6 Instrumented Gait Analysis and Artificial Intelligence

2.6.1 Wearable sensing

Three-dimensional laboratory gait analysis remains the reference standard for detailed biomechanical assessment in CP, but it is expensive, time-consuming and unsuited to frequent measurement during therapy; its efficacy in clinical decision-making has been systematically reviewed [145]. Wearable sensors offer a complementary approach. Instrumented pressure insoles measure plantar pressure distribution and allow foot-contact events, such as initial contact and toe-off, to be detected; the accuracy of pressure-based event-detection algorithms has been evaluated across slopes and walking speeds

[124]. Smart insoles have been used to quantify gait in rehabilitation, for example in a personalised self-management system for stroke survivors, where walking speed and heel-strike performance improved while gait symmetry declined, illustrating that different gait characteristics can change in opposite directions [125]. Surface electromyography (sEMG) provides information on muscle activation and co-contraction, quantified, for example, with the Falconer–Winter co-contraction index [126], and has been used to study the neuromuscular effects of BWS and robotic training in CP [18, 32]. Inertial measurement units (IMUs) provide segment orientations and joint angles, and human-activity-recognition models based on wearable sensors have been validated in children with CP as well as in typically developing children [127].

Robotic devices are themselves rich sources of data. Joint encoders record hip and knee angles at every step, and motor currents or load cells provide estimates of the interaction torque between robot and limb. In principle, these signals allow the patient's own contribution to movement to be separated from the robot's assistance, which is directly relevant to assist-as-needed training (Section 2.2.3). Force sensors in the joints of a treadmill-based exoskeleton have been used, for example, to compute biofeedback values that reflect the patient's active contribution during each step [144]. In practice, translating such signals into clinically meaningful and validated measures for children remains largely unexplored.

2.6.2 Summary indices of gait

Because gait is multidimensional, a long tradition of research has sought to summarise it in a small number of indices. The Gait Deviation Index provides a single score of gait pathology relative to typically developing children [128], and the Gait Profile Score and Movement Analysis Profile decompose overall deviation into joint-level contributions [129]. These indices were developed for laboratory kinematics. For wearable and robot-embedded data, analogous composite indices must be constructed with careful attention to normalisation, weighting and aggregation, which are methodological choices that influence the result and should be tested by sensitivity analysis [36, 37]. Chapter 8 describes the program's approach to this problem in its gait analysis pipeline and its proposed Gait Recovery Index.

2.6.3 Machine learning and AI

Machine learning has been applied to gait and postural data in several ways relevant to CP. Deep sequential networks trained on smart-insole data have been used to identify abnormal gait, with feature-ablation analysis used to examine which signals drive classification [130]. Deep learning has been applied to postural-control data to distinguish hemiplegic from diplegic CP [131]. Beyond classification, model-based optimisation methods, such as Gaussian-process regression and Bayesian optimisation, allow device parameters to be individualised efficiently [28–30], and hierarchical models allow individual estimates to borrow strength from a cohort when individual data are sparse [132].

In speech and communication, automatic speech recognition for dysarthric speech has advanced, including fine-tuned models for Japanese and English dysarthric speech [87], but resources for Kazakh child speech are only beginning to appear [133]. Objective acoustic analysis can be performed with established phonetic software [134, 135], and listener-based intelligibility remains the functional standard [136]. In SAR research, automated engagement detection is developing rapidly (Section 2.5.6) but has not yet been validated in children with CP.

A recurring limitation across these applications is the gap between algorithmic performance and clinical utility. Many models are trained on small, single-site datasets, validated retrospectively and not integrated into clinical workflows. For a therapist at a rehabilitation centre, an AI system is useful only

if its outputs are interpretable, robust to the variability of real sessions and linked to decisions the therapist can actually make, such as adjusting assistance, unloading or task difficulty.

2.7 Implementation in Clinical Services

A technology that performs well in a laboratory study may still fail in routine practice. Early reviews of robot-assisted therapies for children with CP drew attention to the practical requirements of clinical implementation, including staff training, set-up time, patient selection and integration with the existing therapy program [1]. Reviews of usability have shown that the acceptability of robotic and virtual-reality devices depends on the perspectives of both patients and professionals, and that usability problems can limit adoption even when clinical benefit is plausible [10]. For socially assistive robots, the program's scoping review identified cost, technical infrastructure and the need for professional training as the principal barriers to equitable integration, and recommended that future studies report practical endpoints such as safety, set-up time and responsiveness to the child's mood and context, alongside clinical outcomes [58]. Clinical reviews of intelligent robotics in paediatric neurorehabilitation similarly emphasise cooperation between the child, the therapist and the machine rather than automation of therapy [7].

These considerations are amplified in settings with limited resources. The cost of commercial gait-training systems places them beyond the reach of many rehabilitation centres, and devices designed for one health system may not suit the staffing, infrastructure and languages of another. Robot-assisted rehabilitation remains costly and is therefore available mainly in high-income countries, with few solutions designed for low- and middle-income settings [148]. The scoping review noted that SARs might extend therapeutic reach in underserved or remote regions through hybrid clinic–home models and remote monitoring, provided that these barriers are addressed [58]. For the present program, which operated in a national rehabilitation centre serving children from across Kazakhstan, the implications were twofold: devices needed to be manufacturable and serviceable locally, and their software, content and documentation needed to be available in Kazakh and Russian. These requirements are taken up in Chapter 3 and in the device chapters of Part II.

2.8 Integrated, Multimodal Rehabilitation Platforms

The technologies reviewed above have largely developed in separate research communities. Gait robots, BWS systems, perturbation devices and SARs are usually studied in isolation, and the data they produce are rarely combined. The scoping review of SARs in CP explicitly identified a lack of synthesis on personalisation strategies, multimodal interaction and the integration of SARs into hybrid cognitive–physical rehabilitation models [58]. Similarly, the international literature has given limited attention to the deployment of these technologies within the routine workflow of a clinical centre, to their use in non-Western and multilingual settings, and to the data infrastructure needed to aggregate and share their outputs responsibly.

Virtual reality and gamification are frequently proposed as means of enhancing engagement in robotic gait training, and usability studies have considered both robotic and virtual-reality devices from the perspectives of patients and professionals [10]. In children with gait disorders, including children with CP, adding virtual-reality scenarios to robot-assisted treadmill training increased active participation within sessions compared with conventional robotic training [146, 147], although these studies examined immediate engagement rather than longer-term clinical outcomes. They provide the context for the program's head-mounted virtual-reality software for exoskeleton training (certificate №74149), described in Chapter 9.

2.9 Research Gaps Addressed by the Program

Table 2.1 summarises the principal gaps identified in this chapter and indicates where in the book the program's response is described. As in Chapter 1, the table identifies what the program set out to address; whether and to what extent each gap was closed is evaluated in Part IV.

Table 2.1. Research gaps identified in the state of the art and the program's corresponding work.

Area	Gap identified in the literature	Program response	Chapter
Robot-assisted gait training	Inconsistent advantage over dose-matched training; heterogeneous response; little session-level measurement; few paediatric-specific devices	Gait Rehabilitation Robot with embedded sensing; randomised controlled trial in adolescents with CP	4, 10
Body-weight support	Unloading level chosen empirically; speed and BWS confounded in previous studies; no formal multidomain selection method	Adaptive BWS system; within-participant multidomain selection framework with robustness analysis	5, 10
Perturbation-based training	Limited perturbation directions; transverse-plane perturbations during walking with simultaneous EMG insufficiently described	Cable-driven Robotic Perturbation Trainer, from transverse-plane to multi-plane pelvic perturbations	6, 10
Socially assistive robots	Small, short, single-language studies; no Central Asian evidence; heterogeneous outcomes; no session-level trajectories; severe CP underrepresented	QTrobot interventions in Kazakh and Russian; longitudinal, microgenetic, speech and narrative studies; randomised trial registration	7, 11
Outcome measurement for SARs	Engagement poorly defined; speech not measured acoustically or by blinded listeners; no robot–tablet comparison in CP	Segment-level engagement codebook; acoustic and blinded-listener protocol; exploratory robot–tablet comparison	11
Instrumented gait analysis and AI	Few interpretable, validated paediatric indices from wearable and robot-embedded data	GARAS gait analysis and rehabilitation recommendation software; Gait Recovery Index (in development)	8
Data infrastructure	Limited integration of multimodal data; challenges of de-identification in multilingual records; limited open data	NCCR Rehabilitation Platform; planned public de-identified dataset	9, 13

2.10 Summary

Rehabilitation robotics for children with CP has matured from early proof-of-concept systems to a diverse set of technologies with a growing, if uneven, evidence base. Robot-assisted gait training can deliver intensive and repeatable practice, but its benefits over dose-matched conventional training are inconsistent, responses vary with baseline function, and training parameters such as speed and BWS are seldom individualised in a principled way. The level of BWS alters neuromuscular demand and affects different gait characteristics in different ways, which argues for multidomain, participant-specific selection. Perturbation-based training is well grounded in adult neurological rehabilitation, but paediatric implementations remain few, small and limited in perturbation direction. Socially assistive robots are consistently reported to be feasible and engaging for children with CP, yet the evidence is

dominated by small, short, single-language studies with heterogeneous outcomes, and no evidence existed from Central Asia before the program began. Instrumented sensing and machine learning promise objective, frequent measurement, but interpretable and validated paediatric pipelines are scarce, and the integration of devices and data within a clinical workflow has received little attention. Chapter 3 describes how the program was designed to address these gaps.

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Chapter 3. Program Design and Methodology

Abstract. This chapter describes how the research program reported in this book was organised and conducted. The program was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under program-targeted grant BR27199433 (2024–2026), received co-financing from Zein Invest LLP, and was led by Nazarbayev University in partnership with the National Center for Children's Rehabilitation (NCCR) in Astana. The chapter states the program's official objective and ten tasks, describes the consortium and the division of responsibilities, and explains the methodology used to develop and evaluate four rehabilitation devices (the Gait Rehabilitation Robot, an adaptive body-weight support system, the Robotic Perturbation Trainer and a QTrobot socially assistive robot adapted for Kazakh and Russian) and two software platforms (the GARAS gait analysis and rehabilitation recommendation software and the NCCR Rehabilitation Platform for data acquisition and processing). It sets out the safety and regulatory standards applied to device development, the staged clinical research framework, the 2025 pilot randomised trials and the sample-size calculations derived from them, the design and current status of the registered trials, the ethical safeguards, the outcome measures used across studies, and the arrangements for data management and open data. Throughout, the chapter distinguishes between published, under-review and unpublished work, and between completed and ongoing studies, so that readers can judge the maturity of the evidence presented in later chapters.

Keywords: research program design; rehabilitation robotics; medical device development; IEC 60601-1; ISO 14971; randomised controlled trial; sample size; research ethics; outcome measures; data management; open data; Kazakhstan

3.1 Program Overview

The program was conceived in response to the needs and gaps identified in Chapters 1 and 2: the need for high-dose, individualised and engaging rehabilitation for children with cerebral palsy (CP), the scarcity of specialist resources, especially outside major cities, the bilingual Kazakh–Russian context of clinical practice, and the absence of objective, frequent measurement of change. It was funded as a program-targeted project by the Science Committee of the Ministry of Science and Higher Education (MSHE) of the Republic of Kazakhstan under grant BR27199433, "Improving the Rehabilitation and Support of Children with Musculoskeletal Disorders and Neurological Disorders using Innovative Robotic Devices", for the period 2024–2026. The funding application requested KZT 896.2 million of program-targeted financing over the three years [30]. The program also received monetary co-financing from Zein Invest LLP, recorded in the partner contribution plan of the application [30].

The program combined three kinds of activity that are often conducted separately: engineering development of rehabilitation devices and software, clinical evaluation of those technologies in children with CP and related neurological conditions, and the construction of a data infrastructure capable of supporting both. Its clinical work took place at NCCR in Astana, the national referral centre for paediatric rehabilitation, which receives roughly 300 children each month. That throughput made it possible to recruit at a scale that would be difficult in most single-centre paediatric rehabilitation studies. According to the program's records, 170 children took part in the social-robot (QTrobot) studies, 25 children in the perturbation-training trial and 25 children in the gait-robot trial; within each strand, every child was a different individual (Section 3.5.2).

3.2 Objective, Tasks and Work Strands

3.2.1 Program objective

The objective of the program, as stated in Section 2.2 of the funded application, is reproduced verbatim:

> "Providing children with musculoskeletal disorders (with cerebral palsy, brain injuries, spinal cord injuries, paraplegia, muscular dystrophy, Rett syndrome and other diseases) with modern high-tech robotic means (exoskeletons) for effective rehabilitation, assistance for independent movement and the opportunity to socialize." [30]

The application refers to the target population collectively as children with movement and mobility disorders (MMD). Most of the children in the program's studies had CP, and this book uses that term except where a study enrolled a wider group.

3.2.2 Program tasks

The application divided the work into ten tasks, each with a technology readiness level (TRL) at the start and a target TRL at completion [30]. They are closely paraphrased in Table 3.1.

Table 3.1. The ten tasks of program BR27199433 and their technology readiness levels at the start and planned completion of the program (from the funded application [30]).

Task	Content (closely paraphrased from the application)	TRL start → end	Where addressed in this book
1	Assess motor function and cognitive ability in children with movement disorders and develop indicators that quantify the level of disability, combining clinical measurements with instrument-based measurements into new indices	3 → 5	Chapters 8, 10
2	Study postural control using electromyography (EMG), inertial measurement units (IMUs) and plantar-pressure insoles, and develop indicators of postural balance (for example, the effective diameter of centre-of-mass trajectory loops)	3 → 7	Chapters 5, 6, 10
3	Evaluate targeted and time-oriented dynamic balance and develop neuromuscular and biomechanical indicators of it by synchronising EMG timing and intensity, IMU sway and joint-angle measures, and insole centre-of-pressure and load-symmetry measures	1 → 4	Chapters 6, 10
4	Design and develop high-tech robotic devices (exoskeletons) for rehabilitation; improve the gait robot's design and controller for paediatric use and for greater transparency; complete its regulatory requirements	6 → 8	Chapter 4
5	Develop interventions to improve postural control, using the robotic perturbation system to deliver perturbation-based training	3 → 6	Chapters 6, 10
6	Develop perturbation-based interventions to improve balance and walking stability; modify the design and control of the perturbation system and complete its regulatory requirements	6 → 8	Chapters 6, 13
7	Design and develop artificial-intelligence-based computational tools that analyse IMU, EMG and pressure-insole data for assessment, prediction and treatment planning	2 → 6	Chapters 8, 9
8	Design and develop a virtual rehabilitation system, based on mixed reality, that works with the robotic exoskeletons	3 → 6	Chapters 4, 9

Task	Content (closely paraphrased from the application)	TRL start → end	Where addressed in this book
9	Design and develop assistive devices, such as ankle orthoses or hip braces, to help manage orthopaedic complications and prevent contractures	3 → 6	Not reported in this book
10	Develop technological interventions to improve social skills and communication in children with disabilities	1 → 4	Chapters 7, 11

TRL values are those stated in the application; they are planning targets, not independently assessed readiness levels. Task 9 (orthoses and hip braces) is outside the scope of this book.

3.2.3 Work strands

In operational terms, the program's work can be grouped into four strands, which correspond to the parts of this book:

1. *Device development* (Part II): the Gait Rehabilitation Robot, an adaptive body-weight support (BWS) system, the Robotic Perturbation Trainer (RPT) for balance training, and a QTrobot socially assistive robot adapted to converse in Kazakh and Russian.
2. *Software development* (Part III): the GARAS gait analysis and rehabilitation recommendation software and the NCCR Rehabilitation Platform for sensor and clinical data acquisition and processing, together with a virtual-reality (VR) training program for use with the gait robot.
3. *Clinical evaluation* (Part IV): pilot, feasibility, exploratory, controlled and randomised studies conducted at NCCR.
4. *Data stewardship and translation* (Chapters 9 and 13): de-identification and structured management of multimodal data, a planned public dataset, and pathways towards registration and clinical adoption.

The decision to pursue motor and socio-communicative interventions within a single program reflects the broad, multidomain understanding of CP described in Chapter 1 and the observation, made in Chapter 2, that hybrid cognitive–physical rehabilitation models have received little attention in the literature.

3.3 Consortium and Governance

The program was led by Nazarbayev University (NU) through the Department of Electrical and Computer Engineering of the School of Engineering and the Center of Excellence in Medical Robotics and Research (CEMRR), Nazarbayev University Research Administration (NURA), directed by the program leader and author of this book. Two NU co-leads brought clinical and educational expertise: Dr Yeltay Rakhmanov of the School of Medicine and Prof. Sourav Mukhopadhyay of the Graduate School of Education. Research staff were employed through NURA [2, 4]. The clinical partner and site for all trials was NCCR, whose physiotherapists, psychologists and other specialists took part in the delivery and assessment of interventions [5]. The program's engineering team designed, built and maintained the devices and software; the Gait Rehabilitation Robot is supplied by its manufacturer as a registered medical device (Section 3.4.1).

The application named two international advisers [30]. Prof. Sunil Agrawal (ROAR Laboratory, Columbia University, New York) was to attend online meetings with the researchers working at NCCR every two weeks and to advise on clinical trials and research publications. Prof. Shane Xie (University of Leeds) was to collaborate closely with the team and assist the researchers in developing assistive

devices for the ankle and hip joints. Further international collaborators contributed to individual studies, as reflected in the authorship of the program's publications, including investigators from the University of Kansas Medical Center (USA), the University of Canberra (Australia) and Zhejiang University of Technology (China) [3, 4]. Table 3.2 summarises the roles of the principal partners.

Table 3.2. Principal partners and their roles in the program.

Partner	Unit	Principal role
Nazarbayev University	School of Engineering (Department of Electrical and Computer Engineering); CEMRR, NURA	Program leadership; device and software engineering; data analysis
Nazarbayev University	School of Medicine (co-lead: Dr Yeltay Rakhmanov)	Clinical expertise; clinical study design and oversight
Nazarbayev University	Graduate School of Education (co-lead: Prof. Sourav Mukhopadhyay)	Special-education and communication expertise; design of social-robot content and observational methods
National Center for Children's Rehabilitation (NCCR), Astana	Clinical departments	Clinical site; recruitment; delivery of usual care and trial interventions; clinical assessment
International advisers	Prof. Sunil Agrawal, Columbia University; Prof. Shane Xie, University of Leeds	Advice on clinical trials and publications (Agrawal); assistive-device development (Xie)
International collaborators	University of Kansas Medical Center; University of Canberra; Zhejiang University of Technology	Methodological, analytical and editorial contributions to individual studies

The program leader was responsible for the program's scientific direction, budget and reporting to the Science Committee under the rules of program-targeted funding [30]. Clinical procedures at NCCR were conducted under NCCR site approval and NU-IREC oversight (Section 3.6). In the social-robot sessions, a team of four to five adults, including educators and therapists, normally conducted each session, with one or two NCCR clinicians present; children were addressed in their own language, Kazakh or Russian, and parents were involved throughout. During the co-design phase in 2025, 35 families, seven therapists and three teachers contributed information on needs and preferences [30].

3.4 Device-Development Methodology

3.4.1 Translational lineage and regulatory status

The program did not begin from a blank sheet. Its gait rehabilitation work builds on research on lower-limb rehabilitation robotics that the author began in 2007. The gait exoskeleton used in the program, referred to in this book as the Gait Rehabilitation Robot (model A-GEAR-V1), is a registered medical device in Kazakhstan (Class 2a) [6]. Its development and registration preceded the present grant and are mentioned here only as background on the maturity of the underlying technology. Under BR27199433 the program's work on the robot concerned its adaptation for paediatric use, its controller, its integration with load-cell sensing, VR and analysis software, and its clinical evaluation (Task 4; Chapter 4).

The other program devices are at an earlier stage. The adaptive BWS system and the RPT were designed and built by the program team and have been used with children under ethics approval (Chapters 5 and 6), but they are not yet registered medical devices. Both are planned to pass through medical-device

registration with the National Center for Expertise of Medicines and Medical Devices and through registration with SK-Pharmacy, the single distributor for public procurement (Chapter 13). Patent applications for the program's devices will be filed. All copyrights and patents arising from the program are owned by NURA. QTrobot is a commercial product (LuxAI S.A., Luxembourg); the program's contribution concerns its therapeutic content and Kazakh speech, which will not be commercialised.

The development pathway followed for the gait robot, progressing from research and grant funding through laboratory testing and clinical validation to quality-system certification, national registration and first clinical installation, served as the template for the program's other devices. For the BWS system and the RPT, the methodology to date has comprised a written requirements and design report [8, 31], bench verification without human participants (load-cell verification of force tracking for the RPT [3]), small feasibility studies under ethics approval, and iterative redesign; formal design-control documentation and a risk-management file will be compiled for registration.

3.4.2 Design requirements for paediatric devices

Three requirements governed the design of all program devices. The first was *safety*: children with CP may have limited capacity to report discomfort, may present with spasticity, contractures or epilepsy, and may be frightened by unfamiliar equipment, so devices needed multiple, independent safety layers. The second was *adjustability*: devices had to accommodate a wide range of body sizes and functional levels and to allow training parameters, such as assistance, unloading, perturbation magnitude, speed and task difficulty, to be set individually. The third was *measurement*: every device was designed to record data during therapy so that sessions could be documented, outcomes analysed and, eventually, training adapted automatically.

The way these requirements were realised differed between devices, as summarised below and described in detail in Part II.

Gait Rehabilitation Robot. The operating manual specifies an emergency stop that must be available and tested before every session, mechanical locks, safety slings, software and mechanical limits on joint angles and speeds, and continuous error monitoring [6]. It lists absolute contraindications, including acute illness, intractable epileptic seizures, unstable fractures, severe skin lesions at cuff contact points and inability to ensure safety, and relative contraindications, including severe spasticity or contractures that prevent safe alignment of joint axes and severe pain [6]. The robot is a bilateral hip–knee exoskeleton mounted on a suspension system over a treadmill, with hip motion of −35° to +35° and knee flexion of 0–50°, segment speeds up to 60°/s and a patient mass limit of 100 kg; cuffs in all sizes are available at NCCR [6]. Four Futek load cells, one per joint, are standard on the device and are used to measure the child's joint torque contribution (Chapters 4 and 8). In its current form the controller composes the commanded torque from independently bounded terms, with torque caps of 20 N·m at the hip and 16 N·m at the knee, a slew-rate limit, range-of-motion walls, a speed brake and a bound on the work done per excursion [32]. The pre-assessment form developed for paediatric gait-robot training at NCCR records body weight, bilateral leg length and height, which are required to set up the robot and to compute step length from the robot's encoders [7].

Adaptive body-weight support system. The BWS system developed by the program uses a pneumatic cylinder driving a 2:1 cable–pulley suspension, with a pressure sensor, an in-line load cell that forms part of the control loop, and a cable displacement sensor. Unloading is regulated by solenoid supply and exhaust valves under a two-position controller with hysteresis around the set point, with timing constraints and mutual valve interlocking to prevent rapid switching and simultaneous activation of supply and exhaust, and a flow-control throttle to limit abrupt changes in unloading [31]. Pneumatic

actuation was chosen because it provides compliance while the unweighing force changes. The design is described in Chapter 5.

Robotic Perturbation Trainer. The first, published version of the RPT is a four-cable planar parallel mechanism that applies controlled waist-pull perturbations in the transverse plane during treadmill walking. Its published description specifies safety measures at several levels: hardware torque limits, bounds on maximum cable tension, velocity and acceleration limits, real-time monitoring of actuator states, a minimum cable pretension to keep all cables taut, and the use of a body-weight support harness to prevent falls [3]. Bench validation with in-line load cells, conducted without human participants, quantified force-tracking accuracy, repeatability, pretension maintenance and pulse dynamics before clinical use [3]. The final version of the RPT is a reconfigurable cable-driven parallel robot: four motor–pulley units on vertically adjustable carriages at the corners of a 2.5 m × 1.5 m frame around the treadmill, attached to a ring around the pelvis, so that lowering the carriages converts transverse-plane perturbations into sagittal- and frontal-plane perturbations with a vertical component [33]. The device is described in Chapter 6.

QTrobot. QTrobot is a commercially available child-sized humanoid social robot (LuxAI S.A., Luxembourg) [1, 9]; the program used the AI@Edge version. As a non-contact device whose role is limited to speech, gesture, facial expression and tablet-based tasks, it presents a different risk profile from the motor devices. The program's development work concerned the therapeutic content, the bilingual Kazakh–Russian interaction and the routing of Kazakh speech synthesis. Kazakh speech is produced by the ISSAI KazakhTTS model (ESPnet), developed at Nazarbayev University, running in a container on the robot's onboard computer, while other text is sent to the robot's built-in voice [1]. A therapist controlled the pace of each session from a separate tablet and remained present throughout [2, 5]. The platform and its adaptation are described in Chapter 7.

3.4.3 Safety and regulatory standards

The operating manual of the Gait Rehabilitation Robot identifies a set of international standards, together with their national (GOST) equivalents, that govern basic safety, electromagnetic compatibility, risk management, labelling and software life-cycle processes [6]. These are listed in Table 3.3. They are the standards declared for the registered gait robot; for the BWS system and the RPT, conformity assessment against the same set will form part of the registration process described in Section 3.4.1.

Table 3.3. Safety and regulatory standards declared in the operating manual of the Gait Rehabilitation Robot.

Standard	Scope	Declared classification for the gait robot [6]
IEC 60601-1 (GOST R IEC 60601-1)	Basic safety and essential performance of medical electrical equipment	Class I; type B applied parts
IEC 60601-1-2 (GOST R IEC 60601-1-2)	Electromagnetic compatibility of medical electrical equipment	Group 1, Class A
ISO 14971 (GOST R ISO 14971)	Application of risk management to medical devices	—
ISO 20417	Information to be supplied by the manufacturer of medical devices	—
ISO 15223-1 (GOST R ISO 15223-1)	Symbols to be used with information supplied by the manufacturer	—

Standard	Scope	Declared classification for the gait robot [6]
IEC 60529 (GOST 14254)	Degrees of protection provided by enclosures (IP code)	IP20
IEC 62304	Medical device software: software life-cycle processes	Software safety class B

Source: operating manual of the Gait Rehabilitation Robot, model A-GEAR-V1 [6].

3.4.4 Software development and intellectual property

Software was developed alongside the devices to control them, to acquire and process data and to support clinicians. Five software copyright certificates of the Republic of Kazakhstan were obtained for program software in 2026, as listed in Table 3.4. The certificates, like all intellectual property arising from the program, are owned by NURA.

Table 3.4. Software copyright certificates obtained by the program (Republic of Kazakhstan, 2026).

Certificate №	Software	Related chapter
74083	GARAS (gait analysis and rehabilitation recommendation software)	8
74149	Virtual-reality-based exoskeleton training program for patients with CP	4, 9
74396	NCCR_Rehabilitation_Platform_2025	9
74308	Kazakh speech-synthesis routing system for QTrobot	7
74309	Therapy for children with CP using social robots (Kazakh and Russian scripts for robot-assisted therapy)	7, 11

The program's gait analysis software merits a specific methodological comment. Its documentation describes a processing chain from encoder, load-cell and insole signals to temporal and spatial gait parameters, symmetry and variability indices, a patient torque fraction and a composite Gait Recovery Index (GRI) [10]. The software includes a synthetic-data generator that was used to validate the pipeline before patient data were available, and the accompanying worked examples use fictitious data [10, 11]. GARAS has since been run on real NCCR session data. Its recommendations are produced by a rule-based expert system with fixed thresholds, not by a generative language model (Chapter 8). Where this book illustrates the GRI before the trial data have been analysed, the illustration uses simulated data and is labelled as such at the point of use; simulated values are never presented as observations in children.

3.5 Clinical Research Framework

3.5.1 Staged evaluation

The program adopted a staged approach to clinical evaluation, broadly consistent with the Medical Research Council framework for developing and evaluating complex interventions [28]. New devices were first verified on the bench, then implemented in small feasibility or methods studies to establish that the protocol could be delivered safely and that measurements were reliable, then examined in pilot and exploratory studies that characterised responses, refined parameters and provided effect-size estimates, and finally evaluated in controlled and randomised designs. Feasibility studies were reported with reference to established guidance for pilot and feasibility trials [12].

This staging has a direct consequence for the interpretation of evidence in Part IV. Many of the program's studies are deliberately small and some are uncontrolled because they belong to the early stages of this sequence. Their purpose was to establish feasibility, refine protocols and generate hypotheses and effect-size estimates, not to establish efficacy, and they are reported accordingly.

3.5.2 Setting and participants

All clinical studies were conducted at NCCR during children's scheduled rehabilitation stays (Section 1.12.2). Children were recruited from the centre's caseload in collaboration with the clinical team and continued to receive their individually prescribed multidisciplinary rehabilitation throughout. Table 3.5 gives the number of children in each strand of the program.

Table 3.5. Children who took part in the program's clinical work, by strand (program records, October 2026).

Strand	Children	Notes
Social-robot (QTrobot) studies	170	All different children within the strand; pilot-cohort children did not join later cohorts
Perturbation-training trial (RPT)	25	All different children; NU-IREC No. 1081
Gait-robot trial (ACTRN12626001203347)	25	All different children; enrolled from 10 September 2026; 7 children from Astana recruited for follow-up assessments

Because the strands recruited separately, the three figures should not be read as a count of unique children across the whole program: a child could, in principle, have taken part in more than one strand. Eligibility criteria were specific to each study and are summarised in the sections that follow and in Table 3.9. In general, motor studies required a confirmed diagnosis of CP, a functional level compatible with treadmill walking (Gross Motor Function Classification System (GMFCS) levels I–II or I–III), the ability to follow instructions and to report pain, and medical stability, and they excluded children with recent orthopaedic surgery or botulinum toxin injection, uncontrolled epilepsy, severe contractures or cardiorespiratory contraindications [3, 8]. Social-robot studies required a confirmed diagnosis of CP (or, in one longitudinal study, another documented neurological condition), age within the study range, sufficient vision and hearing to interact with the robot and the ability to respond to verbal prompts, and they excluded children with prior structured experience of a social robot or with conditions requiring urgent medical management [1, 5, 13].

3.5.3 Pilot randomised trials in 2025

In 2025 the program conducted three small pilot randomised trials at NCCR, whose main purpose was to test the protocols and to estimate effect sizes and variances for planning larger trials [30]. They are summarised in Table 3.6. Allocation in the gait-robot pilot used a computer-generated sequence [30]. The 21 children in the three intervention arms each received ten sessions. In the two gait-robot pilots, data were recorded with a Noraxon Ultium portable laboratory (EMG and IMU) and Medilogic pressure insoles, and clinical outcomes comprised the six-minute walk test (6MWT), the 10-metre walk test (10MWT), the Timed Up and Go test (TUG), the Berg Balance Scale (BBS) and the Gross Motor Function Measure (GMFM) [30]. The effect-size inputs used for sample-size planning are given here.

Table 3.6. Pilot randomised trials conducted at NCCR in 2025.

Pilot	Intervention arm	Control arm	Children (intervention vs control)	Outcome used for planning
Gait Rehabilitation Robot	Robot-assisted gait training	Conventional gait rehabilitation	6 vs 6	6MWT
Gait Rehabilitation Robot + VR	Robot-assisted treadmill training with head-mounted VR decision tasks	Conventional manual therapy	5 vs 5	6MWT
QTrobot	Ten sessions over three weeks, ten bilingual (Kazakh/Russian) scripts	Conventional therapy	10 vs 10	WISC-V Full-Scale IQ (FSIQ)

3.5.4 Sample-size calculations

The funding application set target sample sizes of 23 children for the gait-robot intervention (6MWT), 25 for the perturbation intervention (Berg Balance Scale) and 30 for the social-robot intervention (WISC-V FSIQ), each for 80% power [30]. The effect sizes and standard deviations behind these targets were not preserved in the application. The program therefore recalculated the sample sizes required for a confirmatory trial from the 2025 pilot estimates.

For a two-arm parallel comparison of means with equal allocation, a two-sided significance level $\alpha = 0.05$ and power $1 - \beta = 0.80$, the number of children required per group is

$$n = 2(z_{1-\alpha/2} + z_{1-\beta})^2 \, \sigma^2 / \delta^2 = 2(1.96 + 0.84)^2 \, \sigma^2 / \delta^2 = 15.68 \, \sigma^2 / \delta^2,$$

where δ is the between-group difference in mean improvement and σ is the pooled standard deviation. For the QTrobot pilot, where the two arms had different standard deviations, the pooled value was taken as $\sigma = \sqrt{[(\sigma_1^2 + \sigma_2^2)/2]}$. The results are given in Table 3.7.

Table 3.7. Sample sizes for a confirmatory trial calculated from the 2025 pilot estimates ($\alpha = 0.05$ two-sided; power 0.80; 15% attrition allowance).

Intervention (pilot)	Outcome	δ	σ (pooled)	Standardised effect δ/σ	*n* per group (calculated)	*n* per group (rounded)	*n* per group with 15% attrition	Total with attrition
Gait Rehabilitation Robot (6 vs 6)	6MWT	44 m	62.5 m	0.70	$15.68 \times 62.5^2 / 44^2 = 31.6$	32	37	74
Gait Rehabilitation Robot + VR (5 vs 5)	6MWT	50.3 m	61 m	0.82	$15.68 \times 61^2 / 50.3^2 = 23.06$	24	28	56
QTrobot (10 vs 10)	WISC-V FSIQ	4 points	6.02 points ($\sigma_1 =$	0.66	$15.68 \times 6.02^2 / 4^2 = 35.5$	36	42	84

Intervention (pilot)	Outcome	δ	σ (pooled)	Standardised effect δ/σ	*n* per group (calculated)	*n* per group (rounded)	*n* per group with 15% attrition	Total with attrition
			7.1, σ_2 = 4.7)					

Attrition-adjusted values were obtained by multiplying the rounded n *by 1.15 and rounding up (32 × 1.15 = 36.8 → 37; 24 × 1.15 = 27.6 → 28; 36 × 1.15 = 41.4 → 42). Dividing by (1 − 0.15) instead, an equally common convention, gives 38, 29 and 43 per group. Pilot-based estimates of δ and σ from groups of five to ten children are imprecise, so these figures are indicative.*

These numbers are larger than those enrolled in the current phase. The program's gait-robot trial and perturbation-training trial each enrol 25 children, which is enough for an explanatory, feasibility-scale randomised phase but not for a confirmatory test of efficacy on the 6MWT or on FSIQ. This is consistent with the program's stated strategy: because the current phase of the grant focuses on pilot and explanatory trials that establish feasibility, acceptability and effect trends rather than final clinical validation, a reduced pilot sampling strategy was adopted (Table 3.8) [30]. A confirmatory trial would need the numbers in Table 3.7, most realistically through a multicentre design (Chapter 13).

Table 3.8. Reduced pilot sampling strategy adopted for the current phase of the program.

Study	Intervention group	Control group
Gait Rehabilitation Robot trial	6 children	6 children
Gait Rehabilitation Robot + VR trial	5 children	5 children
QTrobot trial	10 children	10 children

3.5.5 Randomised controlled trial of robot-assisted gait training

The principal motor trial is an explanatory, parallel, two-arm randomised controlled trial (RCT) registered with the Australian New Zealand Clinical Trials Registry (ANZCTR) as ACTRN12626001203347. It compares robot-assisted gait training with the Gait Rehabilitation Robot against conventional (manual) gait rehabilitation at NCCR.

Participants. Children and adolescents with CP aged 13 to 18 years at GMFCS levels I–III are eligible if they are cognitively able to report pain, have upper-limb manual muscle test grades of 3+ or above and a Modified Ashworth Scale score of 2 or below, have no unconsolidated fractures or fixed contractures, and are in good general health [30]. In the 2025 pilot, a height of 160–195 cm and a shoe size of at least 38 were applied as device-fit criteria [30]

Intervention and comparator. The intervention group receives ten sessions of 20 minutes of robot-assisted gait training; the control group receives conventional (manual) gait rehabilitation. Both groups continue their individually prescribed NCCR programme. Session delivery details are described in Chapter 4.

Outcomes. The primary outcome is the 6MWT, measured at baseline and after the intervention. Secondary outcomes are the 10MWT, TUG, the 88-item GMFM (GMFM-88), the Paediatric Berg Balance Scale, instrumented gait parameters from surface EMG (sEMG), IMUs and pressure insoles, and the GRI computed from the robot's encoders and load cells.

Randomisation and blinding. Allocation follows a computer-generated sequence [30]

Sample size. The application target was 23 children (6MWT, 80% power) [30]; 25 have been enrolled. As explained in Section 3.5.4, this is an explanatory, feasibility-scale phase; a confirmatory trial would require about 37 children per group.

Timeline and status. Enrolment began on 10 September 2026 and 25 children have been enrolled. Until the NU-IREC approved use of the device on 14 October 2026, only pre-assessment was carried out, with children who were staying in Astana and registered with NCCR. The approval was conditional; the conditions have been met. Robot-assisted sessions began on 19 October 2026 and are continuing. Seven children from Astana have been recruited for follow-up assessments. At the time of writing no outcome data from this trial are available, and Chapter 10 presents its analysis plan rather than results.

The design is significant in light of the evidence reviewed in Chapters 1 and 2, which indicated that mechanically assisted walking training has not been shown to be consistently superior to an equivalent dose of conventional walking practice [14, 15]. Because both arms continue usual care, the trial compares robot-assisted gait training with conventional gait rehabilitation as an addition to that care.

3.5.6 Perturbation-training trial

The perturbation-training trial enrolled 25 children with CP under NU-IREC approval No. 1081. Its primary outcome is the Berg Balance Scale, for which the application calculated that 25 children would provide 80% power [30]. Training used the RPT described in Chapter 6, where the trial design, configuration and dates are reported. Results are pending; device-derived balance measures will be summarised with the BRI (Section 6.10.4 and Chapter 10).

3.5.7 Social-robot trial and associated studies

The social-robot work is anchored by an RCT registered as ACTRN12625001214426. The registration was retrospective: the first child was enrolled before the trial was registered. The planning basis of the trial is a comparison of QTrobot-assisted sessions with conventional therapy on WISC-V FSIQ, with an application target of 30 children and the 2025 pilot described in Section 3.5.3 [30].

Around this registration, the program conducted several studies with QTrobot at NCCR, each addressing a different question and using a different design. They included a preliminary quasi-experimental feasibility study [5]; a ten-session longitudinal controlled study of behavioural trajectories with a parallel standard-care group [1]; a qualitative microgenetic study of cognitive behaviour during repeated sessions [2]; an exploratory comparison of engagement in robot-assisted and tablet-based sessions [13]; a feasibility study of acoustic and blinded-listener speech outcomes [16]; and a pre–post study of narrative language after robot-delivered bilingual storytelling [17]. The longitudinal, speech and narrative studies state that they were conducted within the project whose trial is registered as ACTRN12625001214426 [1, 16, 17]. The speech study explicitly notes that it was not itself randomised, that its sample and dose differed from the registered trial protocol and that its outcomes were exploratory additions [16]. These studies are therefore reported in Chapter 11 as studies associated with the registered trial, not as its confirmatory analysis.

3.5.8 Summary of program studies

Table 3.9 summarises the designs of the program's clinical studies as reported in the source documents, together with their status at the time of writing. Results are presented in Chapters 10 and 11.

Table 3.9. Clinical studies of the program: design, participants and status.

Study (device)	Design	Participants (as reported)	Intervention	Status
Gait-robot pilot RCT (Gait Rehabilitation Robot)	Pilot parallel RCT	6 intervention, 6 control	Robot-assisted gait training vs conventional gait rehabilitation	Completed 2025; results pending report
Gait-robot + VR pilot RCT	Pilot parallel RCT	5 intervention, 5 control	Robot-assisted treadmill training with VR vs conventional manual therapy	Completed 2025; results pending report
QTrobot pilot RCT	Pilot parallel RCT	10 intervention, 10 control	Ten sessions over three weeks vs conventional therapy	Completed 2025; results pending report
Robotic Perturbation Trainer methods study (RPT) [3]	Methods description with implementation in two cases; pre, mid and post assessment	2 adolescents (16 and 17 years), spastic dyskinetic (GMFCS III) and spastic diplegic (GMFCS I)	10 treadmill sessions over 5 weeks; randomised transverse-plane waist-pull perturbations of 65–85 N under BWS	Published, *MethodsX* 17 (2026) 104051
Multi-plane RPT validation (RPT, final version) [33]	Technical validation with sEMG analysis	3 healthy adults	Cycle-locked sagittal, frontal and transverse perturbations at 10% of body weight	Manuscript
Perturbation-training trial (RPT)	Clinical trial; see Chapter 6	25 children with CP	Perturbation-based treadmill training	Ongoing; results pending
Individualised BWS selection study (BWS) [8]	Prospective, single-arm exploratory study; within-participant assessment of seven BWS levels	7 children and adolescents (10–17 years), GMFCS I–II; 6 completed training	Three to five 15-minute treadmill sessions at the selected BWS level	Manuscript in preparation
Gait RCT (Gait Rehabilitation Robot)	Explanatory parallel two-arm RCT	25 children, 13–18 years	Ten 20-minute sessions of robot-assisted gait training vs conventional gait rehabilitation	Registered (ACTRN12626001203347); sessions under way; results pending
SAR feasibility study (QTrobot) [5]	Quasi-experimental one-group pre–post	9 children (5–12 years)	Seven scripted sessions on consecutive days, approximately 10–15 min each	Published, *IEEE Trans Med Robot Bionics* (early access)
Longitudinal controlled SAR study	Longitudinal controlled design with	32 intervention (28 analysed) and 32 control, 5–12 years	Ten culturally adapted sessions, Sept–Nov 2025	Under review, *International Journal of*

Study (device)	Design	Participants (as reported)	Intervention	Status
(QTrobot) [1]	parallel standard-care group			*Social Robotics*
Microgenetic cognitive observation study (QTrobot) [2]	Qualitative microgenetic multiple-case design	8 children with spastic CP (7–10 years); 65 analysed sessions	Up to ten thematic sessions	Under review, *IEEE Trans Cogn Dev Syst*
Robot vs tablet engagement study (QTrobot) [13]	Exploratory comparison of two non-equivalent groups	15 children; 8 robot (65 sessions), 7 tablet (69 sessions)	Robot-assisted or tablet-based sessions with comparable content	Manuscript in preparation
Speech intelligibility feasibility study (QTrobot) [16]	Single-group pre–post feasibility study	8 enrolled, 7 analysed (4;10–10;6 years)	Ten storytelling sessions over two weeks	Manuscript in preparation
Narrative language study (QTrobot) [17]	Single-group pre–post feasibility study	10 enrolled, 8 analysed (5–12 years eligible)	Ten story-based modules in Kazakh and Russian	Manuscript in preparation

Note: Participant numbers are reproduced as reported in each source. Several QTrobot manuscripts analyse sub-samples or overlapping session sets of the same cohorts, so the rows should not be summed; the program's total for the social-robot strand is given in Table 3.5.

3.6 Ethics

All clinical studies were reviewed by the Nazarbayev University Institutional Research Ethics Committee (NU-IREC). Approval No. 1081 (21 May 2025) covers the BWS pilot study, the 25-child perturbation-training trial and the QTrobot studies [1, 3, 16]. Use of the Gait Rehabilitation Robot in the gait RCT received conditional NU-IREC approval on 14 October 2026; the conditions have been met, and no robot sessions took place before that date (Section 3.5.5). Site approval was granted by NCCR [1, 5].

Written informed consent was obtained from a parent or legal guardian of every participating child, and assent was sought from the children themselves in a developmentally appropriate form [1, 8]. Consent and assent forms were prepared in English, Kazakh and Russian so that families could review them in their preferred language. In the social-robot studies, verbal assent was sought before each session, participation was treated as voluntary at all times, and children could withdraw from any session without consequences for their access to standard rehabilitation [1, 5].

Particular care was taken with audiovisual data. Video recordings of sessions were used solely for research purposes, stored securely and made accessible only to the research team [1, 5]. Audio

recordings collected for speech analysis cannot be shared publicly, because children could be recognised by people who know them and because parental consent did not include public release [16]. Study identifiers were assigned so that they did not correspond to clinical record identifiers [8].

Both principal trials are registered with ANZCTR: ACTRN12626001203347 for the gait trial and ACTRN12625001214426 for the QTrobot trial. The QTrobot trial was registered retrospectively, after the first child had been enrolled; publications from the social-robot strand should describe it in those terms. An amendment to the NU-IREC approval permitting deposit of a de-identified dataset in a public repository has been conditionally approved (Section 3.9).

3.7 Outcome Measures

The program used a combination of standardised clinical measures, instrumented biomechanical and physiological measures, device-derived indices, and observational and linguistic measures. Table 3.10 lists the measures used across studies, grouped by domain.

Table 3.10. Outcome measures used across the program's studies.

Domain	Measure	Description	Used in
Walking endurance	6-minute walk test (6MWT)	Distance walked in six minutes	Gait RCT (primary); 2025 gait pilots; RPT; BWS
Walking speed	10-metre walk test (10MWT)	Time to walk the central 10 m of a longer walkway at comfortable (and, in some studies, fast) pace	Gait RCT; RPT [3]; BWS [8]
Functional mobility	Timed Up and Go (TUG)	Time to rise, walk 3 m, turn, return and sit	Gait RCT; RPT; BWS
Gross motor function	Gross Motor Function Measure (GMFM; GMFM-88)	Standardised observational measure of gross motor function	Gait RCT; RPT
Balance	Berg Balance Scale; Paediatric Berg Balance Scale	Ordinal scales of static and dynamic balance	Perturbation trial (primary) and RPT (Berg); gait RCT (Paediatric Berg)
Perceived exertion	OMNI Rating of Perceived Exertion Scale	Child-appropriate rating of exertion	BWS [8]
Muscle activity	Surface EMG	Gluteus maximus and medius (RPT); lower-limb muscle montage synchronised with IMUs and insoles (BWS, gait RCT)	Gait RCT; RPT; BWS
Plantar loading and gait events	Pressure insoles	Temporal symmetry, variability, centre-of-pressure behaviour and bilateral loading symmetry	Gait RCT; BWS
Segment kinematics	IMUs	Joint angles and spatiotemporal parameters	Gait RCT; BWS

Domain	Measure	Description	Used in
Composite gait index	Gait Recovery Index (GRI)	Composite of robot-encoder, load-cell and insole measures computed by GARAS	Gait RCT (Chapter 8)
Composite balance index	Balance Recovery Index (BRI)	Composite of insole, encoder and load-cell balance measures (Section 6.10.4)	Perturbation trial (Chapter 10)
Cognition	WISC-V Full-Scale IQ and index scores (adapted for Kazakhstan)	Standardised cognitive assessment	QTrobot pilot RCT; registered QTrobot trial
Social, communication, cognitive behaviour	Structured observational checklist adapted from the SRS-2; behavioural mapping	Session-level ratings of communication, cognition and social skills (Appendix A)	SAR feasibility [5]; longitudinal SAR [1]
Functional tasks	Structured object-sorting tasks	Comprehension, accuracy, verbal communication and prompt dependency at pre and post	Longitudinal SAR [1]
Cognitive behaviour	10-second interval coding organised by five WISC-V index domains	Descriptive within-child profiles and trajectories (not psychometric testing)	Microgenetic study [2]
Engagement	Segment-level 1–5 engagement scale with codebook	Engagement in 10-second segments (Appendix A)	Robot–tablet study [13]
Speech	Acoustic measures (duration, F0, F1, F2, intensity); blinded listener word identification	Dual-layer objective speech outcomes	Speech study [16]
Narrative language	Microstructure (utterances, MLU, NDW, TTR) and macrostructure (story grammar, cohesive ties)	Picture-narration task before and after intervention	Narrative study [17]

Several principles guided the interpretation of these measures. First, where minimal clinically important differences were available, as for the GMFM and 6MWT [18], changes were interpreted against them; where they were not established for paediatric CP, as for the 10MWT, TUG and Berg Balance Scale, changes were reported descriptively [3]. Second, in small studies, inferential statistics were avoided or explicitly treated as exploratory [3, 8]. Third, observational instruments in the social-robot studies were adapted from established instruments, notably the Social Responsiveness Scale, Second Edition [19], and the WISC-V domain structure [20], but were used descriptively rather than as standardised tests; the authors of these studies were explicit that the WISC-V domains served as an interpretive framework and that no psychometric measurement was claimed [2]. The WISC-V itself was administered as a standardised test only in the QTrobot pilot and registered trial. Fourth, inter-rater reliability was assessed for observational coding, using agreement statistics interpreted with conventional benchmarks [21, 22] and intraclass correlation coefficients where appropriate [23]. Finally, session-level observational data were analysed with methods suited to repeated measures, such as linear mixed-effects and growth-curve models [24] and microgenetic case analysis [25]. The device-derived indices (GRI and BRI) are new and have not yet been validated against clinical outcomes; the program's trials provide the first opportunity to do so.

3.8 Data Management

3.8.1 Data types and acquisition

The program generated heterogeneous data: clinical records and assessment forms; synchronised sEMG, IMU and plantar-pressure recordings; robot-embedded signals such as joint encoder angles, motor currents and load-cell forces; VR event logs; video recordings of social-robot sessions; audio recordings of children's speech; and coded observational and linguistic data. In the 2025 pilots, a Noraxon Ultium portable laboratory recorded EMG and IMU data and Medilogic insoles recorded plantar pressure [30]. In the BWS studies, a wireless system (Cometa WaveX) recorded sEMG and probe-mounted IMU channels together with two 16-cell pressure insoles in a single synchronised acquisition, so that no external trigger was needed; belt speed, which the system did not record, was logged manually [26]. Data-collection booklets specified that raw traces, not only computed summaries, were to be exported and archived, because summaries cannot be regenerated without them [26, 27]. The forms and booklets are listed in Appendix A.

3.8.2 Pseudonymisation, storage and access

Participants were identified in research datasets by study codes that did not correspond to clinical record identifiers [8]. Video recordings were stored securely with access restricted to the research team [1, 5]. Because NCCR clinical documents are predominantly Russian-language texts containing Kazakh personal names, national identification numbers and addresses, the program developed rule-based methods for removing direct identifiers and extracting structured clinical variables, such as GMFCS and MACS levels, from these documents (Chapter 9).

3.8.3 The NCCR Rehabilitation Platform

The sensor and clinical data acquisition and processing system, registered as NCCR_Rehabilitation_Platform_2025 (certificate №74396), was designed to bring these data streams together in a structured form that supports both clinical documentation and research analysis. It is described in Chapter 9.

3.8.4 Quality control

Quality control was built into the data-collection protocols. Examples include the requirement to discard initial adaptation strides and to record a minimum number of clean strides at each BWS level [26, 27], the marking of electrode positions to maintain consistent EMG gain across sessions [26], the passive calibration run required before each child's first gait-robot session to establish baseline load-cell values [7], the triplicate administration of clinical tests at each assessment phase in the RPT study [3], independent double coding of samples of video for inter-rater reliability in the social-robot studies [1, 2], and a systematic audio-quality audit in the speech study, which showed that damaged clips could create spurious improvements by lowering pre-test baselines [16]. These experiences are discussed further in Chapters 9 and 12.

3.9 Open Data and Reporting

The program intends to deposit a de-identified dataset in a public repository so that other researchers can reproduce its analyses and build on its data. The NU-IREC amendment permitting this has been conditionally approved; the choice of repository and licence is still under consideration, and the dataset will be released once both are settled and the trial analyses are complete. Some data cannot be made public under the consent obtained: in particular, raw video and audio recordings, which could allow

children to be identified, will not be shared [16]. Several of the program's manuscripts state that analysis code or derived data are available from the corresponding author on reasonable request [2, 8, 16].

To help readers judge the maturity of the evidence presented in this book, Table 3.11 lists the program outputs drawn upon in later chapters with their status at the time of writing. A complete list of program outputs is given in Appendix D.

Table 3.11. Status of program outputs drawn upon in this book.

Output	Status	Venue / identifier
Scoping review: social robots in cognitive and speech rehabilitation for children with CP [4]	Published	*J NeuroEng Rehabil* 2026;23:34; doi:10.1186/s12984-025-01852-0
Robotic Perturbation Trainer methods paper [3]	Published	*MethodsX* 2026;17:104051; doi:10.1016/j.mex.2026.104051
SAR feasibility study [5]	Published (early access)	*IEEE Trans Med Robot Bionics*; doi:10.1109/TMRB.2026.3733187
Longitudinal controlled QTrobot study [1]	Under review	*International Journal of Social Robotics*, SORO-D-26-00192
Microgenetic cognitive observation study [2]	Under review	*IEEE Transactions on Cognitive and Developmental Systems*
Gait exoskeleton controller [32]	Submitted manuscript	—
Multi-plane RPT validation [33]	Manuscript	—
Speech intelligibility feasibility study [16]	Manuscript in preparation	—
Narrative language study [17]	Manuscript in preparation	—
Robot vs tablet engagement study [13]	Manuscript in preparation	—
Individualised BWS selection study [8]	Manuscript in preparation	—
GARAS and the Gait Recovery Index [10]	Software (certificate №74083); run on NCCR data	—

Reporting in this book follows the conventions of the original studies, including the PRISMA extension for scoping reviews used in the program's review [4] and the CONSORT extension for pilot and feasibility trials referred to in the feasibility work [12]. The final reports of the two registered RCTs will follow the CONSORT 2010 statement [29].

3.10 Summary

The program was designed as an integrated effort to develop, evaluate and prepare for translation a suite of robotic devices and software for children with CP, led by Nazarbayev University with NCCR as the

clinical partner, funded by grant BR27199433 and co-financed by Zein Invest LLP. Its objective and ten tasks, with planned gains in technology readiness, framed work on indices of motor and cognitive function, balance assessment, gait and perturbation robotics, AI-based analysis, VR and social robotics. Its device-development methodology built on an earlier translational pathway in gait robotics, emphasised safety, adjustability and embedded measurement, and referenced a set of international standards for medical electrical equipment, risk management and medical device software. Its clinical framework proceeded from bench validation through feasibility studies and three small pilot RCTs in 2025 to two registered randomised trials and a 25-child perturbation-training trial. Sample-size calculations from the pilots show that the current trials are explanatory and feasibility-scale; a confirmatory test of efficacy will require roughly 37 children per group for the gait robot and 42 per group for the social robot. Ethical safeguards included NU-IREC approval, trilingual consent and assent procedures, pseudonymisation and strict control of audiovisual data. Outcome measurement combined standardised clinical tests, instrumented gait and muscle measures, new device-derived indices, and observational, acoustic and linguistic methods, interpreted cautiously in the light of small samples. The status of every output, whether published, under review or unpublished, and of every trial, whether completed or ongoing, has been stated so that the evidence presented in Parts II to IV can be read with appropriate confidence.

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Part II. Robotic Systems

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Chapter 4. Gait Rehabilitation Robot

Abstract. This chapter describes the Gait Rehabilitation Robot, the lower-limb exoskeleton used for robot-assisted treadmill training in program BR27199433. The device is a registered medical device in Kazakhstan (Class 2a). The chapter first sets out the requirements that a treadmill-based exoskeleton must satisfy when it is used with adolescents with cerebral palsy (CP), and then describes the system concept, mechanical architecture and actuation, the composition of the delivery set, and the technical characteristics stated in the operating manual and the technical data sheet. The sensing and control architecture is presented in detail, including the joint-reaction load cells fitted as standard to each of the four joints and the bounded compositional torque controller in its current form, in which commanded torque is assembled from independently bounded terms and clinical modes are masks over those terms. The operator interface and its session state logic are then described. A substantial part of the chapter is devoted to safety: the applicable standards, the layered stopping architecture, hazard zones, electrical and electromagnetic safety, residual risks and contraindications. The installation, session workflow, maintenance and calibration regime are described in the form in which a clinical engineering team would apply them. Finally, the chapter describes the program's registered two-arm gait trial in adolescents aged 13–18 years (ACTRN12626001203347), the two pilot studies that preceded it, and the limitations of the device and of its current documentation. No clinical outcome data from the program trial are reported in this chapter; results are pending and are addressed in Chapter 10.

Keywords: cerebral palsy; gait rehabilitation; lower-limb exoskeleton; robot-assisted gait training; treadmill training; body-weight support; assist-as-needed control; bounded torque control; medical electrical equipment safety; IEC 60601-1; risk management

4.1 Introduction and Scope

4.1.1 Purpose of the chapter

Robot-assisted gait training (RAGT) combines a powered orthosis that moves, or helps move, the hip and knee joints with a treadmill and an overhead suspension that unloads part of the patient's body weight. Its appeal for children and adolescents with CP lies in the possibility of delivering many repetitions of a reasonably physiological stepping pattern under safe conditions, while the therapist's attention is freed from manually guiding the limbs and can be directed toward posture, motivation and progression. A recent systematic review co-authored by members of the program team surveyed robotic exoskeletons used for gait rehabilitation in CP and provides the broader context for the device described here [2]; Chapter 2 of this book discusses that state of the art in detail.

The purpose of the present chapter is narrower: to give a complete engineering and operational description of the specific device deployed in the program, in enough detail that a reader could understand what the device does, how it is set up, what limits and safeguards govern its use, and how it fits into the clinical protocol. The description is drawn from the device's operating manual [9], the product brochure and technical data sheet prepared for the Kazakhstan International Healthcare Exhibition (KIHE) in May 2026 [10], the program's NCCR pre-assessment form [11], the trial registration [12], and a submitted manuscript describing the device's controller [23]. Where these documents disagree, the disagreement is reported rather than silently resolved.

4.1.2 Device naming

Throughout this book the device is called the *Gait Rehabilitation Robot*. It is model A-GEAR-V1, and the unit used with children at the National Center for Children's Rehabilitation (NCCR) in Astana is that

model. Program documents and earlier publications refer to the same technology as P.GEAR or A-GEAR; the NCCR pre-assessment form, for example, is headed *P.GEAR Gait Rehabilitation — Cerebral Palsy* [11], and the controller manuscript describes the device as P.GEAR [23].

4.1.3 Device maturity and relationship to the program

The Gait Rehabilitation Robot was not developed from scratch under program BR27199433. Its lineage begins with doctoral research on lower-limb rehabilitation robotics at the University of Auckland from 2007, continued at Nazarbayev University from 2014, and was advanced toward a clinical product through earlier competitive and World Bank-funded projects [10]. As background on device maturity only, the device is registered by the Ministry of Health of the Republic of Kazakhstan as a Class 2a medical device (registration RK MI (MT)-0№030409, issued 19 January 2026), and the device manufacturer holds an ISO 13485:2016 quality management system certificate (No. 760347) and a medical device manufacturing licence (No. 25037498) [10]. These credentials were obtained under earlier projects and are not outcomes of the present program. A patent application for the robot will be filed; all copyrights and patents arising from program BR27199433 are owned by Nazarbayev University Research Administration (NURA).

The program's contributions in relation to the robot are its use in a registered paediatric clinical trial at NCCR, the instrumentation and analysis pipeline described in Chapter 8, the characterisation of its controller [23], and the integration with the adaptive body-weight support (BWS) system described in Chapter 5. Table 4.1 summarises the status of the information in this chapter.

Table 4.1. Sources and status of the information reported in this chapter.

Topic	Source	Status
Device description, specifications, safety, installation, maintenance	Operating manual [9]	Manufacturer's technical documentation (unpublished)
System concept, data sheet, regulatory background	Product brochure, KIHE 2026 [10]	Promotional material (grey literature)
Controller architecture, safety bounds and identification	Controller manuscript [23]	Submitted manuscript; bench characterisation
Research lineage of mechanism and control	Peer-reviewed papers [1–8]	Published
Paediatric pre-assessment procedure	NCCR pre-assessment form [11]	Program working document (unpublished)
Trial design	Trial registration [12]	Registered; ongoing, results pending
Clinical outcomes of the program trial	—	Results pending (Chapter 10)

4.2 Design Requirements for Paediatric Users

4.2.1 The clinical problem the device must address

Adolescents with CP present a combination of impairments that a gait exoskeleton must accommodate rather than simply override. Spasticity, abnormal gait patterns and variable cooperation are the features that make robotic rehabilitation in CP particularly demanding [10]. The program's pre-assessment form gives a practical picture of the gait deviations that therapists are asked to look for before a child is placed in the device: toe-walking on the affected side, foot dragging or scuffing, hip hiking, circumduction, crouched gait with the knees flexed throughout stance, scissoring of the legs across the midline, reduced

arm swing on the affected side, and dependence on walking aids or physical support [11]. The same form notes that, in hemiplegic CP, the affected side typically takes the shorter step and identifies this asymmetry as the principal deviation the robot is intended to correct [11].

From these clinical features a set of design requirements follows. The device must be able to impose or assist a sagittal-plane hip and knee pattern on each leg independently, because the impairment is frequently asymmetric. It must tolerate resistance from spastic muscles without producing unsafe forces, which implies joint range, torque and speed limits enforced in both software and hardware. It must accommodate a range of body sizes, because adolescents aged 13–18 vary greatly in stature and mass. It must be quick to don and adjust, because cooperation and attention in children are limited resources that should not be consumed by set-up. It must allow the therapist to grade assistance, speed and body-weight support over a course of therapy. And it must provide quantitative information on the child's own contribution, because the central rehabilitation goal is a gradual shift from robot-generated to patient-generated joint torque [10].

4.2.2 Anthropometric envelope

The operating manual states approximate patient limits that define the population for which the device is intended. These are summarised in Table 4.2 together with the corresponding values in the data sheet. The two sources are not fully consistent, and the differences matter for a paediatric application.

Table 4.2. Patient limits stated in the operating manual and the data sheet.

Parameter	Operating manual [9]	Data sheet [10]	Comment
Age	Adolescents 12–17 years and adults	Not stated	Trial population is 13–18 years [12]
Body weight	Up to 100 kg	Up to 100 kg	Consistent
Height	100–190 cm (patient limits); 120–190 cm (technical specifications)	120–190 cm	Internal inconsistency in the manual
Thigh cuff circumference	46–58 cm (size M)	38–68 cm (sizes S/M/L)	Standard set supplies size M; all sizes are available at NCCR
Calf (shin) cuff circumference	32–40 cm (size M)	28–46 cm (sizes S/M/L)	As above

For the program's age range, the lower end of the stature and limb-circumference ranges is the binding constraint. A smaller 13-year-old with CP may have a thigh girth below the 46 cm lower limit of the standard size M cuff; for this reason all cuff sizes (S, M and L), together with the liner inserts listed among the accessories [9], are available at NCCR, covering the wider 38–68 cm thigh and 28–46 cm calf ranges of the data sheet [10]. The controller manuscript gives an independent estimate of the stature range from the segment adjustments: thigh length (hip to knee) is adjustable over 340–475 mm and shank length (knee to cuff) over 145–330 mm, which, taking thigh length as 0.245 × stature, corresponds to approximately 1.39–1.94 m [23]. The authors of that manuscript note that the lower bound is approximately the stature of a fiftieth-percentile ten-year-old, and that, because children with CP are frequently shorter than their typically developing peers, the effective lower bound in this population is higher still [23]. Where a child's height, weight or limb girth falls outside the product limits, the manual lists this as a relative contraindication to be decided individually [9].

The manual also requires that the patient be able to maintain an upright position briefly with the help of the suspension system and be able to follow staff instructions [9]. In CP these two conditions effectively exclude children whose postural control or cognitive and communicative abilities do not permit safe participation, independent of their anthropometry.

The pre-assessment form shows how the anthropometric requirements are operationalised in the trial. Body weight is measured with shoes and heavy clothing removed; height is measured against a wall; and leg length is measured bilaterally as the straight-line distance between the greater trochanter and the lateral malleolus, recorded in metres [11]. The form explains that leg length is required because the analysis software uses it to convert encoder-measured hip angles into step length (Chapter 8) [11].

4.2.3 Functional and kinematic requirements

The kinematic envelope of the device is defined in the manual as typical limits: hip flexion and extension from −35° to +35°, knee flexion from 0° to 50°, segment angular velocity up to 60°/s, step frequency from 0.2 to 1.0 Hz (12 to 60 steps per minute), and step length on the treadmill from 0.2 to 0.8 m depending on stature and settings [9]. Compatible treadmills must provide a low-speed mode from 0.2 to 3.0 km/h with a speed increment no greater than 0.1 km/h [9]. These ranges define a deliberately conservative envelope: the upper limit of 60 steps per minute and 3.0 km/h is well below typical comfortable walking cadence in adolescents, which the pre-assessment form gives as approximately 100–115 steps per minute for ages 13–18 [11]. The device is therefore conceived for slow, controlled, repetitive stepping rather than for walking at natural overground speeds.

The knee range of 0–50° applies to the device used at NCCR; there is no separate paediatric configuration with a larger range. The reference data used in the program's analysis pipeline (Chapter 8) include peak knee flexion values above 50° for the reference child [13]. Those values describe overground walking; under robot guidance, swing-phase knee flexion is limited to the device range, and comparisons between overground and robot-derived knee kinematics must take this ceiling into account.

Other functional requirements are implicit in the manual and brochure. The therapist must be able to enable or disable each of the four joint drives individually (left hip, right hip, left knee, right knee), set the gait speed, and synchronise the robot with the treadmill belt [9]. The device must interface with an external body-weight support system whose unloading can be reduced progressively as the patient improves [9,10]. Session data, including joint angles and torques, must be logged and exportable for outcome assessment [10].

4.2.4 Environmental and installation requirements

Because the device is a fixed installation over a treadmill rather than a wearable overground exoskeleton, the treatment room itself is part of the design. The manual specifies a professional medical environment such as a physical therapy room, with illumination of at least 300 lux at the working surface and no glare on displays; a level, non-slip floor with cables protected in channels; a floor load capacity of at least 300 kg/m²; and minimum clearances of 0.6 m at the sides, 0.8 m at the rear and 1.2 m at the front, the latter doubling as an evacuation zone [9]. Operating conditions are +10 to +35 °C, 30–75% relative humidity without condensation, and atmospheric pressure of 70–106 kPa [9]. Mains supply must be single-phase 220 V, 50 Hz with a protective earth conductor, preferably on a dedicated circuit with a 10–16 A breaker and a 30 mA residual-current device [9]. These requirements are not incidental: several of the residual risks discussed in Section 4.8 (falls, entrapment, electrical hazard and electromagnetic interference) are controlled in part by the room layout and the electrical installation.

4.3 Mechanical Design and Actuation

4.3.1 System concept

The Gait Rehabilitation Robot is conceived as an integrated system with four principal elements: the robotic exoskeleton, an adaptive body-weight support system, a treadmill for gait training, and optional virtual-reality, gaming and projection modules for biofeedback and engagement [10]. The exoskeleton is the core device; the manual treats the suspension and treadmill as compatible third-party or optional systems that must meet stated interface requirements [9].

In use, the patient wears a harness attached to the suspension, which supports part of the body weight and protects against falls. The exoskeleton is attached to the patient's thighs and shanks by cuffs, with its hip and knee joint axes aligned to the anatomical joint axes. The treadmill belt moves beneath the patient at a speed synchronised with the robot's stepping rate. The robot moves, or assists the movement of, the hip and knee in the sagittal plane, while the therapist monitors posture, comfort and the displayed data [9,10].

4.3.2 Exoskeleton base module

The base module comprises left and right lower-limb units supplied as a single set (article A-GEAR-V1), with a mass of 50 kg and overall dimensions of 880 × 650 × 1100 mm (length × width × height) without suspension or cables [9]. Each leg unit carries two powered joints, at the hip and knee, giving four actuated degrees of freedom in total; the ankles are unactuated [9,23]. The manual describes the joints as articulated lever (hinge-lever) assemblies housed in protective casings, with length-adjustment units for the thigh and shank segments secured by M6–M8 fasteners [9]. Adjusters and locks allow the exoskeleton axes to be aligned with the patient's hip and knee axes, and the segment cuffs are then tightened to prevent the axes shifting during movement [9].

Both actuators of each leg are carried on the thigh segment: the hip actuator at its proximal end and the knee actuator at its distal end, each driving its joint directly about a single axis, with no belt or linkage between actuator output and joint [23]. The shank segment carries structure and a cuff only, with a mass of 1.0–1.5 kg against 4.5–5.5 kg for the thigh segment including both actuators [23]. One consequence is that the inertia seen at the knee is dominated by the thigh swinging the knee axis rather than by the shank rotating about it [23]. Each segment ends in an open C-section cuff: a transparent, perforated polycarbonate shell curved to the limb, padded at the skin interface, carried on a bracket that clamps to the segment rails so that cuff height follows the length adjustment, and closed with a webbing strap and ladder buckle [23]. Because the limb is laid into the open section rather than threaded through it, the cuff can be fitted to a limb that cannot be fully straightened, which is a practical advantage in children with knee flexion contractures [23].

The knee design has its roots in the program team's research on biomimetic knee mechanisms. A paper in *IEEE Transactions on Medical Robotics and Bionics* reported the design and transparency assessment of a gait rehabilitation robot with biomimetic knee joints [1]. A transparent robot, in this sense, is one that imposes little resistance on the wearer when commanded to follow rather than lead, which is an important property if the device is to measure and encourage the patient's own effort. As Section 4.6.3 explains, the high-reduction drivetrain of the current device is not usefully backdrivable, so transparency in the current form is obtained by active friction and gravity compensation rather than by the mechanism alone [23].

Two variants of mounting are documented. In the first, the base module hangs from a bracket fixed to an adapter plate bolted to the uprights of a U-shaped suspension frame; in the second, it is carried on a

mounting frame on rollers [9]. With the suspension system, the total installation weighs 150 kg and occupies 880 × 1200 × 2200 mm; with the mounting frame, it also weighs 150 kg and occupies 880 × 1500 × 1800 mm [9].

4.3.3 Actuation

Each joint is driven by an integrated geared brushless direct-current (BLDC) actuator (AK80-64, CubeMars) with a 64:1 reduction, the actuator output being the joint itself [10,23]. Each actuator is commanded by an ODrive v3.6 motor controller running firmware 0.5.6 in torque mode, communicating over a controller area network (CAN) bus at 250 kbit/s [23]. The operating manual records the drive version as V3.6 for both legs on the documented unit and provides a USB service connection to each leg controller [9]. The real-time control law runs at 250 Hz on an ESP32-S3 microcontroller, in a task pinned to a dedicated core; a host computer connected over Wi-Fi acts only as a supervisor (parameter changes, telemetry display and recording) and has no role in the real-time loop, so that loss of the host cannot interrupt control [23]. The operator panel software (version V03_2 on the documented unit) communicates with the drives and, when connected, with the treadmill [9].

The 64:1 reduction places the device outside the quasi-direct-drive regime used in some recent exoskeletons. It provides high torque density at a mass compatible with a child's limb, but the drivetrain contributes roughly 1.7 N·m of friction referred to the joint and the joint is not usefully backdrivable, so interaction torque cannot be inferred reliably from the transmission [23]. This is one reason why joint-reaction load cells are fitted (Section 4.6.1) and why friction must be identified and compensated before each session (Section 4.6.3).

The electrical ratings reflect a moderate-power device: standby consumption is at most 40 W, typical operating consumption at most 300 W, and short-term peak at most 600 W, protected by a 5 × 20 mm T6.3A fuse [9]. The operating mode is intermittent, with active periods followed by cooling pauses. The two sources differ on the rated cycle: the manual specifies at most 30 min on followed by at least 10 min off [9], whereas the data sheet specifies at most 20 min on and at least 10 min off [10]. The program trial uses robot-assisted sessions of 20 minutes (Section 4.11), which lie within both ratings, so a single session does not require an intermediate pause; consecutive sessions with different children on the same unit should nevertheless respect the 10-minute cooling interval.

The research lineage of the actuation and control concepts is broader than the current device. Earlier work by the team concerned an intrinsically compliant robotic gait training orthosis, for which robust nonlinear control [7], adaptive impedance control [8], general control strategies [6] and assist-as-needed control [5] were developed and published. More recent papers have addressed the design and analysis of a multi-degree-of-freedom compliant gait rehabilitation robot [4] and nonlinear model predictive control of a self-aligning compliant gait rehabilitation robot [3]. These papers establish the conceptual basis for the assist-as-needed philosophy adopted in the device, but they describe research platforms whose actuation differs from the geared BLDC drives of the current device; readers should not assume that every property of those platforms carries over.

4.3.4 Interfaces to suspension and treadmill

Because the robot depends on external suspension and treadmill systems, the manual devotes considerable attention to compatibility. The tested suspension systems are the stationary Orthorent C and a suspension system under development by the device manufacturer (working title LiftAssist G2); the tested treadmills are the Alexia HC-TM-C900 0 and the Spirit Fitness LW280 and LW650 models [9]. The interface requirements are summarised in Table 4.3.

Table 4.3. Interface requirements for compatible suspension systems and treadmills.

Interface	Requirement [9]
Suspension lifting capacity (BWS/lift)	At least 100 kg
Suspension frame/carriage static capacity	At least 150 kg (static, without dynamics)
Suspension geometry	U-shaped frame; distance between posts 1.0 m ± 0.10 m
Mounting area on each upright	Clear area of at least 80 × 600 mm
Threaded mounting points	Three per upright at 150 mm pitch, M8 × 1.25 or M10 × 1.5
Fastener grade and torque	Class 8.8 or higher, oversized washers; M8: 25–35 N·m, M10: 45–60 N·m (dry thread)
Clearances	At least 10 mm to adapter elements along the full carriage travel
Treadmill speed	Low-speed mode 0.2–3.0 km/h, increment ≤ 0.1 km/h
Treadmill safety interface	External E-STOP input and dry-contact or API connector for a STOP signal
Treadmill deck	Belt height ≤ 250 mm; side clearance at handrails ≥ 0.6 m; front clear zone ≥ 1.2 m
Electrical	220 V, 50 Hz with protective earth; signal and power cables routed separately; cable shields bonded to PE on the exoskeleton side

The treadmill STOP interface is a safety-critical element. When the robot's emergency stop is pressed, a dry-contact signal must stop the treadmill as well; otherwise a patient whose legs have been halted by the robot could be carried backward by a moving belt. The troubleshooting guidance explicitly addresses the failure mode in which the treadmill does not stop after a robot fault, attributing it to incorrect wiring or reversed polarity of the dry-contact output, or to power wrongly applied to that output [9].

4.4 Components and Delivery Set

The standard delivery set, as listed in the operating manual, is reproduced in Table 4.4. The standard set contains only size M cuffs, and the manual lists two thigh cuffs but four shin cuffs, which suggests two cuffs per shank segment. At NCCR, cuffs in all sizes are available in addition to the standard set.

Table 4.4. Standard delivery set of the Gait Rehabilitation Robot.

Item	Contents [9]	Quantity
Basic lower-limb exoskeleton module (left/right)	Article A-GEAR-V1; mass 50 kg	1 set
Fixation cuffs	Thigh, size M (girth 46–58 cm)	2
	Shin, size M (girth 32–40 cm)	4
Control panel and operator software	Emergency stop button (E-STOP) on cord	1
	Control panel with screen	1
	Control panel power supply	1

Item	Contents [9]	Quanti ty
Cable kit	Common power cable (220 V, 10 A), 10 m	1
	Inter-unit power cable (220 V, 10 A, shielded), 1.5 m	2
	Communication cable, 1.5 m	2
	Power distribution panel	1
Fasteners and mounting elements	Fastener set with torque chart ("moment map")	1 set
	Adapter brackets for the suspension carriage	1 set
Documentation	Operating manual; passport/warranty card	1 each

Accessories supplied or ordered separately include a set of liner inserts in sizes S, M and L for adjusting cuff fit, a two-shelf service trolley or storage stand, a set of 40 heat-shrink marking tags for cables and assemblies, and 50 mm × 1200 mm fixation belts with quick-release buckles [9]. Options include the mechanical adapter to a suspension system, the mounting frame on rollers, a partial body-weight unloading module with a range of 10–60 kg, and an extended software package providing protocols, CSV and HL7 export, and PDF reports [9]. The minimum spare parts kit comprises M10 and M8 class 10.9 fasteners with washers and thread locker, an IEC C13–C14 power cable and a shielded communication cable, an E-STOP button assembly, and pairs of thigh and calf cuffs; consumables include textile covers and linings for the cuffs in sizes S to XL, belts and slings, cable clips, fuses, lint-free wipes, approved disinfectants, desiccant and replacement safety pictograms [9].

The brochure lists optional mixed-reality and projection modules that present virtual therapy scenes and biofeedback during training [10]. These are not part of the standard delivery set in the manual. Within the program, a head-mounted virtual-rehabilitation application developed for treadmill walking in the robot (Chapter 9) was used in the 2025 Gait Rehabilitation Robot + VR pilot study (Section 4.11.1).

4.5 Technical Characteristics

Table 4.5 consolidates the technical characteristics of the device. Values are taken from the operating manual unless otherwise indicated; where the data sheet gives a different value, both are shown.

Table 4.5. Technical characteristics of the Gait Rehabilitation Robot (model A-GEAR-V1).

Parameter	Value	Sourc e
Model	A-GEAR-V1	[9,10]
Actuated joints	Hip and knee, left and right (4 drives); ankles unactuated	[9,23]
Drive technology	Integrated geared BLDC actuators (AK80-64), 64:1 reduction	[10,2 3]
Motor controllers	ODrive v3.6 (firmware 0.5.6), torque mode, CAN bus 250 kbit/s	[23]
Real-time controller	ESP32-S3, 250 Hz control loop; host supervisor over Wi-Fi	[23]
Joint torque sensing	Futek load cell in the reaction path of each joint (4)	[23]
Commanded torque cap	20 N·m (hip); 16 N·m (knee)	[23]
Hip range of motion	−35° to +35° (flexion/extension)	[9,10]
Knee range of motion	0° to 50° (flexion)	[9,10]
Segment angular velocity	Up to 60°/s	[9,10]

Parameter	Value	Source
Step frequency	0.2–1.0 Hz (12–60 steps/min)	[9,10]
Step length on treadmill	0.2–0.8 m (dependent on height and settings)	[9,10]
Treadmill belt speed (compatible models)	0.2–3.0 km/h, increment ≤ 0.1 km/h	[9,10]
Patient body mass	Up to 100 kg	[9,10]
Patient height	120–190 cm (manual patient limits state 100–190 cm)	[9,10]
Segment length adjustment	Thigh 340–475 mm; shank 145–330 mm	[23]
Body-weight support (optional module)	10–60 kg partial unloading (comparison table in [10] states 10–100 kg)	[9,10]
Base module mass	50 kg	[9,10]
Base module dimensions (L × W × H)	880 × 650 × 1100 mm	[9,10]
System mass with suspension or frame	150 kg	[9,10]
System dimensions with suspension	880 × 1200 × 2200 mm	[9,10]
System dimensions with mounting frame	880 × 1500 × 1800 mm	[9,10]
Power supply	220 V, 50 Hz, Class I (protective earth required)	[9,10]
Power consumption	Standby ≤ 40 W; typical ≤ 300 W; peak ≤ 600 W	[9,10]
Fuse	5 × 20 mm, T6.3A	[9]
Operating noise	≤ 80 dBA at 1 m	[9]
Protection against electric shock	Class I; Type B applied parts	[9,10]
Enclosure protection	IP20	[9,10]
Operating mode	Intermittent: ≤ 30 min on / ≥ 10 min off (data sheet: ≤ 20 min on / ≥ 10 min off)	[9,10]
EMC classification	Group 1, Class A (IEC 60601-1-2)	[9,10]
Software safety class	Class B (IEC 62304)	[9,10]
Operating environment	+10 to +35 °C; 30–75% RH, non-condensing; 70–106 kPa	[9,10]
Storage and transport	−30 to +50 °C; 10–85% RH, non-condensing	[9,10]
Encoder accuracy	Zero offset ±1.0°; error over range ≤ ±2.0°	[9,10]
E-STOP response	≤ 500 ms to onset of braking	[9,10]
Treadmill synchronisation interface response	≤ 100 ms	[9]
Service life	5 years or 20,000 motor-hours, whichever comes first	[9,10]
Operator software version (documented unit)	V03_2	[9]
Drive version (documented unit)	V3.6 (left) / V3.6 (right)	[9]

The manufacturer's warranty covers free elimination of manufacturing defects, replacement of failed components and restoration of functionality, and is conditional on operation according to the manual

with protective earthing, scheduled maintenance, no unauthorised interference with the electrical compartment or software, and the use of compatible suspension systems and treadmills with a correctly connected synchronisation interface [9]. Mechanical damage from impact or improper transport, damage due to a missing protective earth, overload, flooding or fire, wear of consumables and textiles, and the consequences of installation contrary to the torque chart or of design changes are excluded [9]. The warranty period itself is that stated in the passport/warranty card supplied with each unit; the figures printed in the manual's warranty clause are internally inconsistent and are not reproduced here.

4.6 Sensing and Control Architecture

4.6.1 Onboard sensing

The manual lists the measuring units that are subject to calibration [9]. Each hip and knee module carries a joint angle encoder. Step speed or step frequency is either measured by a dedicated sensor or, more commonly, calculated from the encoder signals. Depending on the configuration, an inertial measurement unit (IMU) or inclinometer may be installed, and, where the body-weight support module is included, a load sensor monitors the unloading force. The treadmill synchronisation interface and the emergency stop circuits are also treated as verifiable functions [9].

In addition to the encoders, four Futek load cells, one per joint, are fitted as standard. Each sits in the reaction path of its joint, between a fixed lever and a reference plane (the pelvis for the hips and a thigh-fixed plane for the knees), so that it measures torque downstream of the gearbox, free of the assumed drivetrain efficiency and friction model that a motor-current estimate requires [23]. In the program's analysis software (the Gait Recovery Index and the GARAS software, both described in Chapter 8), the load-cell force multiplied by the joint moment arm is treated as a direct measurement of the patient's joint torque contribution [13,14]. Two qualifications apply to that measurement. First, a reaction-path load cell also reads the machine's own torque, for example the torque needed to carry the device's segments and overcome drivetrain friction; this contribution must be removed, which is the purpose of the passive calibration trial performed before the first session (Sections 4.6.4 and 4.11.2) [11,23]. Second, its accuracy depends on calibration and on the moment-arm estimate. In bench calibration against known loads, mechanically identical joints required different moment-arm constants (for example 0.089 m and 0.164 m at the right and left hips, against 0.136 m and 0.139 m previously assumed), and the calibrated values are now stored in the firmware [23]. An alternative, also documented, estimates joint torque from motor current through a torque constant and an assumed drivetrain efficiency [15,23]; in the current device it serves as a secondary estimate.

For research purposes within the program, the robot's own signals are complemented by a pair of 16-sensor plantar pressure insoles sampled at 200 Hz for gait event detection [13,14]. During training, the controller broadcasts telemetry at 100 Hz, recorded as a session file accompanied by a sidecar that identifies the exact software build and the complete controller configuration in force [23].

4.6.2 Control concept

The control philosophy of the device is *assist-as-needed*: the controller senses the state of each joint and modulates motor assistance so that each leg receives the level of support it requires at each phase of the gait cycle [10]. Calibration is performed from the operator panel with a single button press [9,10]. The scientific basis of assist-as-needed control for a gait training orthosis was published by the team in 2017 [5], building on earlier adaptive impedance control [8]. The essential idea is that a purely position-controlled exoskeleton, which drives the limbs along a fixed trajectory regardless of the patient's effort, risks encouraging passivity; an assist-as-needed controller instead reduces its assistance when the

patient's own contribution is sufficient to keep the limb near the desired pattern, and increases it when the patient falls short. In children with CP, this property is expected to encourage active participation, although the clinical value of a particular controller must be established by trial data rather than assumed.

The manual describes the operator-adjustable movement parameters as amplitude, speed and phase [9], and the therapist-set session parameters include joint selection, movement speed (in degrees per second and step frequency), belt speed and body-weight support level [10]. Torque assistance can be adjusted independently for each of the four joints [10]. Safety limits on angle and speed are enforced both by software and by mechanical stops [9]. This dual protection is important: a software limit alone cannot protect against a firmware fault, while a mechanical stop alone could allow high impact forces at the end of the range. The controller that implements this concept is described in the next section.

4.6.3 Bounded compositional torque controller

The controller in its current form has been described and characterised on the bench in a submitted manuscript by members of the program's engineering team and the author [23]. Its design responds to a practical problem: a rehabilitation device accumulates operating modes (carry the limb, hold it, assist, resist, guide it along a path), and if each mode is implemented as a separate control path, each is a new opportunity to omit a limit, so that the safety argument must be re-made for every mode.

Composition of commanded torque. The commanded torque at each joint is the sum of independently bounded terms: gravity compensation, friction compensation, a constant feed-forward term, the corridor assist term described below, a path wall, viscous damping, a range-of-motion (ROM) wall and a speed brake [23]. A clinical mode is defined as a mask over these terms rather than as a separate control path, and the whole mode ladder exists once in the firmware as a table of term masks resolved when a mode is selected. The three safety terms (damping, ROM wall and speed brake) are combined into every torque mode when the table is resolved, so that a torque mode lacking them cannot be expressed. The modes are *Transparent* (gravity and friction compensation only, with the reference frozen), *Assist* and *Resist* (identical except for the sign of the feed-forward term), *Path* (a compliant tunnel around the reference, in the manner of patient-cooperative path control), and *Corridor-AAN* (the assist-as-needed corridor at a fixed, treadmill-paced cadence). A *Position* mode, which commands the motor controller's position loop directly, is outside the torque summation; it is bounded by the drive's own current limit and by the range of motion, and the bounds below are not claimed for it [23].

Assist law. In Corridor-AAN mode the assistance is driven by the lag of the joint behind the reference along the direction of travel. A smooth direction term fades to zero at the reference's turning points, where "behind" is undefined. Assistance is one-sided, so a child who is ahead of the pattern is never braked, and it is zero inside a dead zone whose half-width is scheduled by gait phase (3.0° in stance, 1.5° in swing, so that the corridor is tighter in swing, where a weak limb fails to clear and advance). Beyond the dead zone the assist torque rises linearly with the excess lag, with gains of 0.036 N·m/° at the hip and 0.027 N·m/° at the knee, and saturates at a lag of 18° [23]. The overall gain is the product of a therapist-set level (at most 30) and an adaptation factor that evolves as a leaky integrator on normalised need, with equal growth and forgetting rates of 0.15 s^{-1} (a time constant of about 6.7 s) and a floor of 0.15 that prevents complete withdrawal of assistance. The adaptation therefore follows the average need over a session timescale while attenuating within-stride variation by a factor of about 15 at the gait fundamental [23]. The authors do not claim novelty for the assist law itself, which descends from established dead-zone and forgetting-factor formulations.

Safety bounds. Because each term has a bounded range and the summed torque is clamped after the summation, the bounds in Table 4.6 are algebraic consequences of the composition rather than outcomes

of tuning: they hold for every torque mode, any participant behaviour and any parameter choice within the permitted ranges [23]. The maximal assist term at the highest therapist gain (30 × 0.648 = 19.4 N·m at the hip) lies below the hip cap by design. The slew limit means that the full cap cannot be reached in less than 750 ms, while a clinically meaningful 5 N·m can still be developed within about 185 ms. The per-excursion work bound is weaker than passivity: it limits the mechanical work in a single bounded-range excursion but not the cumulative energy delivered over many cycles, and the authors state explicitly that the controller is not passive, since friction compensation is positive velocity feedback by design [23]. The bounds apply to commanded torque; the torque delivered at the limb follows it through the drivetrain and is observed, after calibration, by the joint load cells (Section 4.6.1).

Table 4.6. Safety envelope of the controller in its current form (torque modes; true joint units) [23].

Bound or safety term	Value
Commanded torque cap	20 N·m (hip); 16 N·m (knee)
Slew-rate limit	27 N·m/s (time to reach the cap ≥ 750 ms)
Work in a single excursion	≤ 22.5 J (hip); ≤ 15.5 J (knee)
Assist term	≤ gain × 0.648 N·m (hip) or 0.486 N·m (knee); saturates below the cap
Friction compensation	Clamped at 4 N·m; faded to zero over 0.4 s when the gait is stopped
ROM wall	1.1 N·m/° plus 0.18 N·m/(°/s) within a 9° band inside each range limit
Speed brake	Opposing torque proportional to joint speed above a threshold
Viscous damping	Always active in torque modes
Power cut	Mushroom-head emergency button with no software path

The manuscript also reports the provocation of each safety term on the bench, and the results are instructive about the limits of construction as evidence [23]. The ROM wall was measured quasi-statically at 2.491 N·m/° against a specified 2.500 N·m/° in device units, once a telemetry timing artefact that had made it appear incoherent was removed. The torque cap was never reached from any setting available at the operator interface (the highest commanded torque recorded was about 8 N·m below it), so its operation has not been exercised. The speed-brake thresholds inherited from the actuator nameplate lay above any speed the drivetrain could reach and were therefore lowered to 35°/s and 25°/s, about 1.5 times the fastest joint motion recorded on the device, so that the term lies within the range that a fault could reach. Finally, an unplanned observation showed that a term mask correct during operation can be wrong at the transition out of it: pressing stop froze the reference while friction compensation remained active, leaving the knee freer than an unpowered joint until compensation was made to fade out over 0.4 s.

Identification and physical admissibility. Before each session, the unloaded robot is swept through its range and a five-parameter model of motor current is fitted for each joint by least squares, with gravity represented by a sine–cosine pair, viscous and Coulomb friction by velocity terms, and a constant offset [23]. Each half of the model (gravity and friction) is accepted only if it passes a signal-to-noise criterion and a physical-admissibility test: the fitted friction must oppose motion at every speed in the operating range, which for this model reduces to a non-negative Coulomb coefficient and a viscous term that cannot reverse the sign within the speed range. On the device, both knees initially returned Coulomb friction of the wrong sign while passing the signal-to-noise gate; the admissibility test rejected them, and the investigation that followed exposed an inverted current-sign convention in the measurement path of the knee axes, which was then corrected [23]. Two further findings shape how the device is used. Over the narrow arc swept at therapy amplitude the gravity regressors are nearly collinear, so a sweep must be wide enough for the gravity terms to be separately meaningful; and the knee gravity coefficient

does not reproduce in sign between sessions, so the knee currently runs with friction compensation and without gravity compensation, while the hip runs with both [23]. The manuscript also shows that setting friction compensation to full cancellation leaves the joint at the stability limit of the coupled system (a sustained 1.1 Hz limit cycle against an elastic load), and recommends that the therapist-adjustable range be bounded below unity [23].

Behaviour against a resisting limb. The assist law responds to lag, and lag cannot by itself distinguish a weak limb from a resisting one; in a spastic limb, assisting into a catch may load the stretch reflex. In bench bouts in which an operator applied graded opposition by hand, commanded assist under the current law rose by about 0.24 N·m per N·m of opposition measured by the load cell, whereas an experimental gate that withholds assistance when the load cell indicates opposition flattened that relation [23]. The gate is not part of the clinical configuration: it also withheld about 22% of the available assist when the limb was barely opposed, which would amount to a change in training dose on every stride, and the authors recommend that it be restricted to sustained opposition before it reaches a patient [23]. These bench results were obtained without human participants, with a hand rather than a spastic limb as the resisting agent; their clinical relevance remains to be established.

4.6.4 Torque and pressure biofeedback

Because the rehabilitation goal is to reduce robot-generated torque while the patient's own torque increases, the operator interface displays both quantities in real time, for therapist monitoring and for patient motivation [10]. Foot pressure distribution is displayed as additional biofeedback to encourage more symmetrical loading of both feet [10]. In the program's analysis pipeline (Chapter 8), robot and patient contributions are separated by a passive calibration trial, during which the robot moves the relaxed limb: the load-cell values recorded in that trial provide the reference against which the joint torque during active walking is compared [11,13].

4.6.5 Software classification and data export

The operator software is classified as Class B under IEC 62304 [9,10,22], meaning that a software failure could contribute to a hazardous situation resulting in non-serious injury. This classification determines the rigour of the software life-cycle processes required of the manufacturer. Session data can be exported in CSV format [10]; the extended software option adds HL7 export and PDF reports [9]. Export of the error log is part of the service procedure [9].

In summary, the functional architecture comprises the operator panel and its software; the host supervisor; the real-time controller on the ESP32-S3; four ODrive motor controllers on a CAN bus driving the hip and knee actuators; joint encoders and joint-reaction load cells at each joint; the optional IMU and BWS load sensor; the hardware emergency stop circuit with its power cut; and the dry-contact synchronisation and STOP interface to the treadmill [9,23].

4.7 Operating Modes and User Interface

4.7.1 Controls

The manual identifies seven principal controls and interfaces on the device: power indicators for the left and right leg modules (green when powered), USB service connections to each leg controller, the control panel graphical user interface, the mains inlet, and the emergency stop button, which stops the robot immediately and issues a STOP to the treadmill [9].

4.7.2 Graphical user interface

The operator interface is organised into four regions [9]. A joint selection panel on the left contains four toggle switches, one for each drive (hip right, hip left, knee right, knee left); a drive participates in the movement only when its switch is on. This allows, for example, a therapist to assist only the affected side in a child with hemiplegia, or only the knees in a child whose hip control is adequate. A session control panel at centre-right contains four square buttons — CONNECT, CALIBRATE, STOP and ERRORS — and a large vertical START button. A speed bar at bottom left contains a horizontal slider for the gait speed with a numeric readout. A status bar at the bottom centre displays prompts and the current status; on start-up it instructs the operator to press CONNECT first [9].

4.7.3 Session state logic

The interface enforces a simple state sequence that prevents the device from moving before it is ready. Its logic, reconstructed from the manual, is summarised in Table 4.7.

Table 4.7. Operator actions and device states.

Action	Effect [9]	Preconditions and notes
CONNECT	Establishes communication with the drives and sensors and, if connected, the treadmill	Success is indicated by a green status indicator at the upper right of the GUI
CALIBRATE	Performs zero calibration of the joints	Must be performed with the device stopped and without the patient; completes with the status "Calibrated!"
START	Starts the training movement	Active only when the device is connected/ready and calibrated and no errors are active
STOP	Software ("soft") stop of the running sequence	Not an emergency stop
ERRORS	Displays active and historical errors with hints	Errors must be cleared and a RESET performed before restarting
E-STOP (hardware)	Immediate emergency stop; STOP signal to treadmill	Located on the frame and on a cord; used in any emergency

The distinction between the software STOP and the hardware E-STOP is emphasised repeatedly in the manual [9]. The software STOP ends the movement sequence in an orderly way and is used, for example, to pause and adjust a cuff. The E-STOP is a hardware function that does not depend on the software and is the only correct response to an emergency. In the current controller, the controller settings are pushed from the host to the device as a checked sequence on every CONNECT, and a partial push is reported together with the setting at which it stopped [23].

4.7.4 Operating parameters across a course of therapy

The manual describes a progression in which, once the patient is walking with the device, the therapist works on symmetry, rhythm and foot placement, and gradually increases speed and session duration while decreasing the proportion of body weight carried by the suspension [9]. If fatigue or pain appear, parameters are reduced, a break is taken, or the session is ended [9]. A physiotherapist at NCCR has described personalising rehabilitation by adjusting robot torques, belt speeds and the level of body-weight support on the basis of the data displayed [10]. The controller manuscript adds a caution relevant

to dosing: because the therapist's gain and the adaptation factor enter the assist term as a product, the same gain setting can deliver different effective assistance depending on the state of the adaptation law, and the authors recommend that the product, or the adaptation factor alongside the gain, be displayed [23]. The progression rules used in the program trial are addressed in Section 4.11.3.

4.8 Safety

4.8.1 Classification and applicable standards

The Gait Rehabilitation Robot is medical electrical equipment and is designed to the family of standards listed in Table 4.8 [9,10]. The manual cites the Russian GOST R adoptions alongside the international standards but, with the exception of GOST R IEC 60601-1-2:2022 for electromagnetic compatibility, does not state edition years; the editions listed in the references are the current consolidated editions of each standard.

Table 4.8. Standards cited for the Gait Rehabilitation Robot.

Standard	Subject	Reference
IEC 60601-1 (GOST R IEC 60601-1)	Basic safety and essential performance of medical electrical equipment	[16]
IEC 60601-1-2 (GOST R IEC 60601-1-2)	Electromagnetic compatibility	[17]
ISO 14971 (GOST R ISO 14971)	Application of risk management to medical devices	[18]
ISO 20417	Information to be supplied by the manufacturer of medical devices	[19]
ISO 15223-1 (GOST R ISO 15223-1)	Symbols used in labelling	[20]
IEC 60529 (GOST 14254)	Degrees of protection provided by enclosures (IP code)	[21]
IEC 62304	Medical device software life-cycle processes (Class B)	[22]

Under these standards, the device is classified as Class I for protection against electric shock (it relies on a protective earth conductor), with Type B applied parts, meaning that the parts contacting the patient have no electrical contact with the patient [9]. The enclosure rating is IP20: the device is protected against solid objects of 12.5 mm and larger but not against water, which explains the strict restrictions on liquid cleaning [9]. For electromagnetic compatibility it is Group 1, Class A equipment, intended for professional rather than domestic environments [9]. It is not intended for use in the presence of flammable anaesthetic or oxygen mixtures [9]. The controller manuscript describes its safety framing as following the risk-control logic of the personal-care-robot and medical-software standards, without claiming conformance on that basis [23].

4.8.2 Layered stopping architecture

The device has three ways of stopping: the software STOP, the hardware E-STOP, and the dry-contact STOP to the treadmill that is triggered by the E-STOP [9,10]. The E-STOP must initiate braking within 500 ms [9], and the treadmill synchronisation interface must respond within 100 ms [9]. The emergency power cut has no software path [23]. The manual requires that the E-STOP be accessible to both the operator and the assistant and be tested before each session, ideally at the start of each shift, by pressing it and confirming that both the robot and the treadmill stop [9]. Emergency stops on the suspension and

treadmill must also be checked before starting [9]. A failure of the E-STOP, or a treadmill that does not receive the STOP signal, is grounds for immediate removal from service [9]. Beneath these stopping functions, the torque cap, slew limit, ROM wall, speed brake and damping of Section 4.6.3 bound what the controller can command during normal operation [23].

4.8.3 Mechanical hazards and no-go zones

The principal mechanical hazards are entrapment and crushing at the hip and knee joints, at the bracket and suspension frame, along cable runs and at the treadmill [9]. The device carries "pinch hazard" warning signs with arrows indicating the direction of motion; hands and fingers must be kept at least 50 mm from moving parts, while a 10 mm technological clearance is maintained along the trajectory of moving parts but is not intended for access [9]. Placing hands or tools into restricted areas, or allowing bags, textiles or cables to lie within the range of motion, is prohibited, and adjustments are to be made only when the device is stopped [9].

4.8.4 Electrical safety

Before switching on, the operator visually inspects the earthed socket, the power cable and plug, the accessibility of the E-STOP, the separation of power and signal cables, and the presence of the safety labels [9]. Connection is permitted only to an earthed 220 V, 50 Hz supply; floating earths, ungrounded stabilisers or uninterruptible power supplies, and extension cords without an earth contact are prohibited [9]. If a software error, burning smell or unusual heating occurs, the prescribed sequence is E-STOP, power off, evacuation of the patient, and notification of the responsible person [9].

Periodic electrical safety testing by medical equipment service staff is required at least every 12 months and after any repair. The manual specifies a protective earth resistance of no more than 0.2 Ω and an insulation resistance of at least 2 MΩ, with leakage currents within the limits of IEC 60601-1: at most 0.5 mA through the protective conductor in normal condition, at most 0.1 mA enclosure touch current, and 0.01 mA patient leakage current for Type B applied parts [9]. A device that fails any of these tests is removed from service, labelled and sent for repair [9]. (The annual maintenance table in the same manual gives a protective earth criterion of less than 0.1 Ω "or according to the enterprise standard" [9], a stricter value than the 0.2 Ω quoted for periodic testing.)

4.8.5 Electromagnetic compatibility

The device is designed to the immunity and emission levels of IEC 60601-1-2, and the manual gives an impulse (burst) immunity test level of ±2 kV on mains lines [9]. Its practical guidance concerns separation from radio-frequency transmitters, summarised in Table 4.9. Where the power and frequency of a nearby transmitter are unknown, a separation of at least 3 m from smartphones in hotspot mode and from walkie-talkies is recommended [9]. Symptoms of interference include spontaneous shutdowns, communication errors and jerky movement; the response is to increase the distance to the transmitter, separate or shield cables and restart the session sequence, and, if symptoms persist, to remove the patient and file an incident report [9]. Operators may not use radio headsets or walkie-talkies closer than the recommended distances during a session, and the device should not be placed near MRI rooms, radio stations or other strong sources of RF interference [9]. Because the host supervisor communicates with the real-time controller over Wi-Fi but has no real-time role, loss of that link does not interrupt control [23].

Table 4.9. Recommended minimum separation distances between portable RF transmitters and the Gait Rehabilitation Robot.

Rated transmitter power	150 kHz–80 MHz	80–800 MHz	800 MHz–2.7 GHz
0.01 W	0.12 m	0.12 m	0.23 m
0.1 W	0.38 m	0.38 m	0.73 m
1 W	1.20 m	1.20 m	2.30 m
2 W (DECT/radio)	1.70 m	1.70 m	3.25 m
5 W (professional radio)	2.68 m	2.68 m	5.14 m

Source: operating manual [9].

4.8.6 Residual risks

Risk management under ISO 14971 identifies hazards, estimates and controls risks, and documents the residual risks that remain after controls are applied, together with the information given to users about them. The manual lists six residual risks and the associated warnings, summarised in Table 4.10 [9].

Table 4.10. Residual risks after risk control and the associated measures.

Residual risk	Measures and warnings [9]
Pinching of soft tissues or fingers at hinges and suspension	"Pinch hazard" signs; adjustment only when the device is stopped; hands kept out of restricted zones
Patient fall with inadequate support	Safety lanyards mandatory; hold test before starting; assistant positioned at the side; E-STOP accessible
Electrical hazard from a damaged cable or missing protective earth	Operation only with PE; visual inspection; "grounding required" sign; ban on improvised extension cords
Joint pain or overload from improper adjustment	Software limits; gradual increase of amplitude; stop if pain exceeds the set level
Skin reactions to cuffs and covers	Individual fit; approved materials and disinfectants; skin inspection before and after; replacement of covers if irritation occurs
Electromagnetic interference	Minimum distances to transmitters; separate routing of power and signal cables

The mandatory text warnings on the product and in the manual reinforce these measures: keep hands and clothing away from hinges and the suspension mechanism; operate only with protective earth connected; align the hinge axes with the anatomical axes, secure the cuffs and check the safety harness before starting; and stop and assess the patient in the event of pain or discomfort [9].

4.8.7 Contraindications

The manual distinguishes absolute and relative contraindications, with the final decision resting with the attending physician [9]. Absolute contraindications include acute conditions and fever; severe cardiorespiratory failure (NYHA class III–IV) and uncontrolled arrhythmias; intractable epileptic seizures; acute thrombosis or embolism; unstable fractures or ligament injuries and fresh postoperative wounds in the fixation zone; severe skin lesions at cuff contact points or infections requiring isolation; and inability to ensure safety, including refusal of restraint or cognitive impairment that prevents cooperation. Relative contraindications include uncontrolled hypertension or hypotension and severe orthostatic reactions; severe spasticity or contractures that prevent safe alignment of the joint axes; severe pain (6 or more on a visual analogue scale) at rest or with movement; and anthropometry outside the product limits [9].

Several of these items are particularly pertinent in CP. Where a child has a seizure disorder, the distinction between controlled and intractable seizures must be made explicitly at screening. Severe spasticity and fixed contractures, especially knee flexion contractures and hip adduction, may prevent the robot axes from being aligned with the anatomical axes and are therefore a relative contraindication. Communication and cognitive impairments may make it difficult for a child to report pain, which places greater weight on observation by the therapist and on skin inspection after each session.

4.8.8 Paediatric considerations

The safety documentation of the device was written for a population that includes adults and adolescents [9] and does not contain provisions specific to children with CP. For use in the program, the following considerations follow from the material above: confirmation that each child's anthropometry lies within the device limits, with particular attention to minimum limb girth and stature; a conservative initial range of motion, speed and assistance; observation of the skin at cuff sites, given that children may not report discomfort reliably; the presence of an assistant on each side; and explicit pain and distress stopping criteria. The bench findings of Section 4.6.3 add two device-specific points: the current assist law can escalate against a resisting limb, so therapists should watch for resistance and catches during swing rather than rely on the controller to detect them; and friction compensation should not be set to full cancellation. The trial-specific adverse-event definitions and stopping rules approved by the ethics committee are addressed in Section 4.11.3.

4.9 Installation and Operation Workflow

4.9.1 Transport, storage and unpacking

The device is shipped in rigid cases with fitted foam inserts that secure each unit, with joint modules locked in a neutral position, textiles bagged separately, cables coiled without kinks tighter than eight times the cable diameter, and a sealed bag with indicating silica gel desiccant in each container [9]. Transport and storage conditions are −30 to +50 °C and 10–85% relative humidity without condensation; containers must withstand a drop from 0.5 m [9]. After cold transport, the packaging is kept at room temperature for at least four hours before opening to avoid condensation, and in long-term storage beyond six months the desiccant is renewed every six months [9]. Unpacking follows a sequence of container inspection (with photographs if damaged), acclimatisation, careful opening, removal of transport locks, visual inspection and a check of the desiccant indicator [9].

4.9.2 Mechanical installation

The manual stipulates that installation is performed by a specialist [9]. With the suspension and treadmill de-energised and the carriage secured, the adapter plate is offered up to the suspension uprights, its 600 × 80 mm hole pattern for six M10 fasteners is marked, and holes are drilled for M10 threaded rivet nuts, three per upright. After deburring and, if necessary, priming, the rivet nuts are installed, and the adapter is fixed with class 10.9 M10 screws, pre-tightened crosswise and then torqued to 60 N·m. A clearance of at least 10 mm to the moving parts of the carriage is verified along its entire travel. The bracket is then fixed to the adapter with class 10.9 M8 screws torqued to 35–40 N·m, and the base module is hung on the bracket and aligned, using a 10 mm spacer if necessary [9]. Power and signal cables are connected and routed separately, crossing at right angles where they must cross, with a bend radius of at least eight times the diameter and with signal cable shields bonded to protective earth on the exoskeleton side [9]. Tightening torques are re-checked after 24 hours of operation [9].

The treadmill is positioned with at least 0.6 m of clearance at the handrails, its low-speed mode and external STOP input are confirmed, and any synchronisation harness is routed clear of the belt and carriage [9].

4.9.3 Pre-commissioning checklist

Before first clinical use, a checklist covering mechanics, electrical interfaces and function is completed and entered in a commissioning log [9]. The mechanical checks confirm the fastener torques, connection and load testing of the safety slings, clearances and warning signs. The electrical checks confirm the earthed socket and intact cable, a successful E-STOP test that stops both the robot and the treadmill, and correct cable separation and shielding. The functional checks confirm that the operator software starts without errors and displays angle and speed limits, that the device performs step-by-step movement without a patient, and that a test session with a dummy or an assistant can be run at low belt speed (0.2–0.5 km/h) [9].

4.9.4 The therapy session

The session workflow described in the manual can be divided into six phases.

Equipment preparation. The operator inspects cables, belts and fasteners and the legibility of safety signs; checks that the E-STOP is accessible and resets correctly; checks the stops on the treadmill and suspension; moves the drives to the zero position with the legs straight; connects the device to the earthed mains supply and releases the E-STOP; waits for the GUI; and then performs CONNECT and CALIBRATE, confirming that no errors are active [9]. In the current controller, the identification sweep of Section 4.6.3 is performed on the unloaded device at this stage, before the patient is attached [23].

Patient preparation. The patient is briefly assessed for tolerance of upright posture, vital signs and the condition of the skin at fixation sites; the procedure is explained and the patient is asked to signal discomfort or pain; and the suspension harness or vest is fitted [9]. In the program, the pre-assessment described in Section 4.11.2 precedes the first session.

Suspension set-up. The pathway is cleared, with access from both sides; the patient is attached to the suspension and lifted slightly, brought to the treadmill if the suspension is mobile, and the robot moved to its rearmost position for ease of fitting [9].

Donning. The robot axes are aligned with the patient's hip and knee axes using the adjusters and locks, the cuffs are secured, and the fit is checked for excessive pressure, twisted straps and trapped clothing or skin [9].

First steps and training. With the patient raised slightly above the belt, the fit and the patient's well-being are confirmed. The minimum speed, amplitude and assistance are set and START is pressed. The alignment of the device is observed; if necessary the operator presses STOP, adjusts and restarts. The treadmill is then started and its speed synchronised with the robot, and the patient is gently lowered onto the belt while the operator remains ready to use the E-STOP [9]. Training then proceeds with attention to symmetry, rhythm and foot placement, with gradual progression of speed and duration and reduction of body-weight support [9].

Ending the session. The robot is stopped with STOP and then the treadmill is stopped; the fastenings are released and the device is moved back; the patient is lifted, moved off the treadmill, lowered and unfastened from the suspension; the skin is inspected; the device is returned to its initial position and switched off if no further session follows; and the surfaces are cleaned with approved agents [9].

4.10 Maintenance, Verification and Calibration

4.10.1 Cleaning and disinfection

Because the device has IP20 protection, cleaning is performed only with the power disconnected and with the agent applied to a cloth rather than directly to the device [9]. Hard surfaces may be cleaned with 70% isopropyl or ethyl alcohol, quaternary ammonium compounds, hydrogen-peroxide-based preparations (wiped, not sprayed) and pH-neutral foams, with an exposure time of one to five minutes [9]. Textile covers and belts are machine washed at 30–40 °C on a delicate cycle and dried at no more than 60 °C, or disinfected with quaternary ammonium compounds or alcohol wipes [9]. Chlorine-containing agents above 0.05%, abrasives, solvents, spraying into crevices, pressure washing, immersion and autoclaving are prohibited [9]. After cleaning, surfaces are dried for at least 15–30 minutes before power is reconnected [9].

4.10.2 Scheduled maintenance

The maintenance schedule, which operators and service technicians share, is summarised in Table 4.11. All maintenance activities are recorded in a maintenance log that is retained for at least five years [9]; a warranty claim is not accepted without a completed log [9].

Table 4.11. Maintenance schedule.

Interval	Operations [9]	Acceptance criteria [9]
Daily (before shift)	External inspection of frame, assemblies and cables; legibility of labels; cuff fixation; E-STOP function; treadmill synchronisation (if fitted); short idle run	No cracks, play or snags; labels legible; E-STOP acts instantly; no GUI errors
Weekly	Cleaning and disinfection; check of cable routing and clips	Cables intact, bend radius ≥ 8 × D, clips secure
Quarterly	Fastener torques of accessible parts per torque chart; seams of belts and textiles; PE terminal	Torques per chart; belts intact; PE terminal not oxidised
Six-monthly	Free movement and clearances (≥ 10 mm); hidden cable damage	Clearances met; conductor resistance normal
Annually	Full fastener check; insulation resistance and PE continuity; plug and connector heating under load; cuffs and covers	PE < 0.1 Ω (or per enterprise standard); insulation normal; heating within tolerance; worn textiles replaced
After an event	After repair, impact or flooding: unscheduled inspection, electrical testing and recalibration	Return to service decided by the responsible person and logged

The torque chart specifies 60 N·m for the M10 adapter plate fasteners with medium-strength thread locker, 35–40 N·m for the M8 bracket fasteners, 8–20 N·m for the M6–M8 segment-length adjustment units, 2–5 N·m for the M4–M5 casing screws (which must not be over-tightened), 3–4 N·m for the M5 protective earth terminal with a spring washer, and hand tightening for cable clips [9]. The controller manuscript records one reason why these checks matter for measurement as well as safety: a knee joint whose mounting screws had worked loose introduced mechanical compliance in series with the drivetrain, which absorbs assistance and corrupts calibration [23].

Textile elements have a service life of six to twelve months or until visible wear [9]. Decommissioning criteria include cracks or deformation of load-bearing parts, play in the hinge-lever assemblies, missing or damaged protective earth, overheating at the plug or socket, E-STOP malfunction, illegible nameplate or safety signs, and recurrent faults that cannot be cleared by standard procedures [9].

4.10.3 Verification and calibration

The measuring functions of the device are calibrated and verified according to the manufacturer's procedure. Table 4.12 gives the tolerances and intervals [9]. The calibration results are recorded in the maintenance log with the instrument numbers and verification dates of the reference instruments, and the device is labelled "CALIBRATED" with the date and the initials of the person performing the work. If a tolerance cannot be met, the device is labelled "LIMITED" with a statement of the restriction (for example, "do not use BWS") [9].

Table 4.12. Calibration and verification tolerances.

Unit	Parameter	Tolerance	Interval
Hip encoder	Zero offset	±1.0°	Every 6 months or after repair
Knee encoder	Zero offset	±1.0°	Every 6 months or after repair
Hip and knee encoders	Linearity/error over range	≤ ±2.0°	Annually
Step speed (calculated)	Deviation from reference	≤ ±5%	Annually
IMU/inclinometer (if fitted)	Zero drift (pitch/roll)	≤ ±1.0°	Annually
BWS load sensor (if fitted)	Absolute error	≤ ±1.0 kg or ±3% (test points 10/30/50 kg)	Quarterly
Treadmill synchronisation interface	STOP logic and delay	Response ≤ 100 ms	Quarterly
E-STOP / external STOP	Stop time	≤ 500 ms to onset of braking	Every shift (functional test)

Source: operating manual [9].

The joint load cells are not listed in the manual's calibration table. The controller manuscript describes a differential calibration in which a known mass (1–2 kg) is hung on the limb at a measured radius, giving known torques of 5.2–12.9 N·m at the hip; comparing otherwise identical loaded and unloaded sweeps cancels standing offsets, and the resulting moment-arm constants are stored in the firmware [23]. The same work warns that a two-point static check on a channel with a large standing offset can wrongly condemn a working load cell, and that differential calibration avoids this failure by construction [23]. A periodic load-cell check of this kind, with its interval recorded in the maintenance log, is advisable whenever the device is used as a measuring instrument.

For research use, these tolerances have a direct bearing on data quality. An encoder zero offset of up to ±1.0° and a range error of up to ±2.0° propagate into the step-length and symmetry estimates derived from hip angles (Chapter 8), and moment-arm errors propagate directly into load-cell torque. The controller manuscript also reports a hip travel deficit of about 5% relative to commanded motion, attributed to load-dependent mounting compliance [23]. When the device is used as a measuring

instrument in a trial, it is therefore advisable to record the calibration status and software build alongside every session dataset; the session sidecar described in Section 4.6.1 already does this for the controller configuration [23].

4.10.4 Troubleshooting

The manual provides a symptom–cause–action table for the most common faults [9]. Its logic is instructive: most faults that an operator may address are failures of a precondition in the state sequence (no power, no connection, calibration not completed, START inactive because of an active stop or fault), and the prescribed actions restore the precondition. Faults involving the electrical compartment, fuses, connectors or treadmill synchronisation circuits are reserved for authorised service [9]. Patient-related symptoms — pain, discomfort and skin irritation — are treated as device faults in the sense that they prompt a stop, a check of axis alignment and cuff tension, and a reduction of amplitude, speed or body-weight support; persistent pain ends the session [9]. When service is required, the operator supplies the serial number, software and firmware versions, the date of the last maintenance and calibration, a description of the symptom and an export of the error log [9].

4.11 Clinical Protocol under the Program

4.11.1 Trial design and status

Within program BR27199433, the Gait Rehabilitation Robot is evaluated in an explanatory, parallel, two-arm randomised controlled trial at NCCR, Astana, registered with the Australian New Zealand Clinical Trials Registry as ACTRN12626001203347 [12]. The trial compares robot-assisted gait training with conventional (manual) gait rehabilitation in children and adolescents with CP aged 13–18 years. Children in the intervention arm receive ten sessions of 20 minutes of robot-assisted gait training. The primary outcome is the six-minute walk test (6MWT), measured at baseline and after the intervention. Allocation follows a computer-generated sequence. The design is summarised in Table 4.13.

Eligibility follows the program application: age 13–18 years; Gross Motor Function Classification System (GMFCS) levels I–III; cognitive ability sufficient to report pain; upper-limb manual muscle testing grade of 3+ or above; Modified Ashworth Scale score of 2 or below; no unconsolidated fractures or fixed contractures; and good general health. In the 2025 pilot studies, a height of 160–195 cm and a shoe size of at least 38 were applied as device-fit criteria.

Enrolment began on 10 September 2026, and 25 children have been enrolled, against a target of 23 in the program application. The robot's use with children required review by the Nazarbayev University Institutional Research Ethics Committee (NU-IREC), which granted conditional approval on 14 October 2026; the conditions have since been met. Between the start of enrolment and that approval, only pre-assessment (Section 4.11.2) was carried out, with children who were staying in Astana and registered with NCCR. Robot-assisted sessions began on 19 October 2026 and are continuing. In addition, seven children from Astana have been recruited for follow-up assessments. With 25 children, the current phase is explanatory and of feasibility scale, consistent with the program's reduced pilot sampling strategy; Chapter 3 sets out the larger sample that a confirmatory trial would require on the basis of the pilot data.

Table 4.13. Design of the program gait trial.

Element	Description
Registration	ACTRN12626001203347 [12]

Element	Description
Design	Explanatory parallel two-arm randomised controlled trial
Setting	National Center for Children's Rehabilitation (NCCR), Astana
Population	Children and adolescents with CP aged 13–18 years, GMFCS I–III
Intervention arm	Robot-assisted gait training with the Gait Rehabilitation Robot, 10 sessions of 20 min
Control arm	Conventional (manual) gait rehabilitation
Primary outcome	6MWT, baseline and post-intervention
Secondary outcomes	10-metre walk test (10MWT); Timed Up and Go (TUG); GMFM-88; Paediatric Berg Balance Scale; sEMG, IMU and insole gait parameters; Gait Recovery Index
Randomisation	Computer-generated allocation sequence
Sample size	Target 23 (application, 6MWT, 80% power); 25 enrolled; follow-up assessments in 7 children from Astana
Ethics	NU-IREC conditional approval of device use, 14 October 2026; conditions met
Timeline	Enrolment from 10 September 2026; pre-assessment only until 14 October 2026; robot sessions from 19 October 2026

Preceding pilot studies. Two pilot studies with the robot were completed in 2025 at NCCR. In the Gait Rehabilitation Robot pilot randomised trial, six children were allocated to robot-assisted training and six to a control group, using a computer-generated allocation sequence. In the Gait Rehabilitation Robot + VR pilot, five children received robot-assisted treadmill training with integrated head-mounted virtual-rehabilitation tasks (Chapter 9) and five received conventional manual therapy. Both pilots used the 6MWT as the principal outcome, and clinical assessment in 2025 was supported by a Noraxon Ultium portable laboratory (EMG and IMU) and Medilogic pressure insoles. The between-group differences and standard deviations from these pilots were used to compute the sample sizes reported in Chapter 3; their full results are not yet available (Section 4.11.4).

4.11.2 Pre-assessment at NCCR

Before a child is placed in the robot, the program's pre-assessment form is completed [11]. It records the patient identifier, age, sex, CP type (hemiplegia, diplegia or other), affected side and GMFCS level, and proceeds through five sections.

The first section collects the body measurements needed to set up the robot: body weight, bilateral leg length measured from greater trochanter to lateral malleolus, and height [11]. The second section obtains spatial gait parameters without the robot by the footprint method: chalk is applied to the heels, the child walks along a paper strip in a corridor of at least 6 m, and step length, stride length and step width are measured from at least three left and three right heel marks; foot progression angle is observed and classified as toe-in, normal (7–10°) or toe-out [11]. The form gives a typical step width for children of 8–12 cm, noting that a wider base suggests balance compensation [11]. The third section contains walking tests timed with a phone stopwatch: cadence by counting steps over 30 s; the 10MWT over the central 10 m of a 14 m walkway, three trials at comfortable pace and one at fast pace; the TUG; and, where a corridor of at least 20 m is available, the 6MWT [11]. The fourth section is an observational checklist of gait deviations (Section 4.2.1), and the fifth section summarises the key values for the left (affected) and right sides [11].

The form provides guide values for assessors: comfortable walking speed of approximately 1.0–1.3 m/s and cadence of approximately 100–115 steps per minute for ages 13–18, and TUG times below 10 s as normal, 10–20 s as mild difficulty and above 20 s as significant impairment [11]. These are the program's screening thresholds, intended to help assessors interpret a measurement at the bedside; they are not paediatric normative reference values, and they play no part in eligibility or in the analysis of outcomes.

Two features of the form connect it directly to the device and to the analysis pipeline. First, the spatial gait parameters measured overground before robot training are intended to be compared with the parameters estimated from robot data after the session [11]. Second, the form instructs the assessor to perform a short passive calibration on the robot before the first training session: the robot moves the child's legs while the child is fully relaxed, providing baseline load-cell values without which the joint strength component of the Gait Recovery Index cannot be computed [11]. That component, and the index as a whole, are described in Chapter 8.

4.11.3 Delivering robot-assisted sessions

Each robot-assisted session follows the workflow of Section 4.9.4 and lasts 20 minutes, within the rated operating cycle of the device (Section 4.3.3). The controller is used in its current form (Section 4.6.3), with joint selection, belt speed, assist gain and body-weight support set by the therapist through the operator interface.

4.11.4 Outcomes and results

Results of the program trial are pending. Robot-assisted sessions began on 19 October 2026, and participant flow, baseline characteristics, adherence (sessions delivered per child), adverse events and device deficiencies, and primary and secondary outcomes will be reported when the intervention phase and post-intervention assessments are complete. Chapter 10 brings together the program's gait evidence and shows how the trial data will be analysed with the Gait Recovery Index.

4.12 Limitations

Several limitations of the device and of its current documentation should be borne in mind when interpreting the clinical work reported later in the book.

The first concerns the population. The device documentation describes an intended population of adolescents aged 12–17 years and adults, with patient limits of 100 or 120 to 190 cm in height [9], and the controller manuscript derives an accommodated stature of approximately 1.39–1.94 m from the segment adjustments [23]. The program's participants are 13–18 years old, and the smaller members of this group may lie at or beyond the lower end of these ranges. Cuffs in all sizes are available at NCCR, but the device's suitability for each child must still be verified individually.

The second concerns the movement envelope. The device operates in the sagittal plane at the hip and knee, with no powered ankle and no stated provision for frontal-plane pelvic motion. Gait deviations of CP that involve the ankle (toe-walking, equinus) or the frontal and transverse planes (circumduction, scissoring, hip hiking) are not directly addressed by the actuation, although they may be influenced indirectly. The knee range of 0–50° and the maximum cadence of 60 steps per minute constrain the gait pattern to slow walking with limited swing-phase knee flexion.

The third concerns the control system. The controller in its current form has been characterised on the bench without human participants [23]. Its safety bounds are bounds on commanded torque and its per-excursion work bound is weaker than passivity; the torque cap has not been exercised from any setting

reachable at the interface; knee gravity is not compensated; the lag-driven assist law escalates against a resisting limb and its need signal cannot distinguish a blocked joint from a free one; and an experimental gate that addresses this changes the training dose on every stride and is not yet suitable for patients [23]. Because the therapist's gain and the adaptation factor act as a product, the "dose" of robotic assistance in the trial should be reported as delivered torque from the load cells rather than as the gain setting alone.

The fourth concerns measurement. Joint torque is measured by joint-reaction load cells whose readings include the machine's own torque, must be referenced to a passive calibration, and depend on calibrated moment arms that differed substantially between mechanically identical joints [23]. The encoder tolerances of ±1–2° are not negligible relative to some of the asymmetries the program aims to detect, and load-dependent mounting compliance at the hip reduces travel relative to command [23].

The fifth concerns documentation consistency. The sources disagree on the duty cycle (20 or 30 min on), the height range, the cuff ranges, the body-weight support range and the protective earth resistance criterion, and the warranty clause of the manual contains apparent typographical errors. The manual and the controller manuscript also describe the hardware at different levels of detail, and the joint load cells and their calibration are not yet included in the manual's calibration table. These discrepancies do not by themselves indicate a safety problem, but they should be reconciled in the controlled versions of the manual and data sheet.

Finally, the evidence base specific to the device is still being built. Neither the program trial nor the 2025 pilot studies have yet produced published outcome data, so the clinical value of the device for adolescents with CP remains to be established.

4.13 Summary

This chapter has described the Gait Rehabilitation Robot used in program BR27199433, a registered Class 2a medical device. The device is a four-actuator, sagittal-plane hip–knee exoskeleton driven by integrated geared brushless actuators, mounted on an overhead suspension frame or rolling frame above a compatible rehabilitation treadmill, and operated by a therapist through a touchscreen interface that enforces a connect–calibrate–start sequence. Its kinematic envelope (hip ±35°, knee 0–50°, up to 60°/s and 60 steps per minute) is designed for slow, controlled stepping with partial body-weight support. Futek load cells in the reaction path of each joint measure joint torque, which the program's software treats as the patient's joint torque contribution after reference to a passive calibration. The controller in its current form composes commanded torque from independently bounded terms, defines clinical modes as masks over those terms, forces damping, a range-of-motion wall and a speed brake into every torque mode, caps commanded torque at 20 N·m at the hip and 16 N·m at the knee with a slew limit of 27 N·m/s, and screens its own identified friction models for physical admissibility. Safety rests on these bounds together with a layered architecture of software stop, hardware emergency stop and a dry-contact stop to the treadmill, mechanical range limits, defined hazard zones, electrical and electromagnetic safety requirements under the IEC 60601 family, and a documented ISO 14971 residual risk analysis. In the program, the robot is evaluated in a registered two-arm randomised trial in adolescents with CP aged 13–18 years at NCCR, with ten 20-minute sessions of robot-assisted training and the 6MWT as primary outcome; 25 children have been enrolled, robot sessions began on 19 October 2026, and results are pending. Chapter 5 describes the body-weight support system with which the robot can be used, and Chapter 8 describes the analysis pipeline that converts the device's sensor data into the Gait Recovery Index.

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Chapter 5. Adaptive Body-Weight Support System

Abstract. This chapter describes the adaptive body-weight support (BWS) system designed by the author's team within program BR27199433 as a standalone device for treadmill-based gait rehabilitation of children with cerebral palsy (CP), and the method the program devised for selecting an individualised level of unloading for each child. It sets out the clinical and biomechanical rationale for treating the magnitude of unloading as a parameter to be tuned per child, then describes the pneumatic suspension hardware: a portal frame over the treadmill, a 63 mm bore, 400 mm stroke pneumatic cylinder with a 2:1 cable–pulley suspension giving about 800 mm of travel, an in-line load cell that participates in closed-loop control, cable displacement and pressure sensing, and an Arduino Mega controller implementing two-position control with hysteresis, valve interlocking and layered protective functions. The fixed-level regulation used in the pilot study is described, together with a gait-phase-synchronised mode that is under development. The core of the chapter is a within-participant, multidomain decision framework that ranks experimentally tested BWS conditions using plantar-pressure-derived measures of temporal symmetry, temporal variability, centre-of-pressure behaviour and bilateral loading symmetry, together with a set of robustness analyses and a proposed model-based extension that would estimate a continuous optimum. Session protocols and data-collection booklets are described in detail. Finally, the chapter reports an exploratory pilot study in seven children and adolescents with CP (manuscript in preparation), in which the best-performing tested condition ranged from 5% to 30% BWS across participants, and discusses what such data can and cannot establish.

Keywords: cerebral palsy; body-weight support; treadmill training; pneumatic actuation; plantar pressure; centre of pressure; multi-criteria decision making; individualised rehabilitation; gait-phase synchronisation

5.1 Introduction and Rationale

5.1.1 Walking practice in children with cerebral palsy

Cerebral palsy is an umbrella term for a heterogeneous group of permanent disorders of movement and posture that arise from nonprogressive disturbances of the developing fetal or infant brain [1]. For many children and adolescents with CP, preserving or improving walking is among the most important goals of rehabilitation. The impairments that limit walking are not uniform: in spastic CP, weakness, shortened muscle–tendon units, spasticity and impaired selective motor control all contribute, but their relative weight differs considerably between children [2]. Two children with the same diagnosis and functional classification may therefore walk poorly for quite different reasons.

International guidance emphasises goals chosen by the child and family, active practice of whole functional tasks, and interventions matched to age, ability, preferences and setting [3]. Walking practice is accordingly central to therapy, and on a treadmill it is often combined with partial body-weight support, in which a harness and overhead suspension carry a fraction of the child's weight so that many repetitions of stepping can be performed safely.

The evidence for mechanically assisted walking with BWS is modest. A Cochrane review found that it may improve walking speed slightly relative to no walking training but has not been shown to be consistently superior to an equivalent amount of overground practice [4]. For the designer of a BWS device, the implication is that unloading is not intrinsically therapeutic, so its magnitude should be neither fixed by convention nor maximised for comfort; it is a training parameter to be chosen deliberately.

5.1.2 Why the level of unloading should be individualised

Laboratory studies show that changing the level of support changes the mechanical and neuromuscular task of walking. In children with CP, progressively greater BWS reduced the activity of several antigravity muscles, including the gluteal muscles and vastus lateralis, while the complexity of muscle synergies changed little; that is, unloading made walking less demanding without obviously reorganising motor control [5]. In children with unilateral CP walking at 0%, 20% and 40% BWS, the immediate neural and biomechanical responses differed across conditions, with few changes in synergy measures but condition-specific changes in measures of gait deviation [6]. Taken together, these studies suggest that the response to support depends both on the child and on the aspect of gait under examination.

The importance of choosing training parameters carefully is also visible in research on robot-assisted gait training. In a randomised study in children with CP, different combinations of walking speed and BWS (faster with less support, slower with more support, and intermediate settings) produced gains in different functional domains, and the investigators recommended adjusting training intensity according to the goal being pursued [7]. Because speed and support were changed together in that study, it does not isolate the effect of BWS magnitude. Nevertheless, it reinforces the conclusion that a single support percentage applied to every child is unlikely to be the best choice for all.

A further complication motivates the approach of this chapter: a level of support that improves one feature of gait may worsen another, for example reducing stride-to-stride variability while increasing left–right loading asymmetry. A selection rule based on one variable would miss such trade-offs. This argues for evaluating several complementary gait characteristics across experimentally applied support levels within each child, treating selection as a multi-criteria decision. The level so identified is the best-performing condition among those tested, not a demonstrated physiological optimum.

5.1.3 Scope of the chapter and status of the evidence

The BWS system described here was designed by the author's team as a standalone device, separate from the Gait Rehabilitation Robot of Chapter 4 and the Robotic Perturbation Trainer of Chapter 6; the suspension harness was designed together with it. The program's use of the system has focused on how body-weight support affects gait parameters and on how to identify a suitable support level for each child; it was not designed or evaluated as a balance-training intervention.

The materials drawn upon in this chapter are at different stages of maturity, and the reader should keep these distinctions in mind. Table 5.1 summarises the status of each body of work.

Table 5.1. Status of the work reported in this chapter.

Component	Source	Status
BWS hardware, pneumatic and electrical design, control firmware	Design report [33]; pilot manuscript [8]	Implemented; used in pilot study
Plantar-pressure gait-event detection and multidomain selection framework	Pilot manuscript [8]	Implemented; applied to pilot data
Pilot study in seven children and adolescents with CP	Pilot manuscript [8]	Data collected and analysed; manuscript in preparation
Model-based continuous optimum (response surface, Bayesian optimisation, extensor-drive constraint)	Internal draft methods texts	Proposed methodology; not yet applied to collected data

Component	Source	Status
Baseline and unweighing-sweep session booklets (Cometa WaveX)	Internal data-collection booklets	Protocol documents for sessions after the pilot
Gait-phase-synchronised BWS mode	Author communication; design report [33]	Under development; no participant data reported

Sections 5.2–5.4 describe the hardware, instrumentation and control; Sections 5.5–5.7 the gait processing, selection method and protocols; and Sections 5.8–5.10 the pilot study, its discussion and its limitations.

5.2 System Hardware

5.2.1 Design concept

The device was conceived as a self-contained, actively controlled frame that straddles a standard treadmill and supports the child through a harness and a single vertical suspension line, with unloading generated pneumatically. Pneumatic actuation was chosen because compressed air provides compliance during changes in the unweighing force, which softens the interaction with the child as the trunk rises and falls within each stride and as the support level is changed, and because the supporting force can be set by regulating pressure rather than position.

5.2.2 Frame, suspension and harness

The system consists of a rigid portal frame with two vertical columns joined by an overhead beam, under which the treadmill is placed; the treadmill handrails remain available to the child. The frame is built from 100 × 100 × 4 mm steel profile tube standing on base plates of 12 mm sheet, bolted to the uprights [33]. The section was chosen with a margin for bending stiffness so that the uprights and beam deflect little under the supporting force; this preserves the portal geometry and the cable trajectory, and so avoids increased pulley friction and jerks during unloading. The wide base plates distribute the load on the floor. In the upper part of the frame, a 6 mm sheet bracket carries the pulley and the pneumatic cylinder and keeps their axes aligned under load [33]. The electronics and pneumatics enclosure is mounted on the upper beam, and the air preparation unit, manual pressure regulator and directional valve are mounted on one upright [33].

Vertical unloading force reaches the child through the suspension harness, attached to an 8 mm diameter load-bearing cable that runs over the pulley to a movable unit driven by the pneumatic cylinder (SC63×400: 63 mm piston diameter, 400 mm rod stroke) [8,33]. The cable is reeved in a 2:1 configuration so that the suspension travel is approximately twice the rod stroke, about 800 mm, against a design requirement of at least 600 mm; with ideal reeving the force at the suspension point is correspondingly halved [33]. This trade of force for travel suits children of modest body mass but widely varying stature.

The design report sizes the actuator as follows [33]. The piston area is $A = \pi \times (0.063\ \text{m})^2 / 4 \approx 31.17\ \text{cm}^2$. At an operating pressure of 7 bar (0.7 MPa), the theoretical rod force is $F = p \times A \approx 2182$ N (≈ 222.5 kgf). Allowing an efficiency of about 0.85 for seal friction, fitting and throttle losses and cable deformation gives approximately 1855 N (≈ 189 kgf) at the rod, and after the 2:1 reeving approximately 95 kgf at the suspension point, before further losses in the pulley block. Because the pressure sensor used for automatic control has a range of 0–0.6 MPa (Section 5.2.4), automatic operation takes place below the 7 bar of this calculation; at 6 bar the same calculation gives about 81 kgf at the suspension

point, which is still well above the largest unloading applied in the pilot (30% of body weight for the heaviest, 58 kg, participant, about 17 kg). The report notes that, should more force be needed, the cylinder diameter could be increased, a 1:1 ratio used over part of the range, or mechanical and pneumatic unloading combined [33].

The supporting force is measured by an S-type strain-gauge load cell (YZC-516C, nominal capacity of about 100 kg, sensitivity 2.0 mV/V, safe overload 150% of full scale) installed in the attachment zone of the load-bearing cable branch, so that it reads the actual supporting force in real time [33]. A cable-type linear displacement sensor (BRT38-L) measures the displacement of the suspension point or the height of the patient attachment point; its cable is routed downward and secured to the movable suspension element [33]. The treadmill model is not specified in the design documentation.

5.2.3 Pneumatic circuit

The pneumatic subsystem generates and regulates the supporting force by controlling the pressure in the working chamber of the cylinder [33]. Compressed air from an external compressor or main line enters an air preparation unit (Optimus AC4010-04) that filters the air, separates moisture and stabilises the supply, which protects the valves, throttles and cylinder and improves the repeatability of force settings. Downstream, a manual pressure regulator ("Profi", 1/4", 0–10 bar) sets the working pressure in manual mode, with an axial pressure gauge (Y-50T-6) for visual monitoring. A five-port directional valve (Maxnic 4H210-8) switches the supply and exhaust lines, admitting air to the cylinder to increase support or venting it to atmosphere to decrease support. For automatic operation, 24 V solenoid valves on separate supply and exhaust channels are driven by the controller: one channel raises pressure and support, the other vents [8,33].

An adjustable throttle fitting on the exhaust line sets the rate of pressure change and therefore the rate of change of supporting force, reducing jerks and oscillations of unloading during pressure increase and release while the child walks; pneumatic mufflers on the exhaust ports reduce noise and aerodynamic impulses near the treadmill [33]. The throttle embodies a trade-off: it smooths the force in fixed-level operation, but it also limits how quickly support can be changed, which matters for the gait-phase-synchronised mode (Section 5.4.3). The throttle settings and the resulting rise and fall times of the supporting force have not been reported.

5.2.4 Sensing and embedded control

The control subsystem has two layers [33]. An Arduino Mega 2560 microcontroller performs the real-time functions: it acquires the pressure, load-cell and displacement signals, executes the control logic and drives the supply and exhaust valves. A host computer connected through a serial interface provides configuration and monitoring, and data are also logged on the controller to an SD card. The electrical design separates a 5 V logic supply (controller, low-voltage measurement circuits and sensor amplifiers) from a 24 V power supply (pressure sensor and solenoid valves), with single-point grounding to limit interference on the analogue channels. The pressure sensor (XDB306, 12–36 V DC supply, 0–0.6 MPa) is read through a shunt resistor where a 4–20 mA output is used; the load cell is read through a strain-gauge amplifier and analogue-to-digital converter (for example an HX711 module); and the valve coils are switched through relay modules or MOSFET drivers with flyback diodes to suppress the voltage spikes produced when inductive loads are de-energised [33].

The firmware is organised in five modules [33]. *SensorManager* reads the sensors, filters the signals (exponential or moving-average filtering of pressure; zero-offset compensation, calibration and median or limit filtering of the load-cell force; conversion of displacement to millimetres and computation of

suspension velocity) and checks plausibility (out-of-range values, stuck values, open or short circuits, and absence of a pressure response while a valve is active). *ControlLoop* computes the valve commands in manual or automatic mode and applies protective limits. *SafetyManager* handles the emergency stop, maximum-pressure monitoring, timeouts and sensor failures and moves the system to a safe state. *DataLogger* writes time-stamped CSV records of raw and filtered pressure and force, displacement, valve states, mode, events and diagnostic counters to the SD card, buffering writes so that logging does not disturb the control loop. *UserInterface* accepts serial commands to set the target pressure or force, the hysteresis band, pressure limits, sampling frequency, operating mode and sensor calibration. Table 5.2 lists the principal components.

Table 5.2. Principal components of the body-weight support system [8,33].

Subsystem	Component	Model/type	Key parameters and function
Structure	Portal frame and base	Steel profile tube and sheet	100 × 100 × 4 mm profile; 12 mm base plates; 6 mm bracket for pulley and cylinder
Pneumatic	Air preparation unit	Optimus AC4010-04	Filtration, regulation and moisture separation of supply air
Pneumatic	Manual pressure regulator	"Profi" 1/4"	0–10 bar; sets supporting force in manual mode
Pneumatic	Pressure gauge	Y-50T-6 (axial), 1/4"	Visual monitoring of working pressure
Pneumatic	Directional valve (distributor)	Maxnic 4H210-8	Five-port valve switching supply and exhaust lines
Pneumatic	Supply and exhaust solenoid valves	24 V	Raise or vent cylinder pressure in automatic mode; interlocked
Pneumatic	Throttle fitting and muffler	Adjustable throttle; porous muffler	On exhaust line; limit rate of pressure change; reduce noise
Pneumatic	Pneumatic cylinder	SC63×400	63 mm bore, 400 mm stroke; ≈ 2182 N theoretical rod force at 7 bar
Mechanical	Cable–pulley suspension and harness	2:1 reeving, Ø8 mm cable	≈ 800 mm suspension travel; ≈ 95 kgf at suspension point at 7 bar ($\eta \approx 0.85$)
Sensing	Pressure sensor	XDB306, 1/4"	0–0.6 MPa; 12–36 V DC; working-line pressure for control and diagnostics
Sensing	In-line load cell with amplifier	YZC-516C (S-type) + 24-bit ADC	≈ 100 kg capacity; 2.0 mV/V; supporting force in the cable; part of the control loop

Subsystem	Component	Model/type	Key parameters and function
Sensing	Linear displacement sensor	BRT38-L (cable type)	Displacement of the suspension point
Control	Embedded controller	Arduino Mega 2560	Sensor acquisition, control logic, protective functions, SD-card logging
Control	Host computer	Serial interface	Setpoint and parameter entry, monitoring
Safety	Hardware emergency stop	E-STOP input	Disables supply control and moves the system to a safe state

5.2.5 Prescribing the level of support

Support is prescribed as a percentage of the child's measured body weight. For a child of body mass m_body, the target unloading corresponds to an equivalent supported mass m_support such that

$$m_{support} = m_{body} \times \frac{\mathrm{BWS}\,(\%)}{100}$$

The child is weighed before each assessment, the setpoint corresponding to the prescribed percentage is established before data acquisition begins, and the controller then maintains that support automatically while the child walks [8]. Because the in-line load cell is part of the control loop, the regulated quantity is the supporting force measured in the cable, corresponding to the target supported mass, with pressure acting as the manipulated variable and as a constraint and diagnostic channel (Section 5.4.1) [33]. The force in the cable is not necessarily the support the child experiences: harness fit, trunk motion and the compliance of the air column all intervene, so the support actually experienced can still differ from the commanded value, as Section 5.7.3 explains.

5.3 Gait Instrumentation

The selection of an individualised support level requires a quantitative description of how the child walks under each condition. The program has used wearable sensors from Cometa (Milan, Italy) for this purpose. Two configurations appear in the source documents, and they should be distinguished clearly.

5.3.1 Instrumentation used in the pilot study

In the pilot study reported in Section 5.8, plantar pressure was recorded with bilateral InsoleX pressure-sensing insoles (Cometa Systems), each containing 64 pressure sensors, giving 128 pressure channels for the two feet, sampled at 100 Hz. Insoles of the appropriate size were placed inside the child's footwear before testing, and recording was continuous throughout each support condition. These signals were used for detecting gait events, computing temporal parameters, quantifying bilateral loading and computing the centre of pressure (CoP) [8].

Surface electromyography (sEMG) was recorded with wireless MiniX sensors (Cometa) at 2000 Hz with 16-bit resolution and a specified bandwidth of 10–500 Hz. Ten channels were recorded: rectus femoris, semitendinosus, tibialis anterior, medial gastrocnemius and soleus on each side. The sEMG was time-aligned with the support conditions and used to describe how muscle activation changed with unloading [8]. No inertial measurement unit (IMU) data are reported from the pilot study.

5.3.2 Integrated WaveX montage used in subsequent sessions

Sessions conducted after the pilot use the integrated Cometa WaveX configuration specified in the program's data-collection booklets, consisting of sixteen combined EMG-and-IMU probes and two instrumented insoles of sixteen cells each, in place of the 64-sensor InsoleX insoles and ten EMG channels of the pilot. A feature of this configuration emphasised in the booklets is that each probe carries both an EMG electrode and a built-in IMU on the muscle belly, so the IMU measures the motion of whichever segment the probe sits on: the thigh for rectus femoris and hamstring probes, and the shank for tibialis anterior, gastrocnemius and soleus probes. No trunk or pelvis sensor is included. Because all streams record through the same acquisition system, EMG, IMU and insole signals are inherently synchronised; only treadmill belt speed must be logged manually, because the acquisition software has no knowledge of it. Table 5.3 reproduces the channel allocation specified in the booklet.

Table 5.3. Sensor montage specified in the WaveX baseline booklet.

Channel	Muscle	Side	Segment carrying the IMU
1, 2	Rectus femoris	L, R	Thigh
3, 4	Medial hamstrings	L, R	Thigh
5, 6	Tibialis anterior	L, R	Shank
7, 8	Medial gastrocnemius	L, R	Shank
9, 10	Soleus	L, R	Shank
11–16	Optional (e.g., gluteus medius or adductors) or spare	—	Thigh / pelvic region
Insole L, R	16-cell pressure insole	L, R	—

The booklets also specify safeguards for data quality: electrode sites are marked with ink so that probes can be replaced at the same place in later sessions (displacement would change gain and invalidate normalisation); a per-child neutral-pose IMU calibration is captured; the insole cell coordinate map is obtained for each insole size, as CoP computation requires it; and raw EMG, IMU and insole traces are archived, not only software summaries, so that every derived quantity can be recomputed. An earlier, non-WaveX version of the baseline booklet envisaged IMUs on the feet, shanks, thighs, pelvis and trunk, an optional trunk-sway assessment, and synchronisation of all streams, including BWS force, on a common trigger; the WaveX version supersedes it. Because the pilot and later configurations differ in insole resolution and EMG montage, CoP and loading measures obtained with the two configurations should not be pooled without a check of their agreement.

5.4 Control Strategy

5.4.1 Fixed-level regulation

In the configuration used for the pilot study, the system maintained a constant prescribed level of support while the child walked, with unloading regulated by controlling air supply and exhaust through separate solenoid valves using feedback from the system sensors [8]. The firmware provides four operating modes [33]. In *manual* mode, controller-driven valve control is disabled and the operator sets the

supporting force with the pressure regulator, while the controller continues to monitor pressure, force and displacement and signals when limits are exceeded. In *automatic pressure* mode (Auto-P), the controller maintains a target pressure; this mode is used mainly for pneumatic debugging and initial tuning. In *automatic force* mode (Auto-F), it maintains a target supporting force measured by the load cell, with pressure as the manipulated variable and as a constraint and diagnostic channel. In the *combined* mode (Auto-PF), recommended for walking, the primary loop maintains the target force while pressure is limited from above and used for rapid detection of leaks or jamming. The load cell is therefore part of the closed control loop in clinical use.

Because each pneumatic path is switched by an on–off solenoid valve rather than a proportional valve, the controller is a two-position (on–off) controller with hysteresis about the setpoint, running at a fixed sampling period [8,33]. When the measured quantity falls below the lower edge of a band around the setpoint, the supply valve opens; when it rises above the upper edge, the exhaust valve opens; within the band neither valve is energised. Expressed schematically, with y the measured, filtered controlled variable (supporting force F in the force modes, pressure p in Auto-P), y* the setpoint and h the half-width of the hysteresis band, the valve commands are

Four refinements adapt this simple law to the inertia of the pneumatic system and to the varying load of a walking child [33]. A minimum on-pulse duration ensures that each valve activation has a noticeable effect, and a minimum off-time after deactivation allows pressure to settle before the next transition; together these prevent chattering at the band edges. A mutual interlock ensures that the supply and exhaust valves are never open simultaneously, with a short interlock delay (of the order of 20–50 ms) at each transition to prevent direct venting and coil overheating. An oscillation guard detects frequent supply–exhaust alternation and responds by widening the band or reducing the regulation frequency. Finally, changes of setpoint are applied as ramps rather than steps, so that the support never changes abruptly. The band half-width and timing constants are configurable through the serial interface; the values used in the pilot are not reported. With the exhaust throttle, these measures yield deliberately gentle regulation that holds support within a deadband throughout each trial.

On–off control with hysteresis is simple and robust, but the delivered force is never exactly constant: it varies within the deadband, and the vertical motion of the child's trunk compresses and expands the air column within each stride. The magnitude of these within-stride fluctuations was not measured in the pilot study, and the pilot manuscript lists direct verification of achieved unloading as a requirement for future work [8]. Because the controller logs the load-cell force at every control step [33], such verification is possible in principle from the device's own records, complemented by the insole-derived effective unloading of Section 5.7.3.

5.4.2 Protective functions

Protective functions operate independently of the main control loop [33]. A hardware emergency-stop input immediately disables supply control and moves the system to a safe state (at minimum closing the supply and, where an emergency vent is available, opening the exhaust). When pressure reaches a set maximum, supply is prohibited, forced venting is applied if a dump valve is fitted, and an over-pressure fault is logged. Sensor failures (open or short circuit, readings out of range, or no pressure change during active supply or exhaust within a timeout) move the system into a fault mode that is latched until the operator resets it and is indicated on the serial interface, by an indicator light and in the log. The design report sets a fault reaction time below 100 ms, achieved through a control-loop frequency of the order of 50–100 Hz and priority for the safety module [33].

The report also makes recommendations for clinical deployment that go beyond the implemented design, and they are presented here as design recommendations rather than as features of the current system [33]: an independent hardware emergency venting circuit that opens on over-pressure or loss of power or controller; a hardware watchdog timer; dual-channel validation in which pressure and force cross-check each other; monitoring of valve coil and driver temperature; a limit on the rate of change of unloading as a safety criterion; persistent storage of settings with firmware-version logging; and static and dynamic acceptance tests (holding a specified unloading, and walking at speeds of 0.1–2.0 m/s) with evaluation of response time and holding stability. It further makes mandatory the installation and testing of a hardware emergency stop, calibration of the load-cell zero and scale and of the pressure-sensor scaling before operation, periodic cross-checks of the pressure gauge against the pressure sensor, and flyback protection on all valve coils.

5.4.3 Limitations of constant unloading and the gait-phase-synchronised mode

Constant support is conventional but not obviously ideal. The program's internal methods drafts note that unloading attenuates load-related afferent input, and that beyond some level distal extensor activity driving push-off may collapse, removing much of the training value of stepping; they also note that the most beneficial support may be a profile over the gait cycle rather than a single number. The working hypothesis behind phase-dependent support is that weight transfer between limbs during double support is a demanding phase in which brief assistance may help, whereas single-limb support is when the child must bear and control body weight on one leg, the capacity that training aims to develop. This hypothesis has not yet been tested.

A gait-phase-synchronised mode is therefore under development. In this mode a personalised baseline of unloading, intended to be the level identified by the selection method of Section 5.6, is maintained throughout the stride; a brief additional pulse of support is delivered during weight transfer (double support); and support returns to baseline during single-limb support. The design report anticipates this direction, recommending smooth unloading profiles synchronised with gait phase and treadmill speed as a software enhancement [33]. The intended support profile can be written schematically as

$$u(t) = u_b + \Delta u\, g(t), \qquad g(t) = \begin{cases} 1, & t \in \text{double support} \\ 0, & \text{otherwise} \end{cases}$$

where u_b is the personalised baseline unloading, expressed as a percentage of body weight, and Δu is the amplitude of the additional pulse. In practice, the profile delivered by a throttled pneumatic actuator will have finite rise and fall times rather than the rectangular shape implied by this expression, and the double-support window of a child walking slowly lasts only a fraction of a second. Whether the pneumatic hardware can deliver an adequate pulse within that window is the first question the mode must answer. Real-time detection of weight transfer, the choice of pulse amplitude and duration, the valve changes needed to achieve the required bandwidth, and limits on maximum total support are design questions still being settled, and no participant data from this mode have been reported. Both the unweighing-sweep booklet and the internal methods draft anticipate comparing phase-modulated and constant support at matched mean unloading; matching is essential, since otherwise any difference could reflect the total amount of unloading rather than its timing.

5.5 Gait Event Detection and Parameter Extraction

The selection method of Section 5.6 depends on gait parameters derived from the plantar-pressure insoles. This section describes the processing pipeline used in the pilot study in enough detail for the

reader to understand the provenance of the metrics; the full set of metric definitions is given in Section 5.6.2.

5.5.1 Preprocessing

Raw plantar-pressure recordings were first inspected visually to identify segments unsuitable for gait analysis, such as moments when the child stopped walking, equipment was being adjusted, or the acquisition produced transient artefacts. Such segments were cropped or removed, and isolated nonphysiological pressure values were corrected; recordings without disturbances were left unchanged. Each of the 128 sensor channels was then low-pass filtered with a fourth-order Butterworth filter with a 20 Hz cutoff, applied forward and backward to avoid phase distortion. Non-finite values were set to zero and negative values were clipped to zero. For each foot, two summary signals were formed: the summed pressure over all 64 sensors and the number of active sensors, where a sensor was counted as active if its pressure was at least 3.125 kPa. All processing was performed separately for each support condition and for each limb [8].

5.5.2 Adaptive detection of foot contact

Pressure-sensing insoles have been used to detect foot-contact events by threshold crossings of pressure signals and by combining information from several sensors [9, 10, 11]. A single fixed threshold is poorly suited to the present application, however, because the magnitude of plantar pressure changes with the child's body mass, the affected side, walking speed and, by design, the level of body-weight support. The pipeline therefore uses thresholds that adapt to each foot and each trial. Let P_{10} and P_{90} denote the 10th and 90th percentiles of the summed-pressure signal for that foot and trial. The dynamic range and the contact-on and contact-off thresholds are

$$\Delta P = P_{90} - P_{10}, \qquad P_{ON} = P_{10} + 0.25\,\Delta P, \qquad P_{OFF} = P_{10} + 0.12\,\Delta P$$

The fractions were set empirically. The higher on-threshold prevents small fluctuations during swing from registering as contact; the lower off-threshold lets contact persist as loading declines in late stance; and the pair introduces hysteresis, preventing rapid toggling near a single level. Contact onset required the summed pressure to reach the on-threshold with at least three active sensors; contact ended when the summed pressure fell to the off-threshold or the number of active sensors dropped to two or fewer. Any candidate change of state had to persist for at least 0.05 s before it was accepted [8].

A transition from the unloaded to the loaded state defines initial contact (IC), and the reverse transition defines toe-off (TO). Each IC was paired with the first following TO that occurred before the next IC to form a complete stance interval; partial contacts at the start or end of a recording were discarded. Every trial was checked visually using diagnostic plots that overlay the summed pressure, the adaptive thresholds, the detected contacts and events, and the active-sensor count for both feet.

5.5.3 Temporal parameters

A gait cycle for each limb runs from one IC to the next ipsilateral IC, with a valid TO between them. For every complete cycle the pipeline computed stride, stance and swing times, and stance and swing as percentages of the cycle. Step time was measured from the most recent contralateral IC to the next ipsilateral IC; thus left step time runs from right IC to left IC. Plausibility limits were intentionally broad to retain slow gait: stride times of 0.40–10.0 s, stance times of 0.15–8.0 s, swing times of 0.10–8.0 s and step times of 0.10–6.0 s were accepted. These limits served only to exclude implausible event combinations; they are not definitions of normal gait [8].

Single- and double-support durations were obtained by overlapping the left and right stance intervals: left single support is time when only the left foot is in contact, right single support when only the right foot is in contact, and double support when both are in contact. Each was expressed in seconds and as a percentage of the common valid analysis interval. The trial-level output therefore comprised stride, step, stance and swing times, stance and swing percentages, single- and double-support durations and percentages, cadence, bilateral symmetry indices, and the variability of stride and stance times, each averaged over the valid cycles in the trial.

5.5.4 Centre of pressure

The CoP was computed for each foot during each validated stance interval, using the sensor coordinates corresponding to the child's insole size. At each sample, the mediolateral (ML) and anteroposterior (AP) coordinates are the pressure-weighted means of the sensor positions,

$$\mathrm{CoP}_{ML}(t) = \frac{\sum_i P_i\,(t)\,x_i}{\sum_i P_i\,(t)}, \qquad \mathrm{CoP}_{AP}(t) = \frac{\sum_i P_i\,(t)\,y_i}{\sum_i P_i\,(t)}$$

where $P_i(t)$ is the pressure at sensor i and x_i, y_i are its ML and AP coordinates. The CoP was computed only at samples with positive total pressure. From each stance-phase trajectory the pipeline derived AP and ML excursion, path length, mean CoP velocity and path efficiency; these were summarised by foot and support condition. Bilateral CoP symmetry was expressed through symmetry indices of the left and right measures, and stance-to-stance repeatability through the coefficients of variation of AP and ML excursion [8].

5.6 Individualised Selection of Body-Weight Support

5.6.1 Problem formulation

The selection problem is posed within each child. A set of support levels B is applied experimentally (in the pilot study, B = {0, 5, 10, 15, 20, 25, 30} percent of body weight), a set of gait metrics is computed at each level, and the task is to rank the levels according to how favourable the child's gait is under each. The method compares conditions within a child; it is not designed to compare gait quality between children, and the scores it produces have no meaning across participants. The individualised level is defined operationally as the tested condition that yields the most favourable multidomain gait response under a prespecified scoring rule [8]. This is a discrete multi-criteria decision problem, and the methods of composite-indicator construction and multiple-attribute decision making provide its natural vocabulary [12, 13, 14].

5.6.2 Gait domains and metrics

Four biomechanical domains were defined a priori: temporal symmetry, temporal variability, CoP characteristics and bilateral plantar-loading symmetry. Metrics were chosen to represent complementary aspects of gait that could plausibly change with support, could be derived consistently from the insole recordings, and had a direction of favourable change that could be specified in advance [6, 15, 16]. In every case the favourable direction is lower: less asymmetry or less variability. Parameters for which no universally favourable direction could be assumed, such as cadence or double-support time, were deliberately excluded from the score. Table 5.4 lists the metrics.

Table 5.4. Metrics included in the multidomain selection framework and their aggregation.

Domain	Metrics	Aggregation within domain
Temporal symmetry	Step-time SI; stance-time SI; single-support SI	Equal mean of normalised metric scores
Temporal variability	Stride-time CV (left, right); stance-time CV (left, right)	Equal mean of normalised metric scores
CoP	Symmetry: SI of AP excursion, ML excursion, path length, mean velocity, path efficiency. Repeatability: CV of AP and ML excursion (left, right)	Equal mean within each subdomain; then 50% symmetry + 50% repeatability
Loading symmetry	Bilateral loading SI	Single normalised metric score

SI, symmetry index; CV, coefficient of variation; AP, anteroposterior; ML, mediolateral.

The symmetry index used throughout is the absolute left–right difference relative to the bilateral mean. For a generic bilateral quantity with left and right values Q_L and Q_R (step time, stance time, single-support percentage, CoP measures or plantar load),

$$\mathrm{SI}_Q = \frac{|Q_L - Q_R|}{(Q_L + Q_R)/2} \times 100\%$$

and the coefficient of variation of a cyclic quantity T (stride time, stance time, AP or ML excursion) on one side is

$$\mathrm{CV}_T = \frac{\mathrm{SD}(T)}{\overline{T}} \times 100\%$$

The CoP measures entering the symmetry indices are defined for each stance phase as

$$E_{AP} = \max_t \mathrm{CoP}_{AP}(t) - \min_t \mathrm{CoP}_{AP}(t), \qquad E_{ML} = \max_t \mathrm{CoP}_{ML}(t) - \min_t \mathrm{CoP}_{ML}(t)$$

$$L_{CoP} = \sum_t \sqrt{\Delta\mathrm{CoP}_{ML}(t)^2 + \Delta\mathrm{CoP}_{AP}(t)^2}\,, \qquad \bar{v}_{CoP} = \frac{L_{CoP}}{T_{stance}}$$

The pilot manuscript gives the symmetry index of CoP path efficiency but not a separate formula for path efficiency itself; the term conventionally denotes the ratio of the straight-line displacement of the CoP between initial contact and toe-off to its path length L_CoP.

5.6.3 Within-participant normalisation

Because the metrics have different units and ranges, each was converted to a dimensionless score between 0 and 100 across the conditions tested for that child. Since lower raw values are better for every metric, the score of metric i at condition j is

$$S_{i,j} = 100 \times \frac{x_{i,\max} - x_{i,j}}{x_{i,\max} - x_{i,\min}}$$

where x_i,min and x_i,max are the smallest and largest values of the metric observed across that child's tested conditions. The best observed value thus scores 100 and the worst scores 0 [8].

Min–max scaling has a well-known weakness: if a metric barely changes across conditions, scaling stretches trivial differences, possibly no larger than measurement noise, across the full 0–100 range, and that metric then exerts as much influence as one that changed substantially. The framework guards against this with a minimum-meaningful-range rule. A metric is deemed insufficiently variable for a given child if its observed range is smaller than the larger of 1.0 percentage point and 5% of its median absolute value across that child's conditions; such a metric receives a neutral score of 50 at every condition and so does not influence the ranking.

5.6.4 Domain aggregation and the decision rule

Metric scores are averaged within domains to produce a temporal-symmetry score S_TS, a temporal-variability score S_TV, a CoP score S_CoP (the equal average of the CoP-symmetry and CoP-repeatability subscores) and a loading-symmetry score S_Load. Aggregating within domains first is a deliberate design choice: without it, a domain represented by many metrics, such as CoP with its seven symmetry and repeatability measures, would implicitly dominate a domain represented by one. The composite score gives the four domains equal weight,

$$S_{overall}(b) = 0.25\,S_{TS}(b) + 0.25\,S_{TV}(b) + 0.25\,S_{CoP}(b) + 0.25\,S_{Load}(b)$$

and the best tested condition is

$$b^{*} = \arg\max_{b \in \{0,5,10,15,20,25,30\}} S_{overall}(b)$$

A condition is eligible only if all four domain scores are available, so that missing data cannot silently alter the effective weighting [8].

Because small numerical differences are not evidence of a real preference, the framework also identifies comparable candidate conditions, namely all conditions scoring within 5 points of the maximum; where there are several, the clinician may choose among them on other grounds, such as tolerance or the child's goals.

The selected level is the tested condition that best balances symmetry, repeatability, CoP behaviour and loading under an equally weighted, prespecified objective. It is neither a demonstrated physiological optimum, nor the optimum of a continuous range, nor evidence that training at that level yields better outcomes; those are empirical questions the framework allows one to ask but does not answer.

5.6.5 Robustness of the selection

Because the framework embodies several choices that could reasonably have been made otherwise, the selection for each child was subjected to four sensitivity analyses [17, 12, 13]. First, the domain weights were varied to test whether the result depended on the equal-weight assumption. Second, alternative normalisation procedures were applied to test dependence on min–max scaling. Third, a leave-one-metric-out (LOMO) analysis removed each metric in turn and recomputed the full procedure, revealing whether any single metric was decisive. Fourth, bootstrap resampling of the underlying observations was used to estimate how often the primary selection would be reproduced under sampling variability; for each child, the proportion of bootstrap samples reproducing the primary selection and the modal bootstrap selection were recorded. In each case stability was summarised as the proportion of scenarios or iterations in which the primary selection was unchanged [8]. The pilot manuscript does not list the

alternative weight sets, the alternative normalisation methods, the bootstrap resampling unit or the number of bootstrap iterations, and these specifications should be stated in any replication. The two-valued alternative-normalisation stabilities reported in Section 5.8.6 (100% or 50%) indicate that two normalisation specifications were compared.

As an additional check on the decision rule itself, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [14] was applied retrospectively to the four domain scores, with the same equal weights and all domains treated as benefit criteria. TOPSIS ranks alternatives by their relative closeness to an ideal solution and distance from an anti-ideal solution, rather than by a weighted sum, so agreement between the two methods indicates that a selection is not an artefact of the aggregation rule. Pareto optimality of the primary selection was also examined; a condition is Pareto-optimal if no other condition is at least as good in all four domains and strictly better in at least one.

5.6.6 Proposed extension: estimating a continuous optimum

Any grid-based search can select only a tested level, while the child's most favourable support may lie between levels, and refining the grid adds walking time and therefore fatigue that would bias later conditions. The program's internal methods drafts therefore propose treating the relation between support and gait quality as an unknown, noisy, participant-specific function to be estimated, reading the optimum from the estimate. This extension is a proposed methodology: it has not yet been applied to the pilot data or to any other collected data.

In the proposed formulation the independent variable is the effective unloading u measured from the insoles (the fractional reduction in total plantar force relative to unsupported walking), since harness losses and trunk motion make delivered support differ from the commanded value; u is bounded to [0, u_max]. The objective combines loading, spatiotemporal and neuromuscular information into a single scalar,

$$J(u) = w_1 S(u) - w_2 D(u) - w_3 C(u), \qquad w_1, w_2, w_3 \geq 0, \quad w_1 + w_2 + w_3 = 1$$

with each component rescaled to [0, 1] within participant. Loading symmetry is computed from the stance impulses I_L and I_R (the force–time integrals over stance) of the two feet,

$$S(u) = 1 - \frac{|I_L - I_R|}{I_L + I_R}$$

so that S = 1 denotes perfectly even loading. Spatiotemporal deviation is a root-mean-square z-score distance of K spatiotemporal parameters p_k from age-matched reference means μ_k and standard deviations σ_k of typically developing children, in the spirit of summary gait-deviation indices [18, 19],

$$D(u) = \sqrt{\frac{1}{K}\sum_{k=1}^{K}\left(\frac{p_k(u) - \mu_k}{\sigma_k}\right)^2}$$

Co-contraction is quantified with the index of Falconer and Winter [20] for the ankle (tibialis anterior–gastrocnemius) and knee (quadriceps–hamstrings) antagonist pairs, using the normalised linear envelopes e_A and e_B of the two muscles,

$$C_{pair} = \frac{2\int \min\big(e_A(t), e_B(t)\big)dt}{\int \big(e_A(t) + e_B(t)\big)dt}$$

averaged over both pairs and both limbs. The weights w_1 to w_3 have not yet been fixed; it remains open whether they will be set a priori or elicited from clinicians, with a sensitivity analysis in either case. The choice of a typically developing reference dataset suited to treadmill walking also remains open; because children walk differently on a treadmill than overground, overground norms cannot be used without correction.

A physiological constraint prevents the optimiser from recommending support so high that push-off is lost. The planned method defines for each plantarflexor m (soleus and gastrocnemius, both sides) an extensor-drive fraction: the integral of the normalised EMG envelope over the push-off window, from heel-off t_ho to toe-off t_to (detected from the insole CoP and force), divided by the same quantity in a same-day unsupported walking trial,

$$f_m(u) = \frac{A_m(u)}{A_m(0)}, \qquad A_m(u) = \int_{t_{ho}}^{t_{to}} e_m\,(t)\,dt$$

The individualised optimum is then the constrained maximiser

$$u^* = \arg\max_{u \in [0,\, u_{\max}]} J(u) \quad \text{subject to} \quad f_m(u) \geq \alpha \quad \forall m$$

with the floor α proposed to lie in the interval 0.7–0.8, its final value to be fixed with a sensitivity analysis.

Two estimators of u* are proposed. In a response-surface approach, J(u) and its components are fitted for each child as smooth functions of effective unloading, using either a second-order polynomial or a penalised spline within a generalised additive model [21], consistent with the expectation that gait quality will first improve and then deteriorate as support increases; the optimum is the constrained stationary point, with uncertainty obtained by bootstrap or the delta method. In an adaptive approach, J is given a Gaussian-process prior [22],

$$J(\cdot) \sim \mathcal{GP}\big(m(\cdot), k(\cdot,\cdot)\big), \qquad y_i = J(u_i) + \varepsilon_i, \quad \varepsilon_i \sim \mathcal{N}(0, \sigma^2)$$

and, after each walking trial, the next level of support is chosen by maximising the expected improvement over the best value J^+ observed so far [23],

$$\mathrm{EI}(u) = \mathbb{E}[\max(0, J(u) - J^+)], \qquad u_{n+1} = \arg\max_u \mathrm{EI}(u)$$

with the extensor-drive constraint enforced through a feasibility-weighted acquisition function. This mirrors human-in-the-loop optimisation of wearable-robot assistance [24]. A coarse initial sweep would seed the process, and the search would stop at a fixed trial budget or when expected improvement fell below a tolerance. Because each child contributes few trials, the method proposes partial pooling through a hierarchical model or multi-task Gaussian process with GMFCS level and age as covariates [25]. The same machinery could optimise a support profile u(φ) over the normalised gait cycle, parameterised by a few control points, linking the method to the phase-synchronised mode of Section 5.4.3. The planned statistical analysis would test for an interior optimum with mixed-effects models including a quadratic term, assess commanded versus insole-measured unloading by Bland–Altman analysis, and relate co-contraction and extensor drive to loading symmetry. This formulation differs from the method applied in the pilot in its objective, its use of EMG and normative data, its use of effective rather than commanded support, and its continuous rather than discrete estimate.

5.7 Session Protocols

5.7.1 Protocol used in the pilot study

In the pilot study, each child's treadmill speed was set at the start of the support assessment to the child's comfortable walking speed and then held constant across all support conditions and throughout subsequent training. Holding speed constant is essential, because walking speed itself influences asymmetry and variability in children with CP [26]; if speed changed with support, its effects could not be separated from those of unloading. Children were asked to walk without holding the handrails whenever they could do so safely; handrail use was permitted only where safety required it.

The seven conditions (0% to 30% in 5-percentage-point steps) were applied consecutively in ascending order without scheduled rest, each for approximately 1–2 minutes. The belt kept running during transitions; recording was paused while the setpoint changed and resumed once unloading had stabilised, so each analysed recording reflected steady walking at one level [8].

5.7.2 Baseline (0% BWS) pre-assessment booklet

The program subsequently formalised data collection in two printed booklets for assessors using the WaveX system. The first governs a baseline pre-assessment at 0% BWS, with the harness donned and the lifting force set to zero; its values are the reference for the whole study. A comfortable self-selected belt speed is determined and logged by hand for reuse in all later sessions; after the belt reaches speed, the first 10–20 strides are discarded and at least 30–40 clean strides recorded.

The booklet records clinical details (including CP subtype, GMFCS level, affected side, spasticity, contractures, botulinum toxin within three months or surgery within six months, orthoses, consent and assent) and a setup checklist (harness at zero force, SENIAM probe placement, signal checks, insole zeroing, IMU calibration, EMG reference, raw-data export). EMG is normalised to this 0% BWS walk rather than to maximal voluntary contraction, a pragmatic choice in children. Data sheets capture spatial, temporal, plantar-loading, EMG-reference (including push-off integrals), co-contraction and dynamic-stability parameters by side, and a tolerance and adverse-event section. Every entry is tagged by provenance (read live, output by the WaveX analysis module, or computed by the team from exported traces), making explicit which values depend on proprietary algorithms and which on the program's own code.

5.7.3 Unweighing-sweep session booklet

The second booklet governs the session in which the support level is varied. It differs from the pilot protocol in several deliberate respects, summarised in Table 5.5. The session begins with a fresh 0% BWS walk on the same day. The booklet explains why: electrodes have been re-applied since the baseline session, so their gain may have changed, and the same-day unsupported walk, not the earlier baseline, must serve as the denominator for the extensor-drive fraction $f(u) = A(u)/A(0)$. The support levels of 10%, 20% and 30% of body weight are then presented in a randomised or counterbalanced (Latin-square) order, which is recorded for each child. At each level the child walks for 1–2 minutes of familiarisation, the first 10–20 strides are discarded, at least 30–40 clean strides are recorded, and the child rests before the next level. Belt speed is carried over unchanged from the baseline session.

Assessors are instructed to compare it with the commanded support, and the booklet notes that any gap between the two is itself a methodological finding. It also operationalises the extensor-drive floor: soleus and gastrocnemius $f(u)$ should remain at or above α (approximately 0.7–0.8), the level at which distal drive falls below the floor marks the upper bound on support, and the intended optimum is the least

support that evens out loading while the floor is respected. Stop rules are to be predefined, and a child who cannot tolerate 30% is not forced; the highest tolerated level is recorded as a finding.

Data sheets mirror the baseline booklet by level, adding commanded force, commanded and effective unweighing, peak-load symmetries, stance impulses and extensor-drive fractions. A final sheet records the per-child optimum: highest tolerated level, the level maximising loading symmetry with the floor met, the level closest to typically developing spatiotemporal norms, whether these coincide, and the reconciled training level for the next session, in which phase-modulated and constant support are to be compared at matched mean support.

Table 5.5. Comparison of the pilot-study protocol with the protocol specified in the unweighing-sweep booklet.

Feature	Pilot study [8]	Unweighing-sweep booklet
Support levels	0, 5, 10, 15, 20, 25, 30% BW	0% (same-day re-reference), then 10, 20, 30% BW
Order	Fixed ascending	0% first; remaining levels randomised or counterbalanced
Duration per level	Approximately 1–2 min	1–2 min familiarisation, discard 10–20 strides, record ≥30–40 clean strides
Rest between levels	None scheduled	Rest before each new level
Belt speed	Comfortable speed, constant across conditions and training	Carried over from baseline, constant across levels
Instrumentation	64-sensor InsoleX insoles; 10 MiniX EMG channels	WaveX: 16 EMG-and-IMU probes; 2 × 16-cell insoles
Support quantity analysed	Commanded (% of measured body weight)	Commanded and effective (from insoles)
EMG role	Descriptive	Extensor-drive constraint; co-contraction
Selection criterion	Multidomain composite of plantar-pressure metrics	Loading symmetry with extensor floor; spatiotemporal proximity to norms; reconciled
Planned cohort size	Seven enrolled	Roster for eight (P01–P08)

The booklets therefore encode responses to several of the limitations identified in the pilot study (Section 5.10), in particular the fixed order of conditions, the absence of rest, and the lack of verification of delivered support. No data collected with these booklets are reported here. The baseline booklet also lists GMFCS levels II and III as the expected range, whereas the pilot study enrolled children at levels I and II.

5.8 Pilot Study in Children with Cerebral Palsy

The results in this section are taken from the pilot study manuscript, which is in preparation [8]; they are pilot data that have not undergone peer review and are presented here in fresh form for a book readership. The study was funded by program BR27199433.

5.8.1 Design and setting

The pilot was a prospective, single-arm exploratory study in which several support conditions were evaluated within each participant, followed by treadmill training at an individually selected level. Participants were recruited as a convenience sample from the National Center for Children's Rehabilitation (NCCR) in Astana, where they were attending their scheduled annual rehabilitation program of approximately one month of multidisciplinary therapy. The sample size reflected the method-development aims of the study and the number of eligible children available during recruitment; the study was not powered to estimate efficacy or population-level effects of support.

The study was approved by the Nazarbayev University Institutional Research Ethics Committee (NU-IREC Approval No. 1081, 21 May 2025). Written informed consent was obtained from a parent or legal guardian, and children gave assent where developmentally appropriate. Data were de-identified before analysis, and the study codes (ABWS1 to ABWS7) do not correspond to clinical record numbers [8].

5.8.2 Participants

Eligible children had confirmed CP, were aged 10–18 years at GMFCS level I or II, could walk safely on a treadmill with or without handrail support, could follow instructions and communicate pain, discomfort or fatigue, and were judged medically suitable by the clinical team. Exclusion criteria covered severe cognitive or communication impairment, acute or unstable illness, recent orthopaedic surgery, severe deformity or contracture, uncontrolled epilepsy, cardiovascular, respiratory or other systemic contraindications, acute pain, and any condition the clinical team considered unsafe [8].

Seven children and adolescents (four male, three female, aged 10–17 years) completed the support assessment and contributed to the selection analysis. Diagnoses were spastic hemiplegia (ICD-10 G80.2), spastic diplegia (G80.1) and dyskinetic CP (G80.3). Six participants went on to complete training and the post-assessment; participant ABWS7 completed the support assessment but was unable to attend the training sessions and post-assessment. Table 5.6 lists the participants.

Table 5.6. Characteristics of the pilot-study participants [8].

Participant	Age (years)	Sex	CP subtype (ICD-10)	GMFCS	Selected BWS (%)	Weight (kg)	Height (cm)
ABWS1	17	Male	G80.2 Spastic hemiplegia	I	15	57	158
ABWS2	12	Male	G80.1 Spastic diplegia	I	15	58	152
ABWS3	10	Female	G80.1 Spastic diplegia	II	20	26	132
ABWS4	17	Male	G80.1 Spastic diplegia	I	25	49	168
ABWS5	17	Female	G80.1 Spastic diplegia	I	20	36	145
ABWS6	17	Female	G80.3 Dyskinetic CP	II	5	40	147
ABWS7	12	Male	G80.2 Spastic hemiplegia	NR	30	44	147

NR, not recorded in the participant table; all participants were reported to be at GMFCS level I or II. ABWS7 completed the BWS assessment and selection analysis only.

5.8.3 Procedures

The protocol comprised a baseline assessment, a single support assessment, offline selection of the individualised level, three to five treadmill training sessions of 15 minutes each at the selected level, and a post-intervention assessment. Baseline and post-intervention assessments were carried out by the same clinical rehabilitation team with standardised procedures and included the 6-Minute Walk Test (6MWT, distance in metres), the 10-Metre Walk Test (10MWT) at comfortable and fast speeds (time in seconds), the Timed Up and Go test (TUG, time in seconds) and the OMNI Rating of Perceived Exertion scale, together with synchronised sEMG and plantar-pressure recordings during overground walking and during treadmill walking at 0% BWS. The support assessment followed the procedure of Section 5.7.1. Three to five sessions of 15 minutes give approximately 45–75 minutes of training at the selected level per participant, excluding assessment walking [8]. The manuscript reports neither the number of sessions completed by each participant nor the fast-speed 10MWT results; the selected levels used in training among the six completers ranged from 5% to 25% BWS.

5.8.4 Analysis

The selection framework of Section 5.6 was applied to each participant's support-assessment data. Clinical outcomes in the six completers were summarised descriptively as medians and interquartile ranges (IQR), with change computed as post minus pre; no inferential testing was performed on the pre–post outcomes, given the sample size and exploratory aims. Individual changes were also reported. Gait outcomes across the seven support conditions were explored with the Friedman test for repeated measures, with Kendall's W as an effect size where applicable; these analyses described responses to unloading and were not intended to assess intervention efficacy [8]. EMG envelopes were normalised to participant-specific reference values and examined descriptively.

5.8.5 Results: individualised selection

The best tested condition varied widely between children, from 5% to 30% BWS (Table 5.7). Two children (ABWS1, ABWS2) were assigned 15%, two (ABWS3, ABWS5) 20%, one 25%, one 30% and one 5%.

Table 5.7. Individualised BWS selections based on the multidomain composite score [8].

Participant	Selected BWS (%)	Composite score	Comparable BWS (%)	Runner-up score	Margin (points)
ABWS1	15	70.77	15	60.53	10.24
ABWS2	15	83.62	15	73.43	10.20
ABWS3	20	76.81	20	69.35	7.47
ABWS4	25	82.67	25	74.44	8.22
ABWS5	20	65.24	20, 25	62.84	2.40
ABWS6	5	77.40	5	62.34	15.06
ABWS7	30	80.96	25, 30	78.10	2.86

Margin is the difference between the highest and second-highest composite scores. Comparable conditions are those within 5 points of the maximum. Composite scores are normalised within participants and cannot be compared between participants.

For five of the seven children a single condition stood clearly above the rest, with margins of 7.47–15.06 points over the runner-up. For ABWS5 and ABWS7, by contrast, the margin was small (2.40 and 2.86

points), and two conditions fell within the 5-point comparable range: 20% and 25% for ABWS5, and 25% and 30% for ABWS7. The primary selection was Pareto-optimal for all seven participants, although most participants had several non-dominated conditions [8].

5.8.6 Results: robustness

Table 5.8 summarises the robustness analyses. Leave-one-metric-out stability was high for all participants (93.8%–100%), indicating that no single metric determined any child's selection. Alternative normalisation reproduced the primary selection in all specifications for five participants, but only in half of them for ABWS4 and ABWS5. Bootstrap resampling reproduced the primary selection in 75.0%–99.7% of resamples for six participants; for ABWS5 the primary 20% condition was reproduced in only 33.9% of resamples, and 10% was the most frequent bootstrap selection. TOPSIS agreed with the primary weighted-sum selection for six of seven participants (85.7%); the exception was ABWS7, for whom TOPSIS selected 25% rather than 30%, both of which lay within the comparable range [8].

Table 5.8. Robustness and sensitivity of the individualised selections [8].

Participant	Primary BWS (%)	Margin	Alt. normalisation stability	LOMO stability	Bootstrap P(primary)	Bootstrap modal BWS (%)	TOPSIS BWS (%)	TOPSIS agreement
ABWS1	15	10.24	100%	100%	99.3%	15	15	Yes
ABWS2	15	10.20	100%	100%	99.7%	15	15	Yes
ABWS3	20	7.47	100%	93.8%	85.0%	20	20	Yes
ABWS4	25	8.22	50.0%	100%	75.0%	25	25	Yes
ABWS5	20	2.40	50.0%	93.8%	33.9%	10	20	Yes
ABWS6	5	15.06	100%	100%	98.4%	5	5	Yes
ABWS7	30	2.86	100%	100%	83.8%	30	25	No

LOMO, leave-one-metric-out; TOPSIS, Technique for Order Preference by Similarity to Ideal Solution.

5.8.7 Results: gait responses to the selected support

Table 5.9 compares each child's gait at the selected support level with unsupported walking at the same belt speed. The most consistent change was in stride-time variability, which decreased in all seven children, by between 1.30 and 19.12 percentage points in mean stride-time CV. Step-time asymmetry decreased in five of seven children, pressure and pressure–time-integral (PTI) asymmetry each in four of seven, and stance-time asymmetry in only two. Double-support time fell in five children (by 2.59 to 16.55 percentage points of the gait cycle) and cadence rose in five. Because belt speed was constant, a

rise in cadence implies shorter steps rather than faster walking. Overall, the selected conditions were characterised by participant-specific combinations of reduced variability, altered temporal organisation and changed symmetry, not by uniform improvement across measures [8].

Table 5.9. Change from 0% BWS to the selected BWS condition for each participant [8].

Participant	Selected BWS	Δ Cadence	Δ Double support (pp)	Δ Step-time SI (pp)	Δ Stance-time SI (pp)	Δ Mean stride CV (pp)	Δ Pressure AI (pp)	Δ PTI AI (pp)
ABWS1	15%	+1.19	−2.59	+6.86	+6.10	−1.30	+16.98	+22.68
ABWS2	15%	−7.46	−11.86	−2.95	+2.52	−10.83	−19.19	−11.99
ABWS3	20%	+2.10	−11.60	−29.72	+10.89	−6.87	−6.28	−19.15
ABWS4	25%	+9.16	+1.74	−3.15	−0.31	−10.94	−4.26	−4.52
ABWS5	20%	+7.36	−12.74	−5.92	+0.76	−19.12	+0.84	+2.19
ABWS6	5%	−6.05	+3.09	+13.96	+11.49	−2.09	+19.43	+21.80
ABWS7	30%	+24.23	−16.55	−4.13	−5.79	−12.86	−16.49	−36.30

Change = value at selected BWS minus value at 0% BWS. pp, percentage points (double support as a percentage of the gait cycle; symmetry indices, asymmetry indices and CV as percentages). The pilot manuscript does not state the unit of cadence; the magnitudes are consistent with steps per minute. Negative changes in SI, AI and CV indicate less asymmetry or variability. A negative change in double support indicates a smaller proportion of the cycle in bilateral support and is not necessarily favourable. AI, asymmetry index of peak plantar pressure or of the pressure–time integral (PTI) between the two feet.

At the group level, the exploratory Friedman analyses did not detect significant differences across support conditions in the temporal-symmetry, loading-symmetry, support-time or temporal-variability measures, and the condition with the most favourable value differed from one outcome to another [8]. The manuscript does not report the Friedman χ^2 statistics or Kendall's W values.

Muscle activation patterns varied across children and muscles. In some children the timing and magnitude of plantarflexor and dorsiflexor activity changed as support increased, whereas others showed relatively stable activation profiles across conditions. Because amplitudes were normalised to participant-specific references rather than maximal voluntary contraction, only within-participant comparisons are meaningful [8].

5.8.8 Results: clinical outcomes after training

Table 5.10 summarises the pre–post clinical outcomes for the six completers and Table 5.11 the individual changes. Comfortable-speed 10MWT time decreased in four of six participants, and TUG time decreased in five of six. Walking endurance, by contrast, generally declined: the median change in 6MWT distance was −50 m, and only one participant (ABWS3) walked farther after training. Median perceived exertion on the OMNI scale fell from 2.5 to 1.5 [8].

Table 5.10. Clinical outcomes before and after individualised BWS treadmill training, n = 6 [8].

Test	Pre, median (IQR)	Post, median (IQR)	Change, median (IQR)
6MWT (m)	320 (313–343)	270 (253–303)	−50 (−85 to −15)
10MWT, comfortable (s)	9.75 (8.70–13.04)	9.55 (8.90–10.52)	−0.98 (−3.20 to 0.63)
TUG (s)	10.65 (9.62–15.14)	9.86 (8.43–10.55)	−1.36 (−3.52 to −0.36)
OMNI perceived exertion (score)	2.5 (0.5–3.8)	1.5 (0.3–2.8)	−0.5 (−1.75 to 0)

Change = post minus pre. Negative changes in 10MWT and TUG indicate faster completion; positive changes in 6MWT indicate greater distance; negative changes in OMNI indicate lower perceived exertion.

Table 5.11. Individual pre–post changes in clinical outcomes [8].

Participant	Δ6MWT (m)	Δ10MWT (s)	ΔTUG (s)	ΔOMNI
ABWS1	−90	−0.86	+0.70	0
ABWS2	−90	+1.13	−1.34	−1
ABWS3	+20	−4.55	−4.24	−3
ABWS4	−10	−1.10	−0.04	0
ABWS5	−30	+1.30	−1.39	−2
ABWS6	−70	−3.91	−6.24	0

5.9 Discussion

5.9.1 Individual responses to unloading

The central finding of the pilot study is that the best tested support level differed markedly from child to child, spanning almost the entire tested range. This is consistent with the heterogeneity of CP: children differ in their combinations of weakness, altered tone, impaired selective motor control and compensatory strategies [6], and these combinations would be expected to interact differently with unloading. Notably, children at the same GMFCS level were assigned very different levels, from 15% to 25% among those at level I, which suggests that functional classification alone is a poor guide to prescription. Other work has related the response to robot-assisted gait training to severity of disability and to treatment exposure [27], and has found that baseline motor function influences gait changes after robotic or conventional BWS treadmill training [28]. These studies support taking baseline function into account but do not provide a method for choosing the level of support; the framework of Section 5.6 is an attempt to fill that gap.

The gait data also illustrate why a multidomain rule is needed: ABWS1, for instance, showed reduced stride variability at the selected level alongside increased step-time, pressure and PTI asymmetry. Similar dissociations have been reported in smart-insole-supported stroke rehabilitation, where speed improved while symmetry declined [11]. The equal weighting of the four domains, however, is a reasoned choice rather than a validated clinical weighting and should be revisited as evidence accumulates.

5.9.2 Certainty of the selection

The robustness analyses show that the confidence one can place in a selection is itself individual. For most children the selection was stable under every perturbation applied. For ABWS5, however, the

margin over the runner-up was small, the result depended on the normalisation method, and bootstrap resampling most often chose a different level, 10%, so that 10%, 20% and 25% all remain plausible candidates for this child. For ABWS7 the weighted-sum and TOPSIS rules disagreed, but only between two levels that were already flagged as comparable. The output of the framework is therefore better thought of as a ranked set of candidates with an attached certainty than as a single prescription. Agreement between decision rules in six of seven children shows that most selections are not artefacts of the aggregation method, but not that they are physiologically optimal or predict better outcomes, which only prospective validation can establish.

5.9.3 Interpreting the gait changes

Several of the gait changes at the selected level require cautious interpretation. An increase in cadence at constant belt speed means shorter steps, not faster walking, and is not in itself an improvement. A reduction in double-support time may reflect a changed stepping strategy or reliance on the harness for stability and should not be read as improved balance or reduced fall risk. Lower EMG amplitude under unloading may simply reflect reduced antigravity demand rather than improved control [5, 29]. And greater bilateral symmetry is not automatically more physiological, particularly in children with bilateral involvement, in whom both limbs are impaired. These considerations explain why the framework includes only metrics with a defensible favourable direction, and why cadence and double-support time were reported descriptively rather than optimised.

5.9.4 Clinical outcomes

The pre–post findings were mixed. Shorter 10MWT and TUG times in most children are compatible with improved short-distance mobility but may also reflect test familiarity or confidence, and the TUG includes transfers and turns. The median changes of about one second are descriptive. The broader literature counsels similar caution. Mechanically assisted training with BWS offers small benefits over no walking training but little or no advantage over dose-matched overground practice [4]; robot-assisted gait therapy has shown advantages for some outcomes, such as walking speed and distance, but inconsistently across outcomes and comparators [30]; and a randomised comparison of robotic and conventional BWS treadmill training found no between-group advantage in gait parameters [28]. Moreover, robotic limb guidance and BWS alone are different interventions, and the present data cannot separate the effect of individualised unloading from that of walking practice or of the concurrent inpatient rehabilitation.

The decline in 6MWT distance in five of six children is an important counterweight to the short-distance results. The training dose of approximately 45–75 minutes was small; by comparison, ten 20-minute robotic sessions improved walking speed and 6MWT distance more than conventional care in children with unilateral CP [31]. A small dose could explain absent gains but not a decline; testing fatigue, motivation, day-to-day variability and the demands of the inpatient program are untested possibilities. Distribution-based estimates of meaningful change in the 6MWT for children with CP at GMFCS levels I–II range from 4 to 28 m [32]; such estimates are not universal thresholds and cannot classify individual responses from a group median, but they indicate that a median decline of 50 m deserves clinical attention and repeat assessment rather than dismissal as noise.

5.9.5 Engineering implications

From an engineering perspective, the pilot raises three issues that shaped later development. First, although the controller regulates the force measured by the in-line load cell, the support the child experiences depends also on harness fit, trunk motion and air-column compliance, so the gap between

commanded and achieved unloading at the feet is unknown and may vary between conditions and children. The sweep protocol computes effective unloading from the insoles, and the load-cell force logged by the controller provides a second, direct measure of the force in the suspension; analysing the two together would separate losses in the harness from fluctuations in the suspension. Second, a seven-level grid already strains children's tolerance yet cannot resolve an optimum between levels, and a boundary selection (ABWS7 at 30%) cannot exclude that higher support would have scored better; the model-based extension of Section 5.6.6 addresses this. Third, constant support treats the whole gait cycle alike, although demands differ sharply between weight transfer and single-limb stance. The gait-phase-synchronised mode under development keeps the individualised baseline but adds help only during weight transfer, preserving the loading demands of single-limb support. Its value will depend on whether the pneumatic hardware can deliver an adequate pulse within the brief double-support window and whether, at matched mean support, it improves gait more than constant assistance. On the safety side, the design report's recommendation of an independent hardware emergency vent that opens on over-pressure or loss of power should be implemented before wider clinical use.

5.10 Limitations

The pilot study and the methods it embodies have several limitations, most of which are acknowledged in the pilot manuscript and some of which are addressed by the later protocol. The sample was small and of convenience, limiting generalisability. One of the seven participants was unable to attend training, so pre–post analyses rest on six children and may be affected by attrition. There was no control group, and the children were receiving concurrent inpatient rehabilitation, so pre–post changes cannot be attributed to the BWS training.

The support conditions were applied in a fixed ascending order without scheduled rest, so order, fatigue and familiarisation effects are confounded with support level, especially for the higher, later conditions. Support was tested on a discrete 5-percentage-point grid between 0% and 30%, so the selection represents the best tested condition, not a continuous optimum; boundary selections are particularly uncertain. Selections were based on a single assessment, so their test–retest reliability is unknown. The support delivered at the child was not verified, so differences between commanded and achieved unloading are unknown. The selected support was held constant during training, without adaptive adjustment or progressive reduction. EMG analysis was descriptive, limiting mechanistic interpretation, and assessor blinding was not reported. Several analysis specifications (the alternative weight and normalisation scenarios, the bootstrap design and the Friedman statistics) are not reported in the manuscript.

On the device side, the regulation parameters (hysteresis band, timing constants and throttle setting) and the dynamic performance of the suspension have not been reported, and the recommended independent emergency vent is not yet part of the implemented design. The model-based extension and the phase-synchronised mode have not yet produced results. Future studies should compare algorithm-guided selection with a prespecified standard strategy at controlled walking exposure, repeat assessments in randomised order to quantify reliability, verify delivered unloading, and test whether the selected level predicts independent functional or patient-centred outcomes.

5.11 Summary

This chapter has presented the adaptive body-weight support system designed within program BR27199433 as a standalone device for treadmill gait training of children with CP. A stiff portal frame carries a 63 mm bore, 400 mm stroke pneumatic cylinder with a 2:1 cable–pulley suspension that gives about 800 mm of travel and, by design calculation, about 95 kgf at the suspension point at 7 bar. An in-

line load cell, a cable displacement sensor and a pressure sensor feed an Arduino Mega controller that regulates the supporting force in closed loop through interlocked supply and exhaust solenoid valves, using two-position control with hysteresis, anti-chatter timing, setpoint ramps and latched protective functions; pneumatic actuation was chosen for the compliance it provides during changes in unweighing force. A gait-phase-synchronised mode that would add a brief support pulse during weight transfer to an individualised baseline is under development.

The main methodological contribution is a within-participant multidomain framework that normalises plantar-pressure metrics of temporal symmetry, temporal variability, CoP behaviour and loading symmetry within the child, combines them with equal domain weights, selects the highest-scoring tested condition, flags comparable conditions, and tests the selection with several robustness analyses. A proposed extension would estimate a continuous, constrained optimum, including adaptive Bayesian optimisation with an EMG-based extensor-drive floor, and structured booklets now standardise sessions with the Cometa WaveX system.

In a pilot study of seven children and adolescents with CP (NU-IREC Approval No. 1081), the best tested support ranged from 5% to 30% of body weight, selections were robust for most children but uncertain for some, and gait at the selected level showed consistent reductions in stride-time variability but heterogeneous changes in symmetry. After three to five 15-minute training sessions, short-distance mobility improved in most of the six completers while walking endurance generally declined. These results support the premise that support should be individualised, but they do not establish a physiological optimum or the clinical efficacy of individualised BWS training. Controlled, randomised-order studies with verified unloading, and the development and evaluation of the phase-synchronised mode, are the next steps.

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Chapter 6. Robotic Perturbation Trainer for Balance Rehabilitation

Abstract. Children with cerebral palsy (CP) commonly have postural control deficits, yet conventional therapy seldom exposes them to the unexpected disturbances that cause falls. This chapter describes the Robotic Perturbation Trainer (RPT), a cable-driven device developed within the program that applies controlled waist-pull perturbations while a child walks on a treadmill under partial body-weight support. It reviews the principles of perturbation-based balance training and reactive balance in CP, derives the design requirements, and presents the mechanical design, kinematic model, bounded tension distribution, controller, protocol, and safety architecture of the four-cable, transverse-plane configuration. Bench validation and a published two-participant implementation in adolescents with spastic diplegic and spastic dyskinetic CP are summarized from the original *MethodsX* report [1]. The chapter then presents the final configuration of the RPT, a reconfigurable multi-plane cable-driven parallel robot whose vertically adjustable carriages switch it between horizontal-plane and spatial perturbations, together with its validation in three healthy adults [28]. It outlines the program's perturbation-training trial in 25 children with CP, whose results are pending, describes the Balance Recovery Index (BRI) being developed to analyse such trials, and closes with a planned next-generation paediatric pneumatic platform and the limitations of the current evidence.

Keywords: cerebral palsy; perturbation-based balance training; reactive balance; cable-driven parallel manipulator; treadmill training; body-weight support; rehabilitation robotics; surface electromyography

6.1 Introduction

Chapters 4 and 5 described the gait exoskeleton and the adaptive body-weight support (BWS) system, both of which mainly assist walking. The Robotic Perturbation Trainer (RPT) does the opposite: during treadmill walking it applies brief, controlled pulls at the waist that the child cannot anticipate, training the reactive balance responses needed to recover from slips, trips, and collisions in everyday life.

The RPT's engineering, protocol, and initial implementation were published as Khawaja et al., *MethodsX* 17 (2026) 104051, doi:10.1016/j.mex.2026.104051 [1], with support from program grant BR27199433 acknowledged. Unless otherwise stated, all device specifications, controller parameters, bench measurements, and participant data in Sections 6.3–6.9 come from [1], reorganized and expanded for a book readership. The RPT was subsequently rebuilt as a reconfigurable multi-plane system, which is the final configuration of the device; it is described from a manuscript by the program team [28] in Section 6.10.2. The perturbation-training trial in children (Section 6.10.3), the Balance Recovery Index (Section 6.10.4) and the planned paediatric pneumatic platform (Section 6.10.5) are program work that has not yet been published.

Sections 6.2–6.3 set out the rationale and design requirements; Sections 6.4–6.8 cover the mechanism, model, control, protocol, and safety of the published four-cable configuration; Section 6.9 reports the published validation; Section 6.10 covers integration with body-weight support, the final multi-plane configuration, the trial in children, the Balance Recovery Index, and the planned next-generation platform; and Sections 6.11–6.12 discuss limitations and summarize.

6.2 Principles of Perturbation-Based Balance Training and Reactive Balance in Cerebral Palsy

6.2.1 Cerebral palsy and postural control

CP is a group of permanent disorders of movement that result from injury to the developing central nervous system around the time of birth [2]. Estimates of its frequency are in the range of two to four cases per 1000 live births [3–5], which makes it one of the most common causes of physical disability in childhood. It is also a major reason for long-term paediatric rehabilitation [6,7]. Chapter 1 discusses the epidemiology and clinical classification of CP in detail. Here the focus is on one aspect of motor function, postural control, and the way it is impaired.

Postural control is the ability to keep the body's center of mass (CoM) over the base of support, and to restore that relationship after it has been disturbed. It depends on the vestibular, visual, and proprioceptive systems working together with the motor system that produces corrective muscle activity [1]. When any of these components is impaired, stability falls and so does functional performance. Children and adults with CP, whether mildly or severely affected, frequently have postural control impairments [8–10]. These impairments are particularly prominent in the spastic diplegic and dyskinetic presentations [1].

The two clinical subtypes represented in the published RPT study illustrate how varied the underlying problems can be. In dyskinetic CP, involuntary and fluctuating movements, including dystonia and choreoathetosis, disrupt coordination and make posture unstable from moment to moment [11–13]. In spastic diplegic CP, the lower limbs are mainly affected. Increased muscle tone and stiffness make walking effortful, and the hip adductors may pull the legs together so that they cross during swing, giving the characteristic "scissoring" gait [1]. The dyskinetic child struggles to suppress unwanted movement. The diplegic child struggles with a stiff, narrow base of support. These different mechanisms are the reason the original authors argue that balance interventions should be matched to each subtype's motor problems [1].

6.2.2 Anticipatory versus reactive balance

Two broad modes of balance control are useful to distinguish. Anticipatory (feedforward) control prepares the body for an expected disturbance, such as stepping off a kerb. Reactive (feedback) control responds to an unexpected one, such as a slip or a push, and must produce an effective correction (a change in hip and trunk muscle activity, or a recovery step) within a very short time.

Conventional balance therapy, built largely on static exercises and walking on stable surfaces, mostly exercises anticipatory control. As the original report notes, such therapies often fail to challenge the balance systems with realistic perturbations, which has motivated interest in interventions that reproduce real-world instability [1,14].

6.2.3 Perturbation-based balance training

Perturbation-based balance training (PBT) addresses this gap. In PBT, the person repeatedly experiences controlled, unexpected disturbances while carrying out a task such as standing or walking. The aim is to improve reactive balance control, that is, the ability to maintain or recover stability when it is threatened [15]. The approach rests on a simple motor-learning principle: a skill is trained by practising it. If the goal is better recovery from unexpected disturbances, the training must contain unexpected disturbances that are large enough to require a real recovery response, yet controlled enough to be safe.

PBT has been applied in healthy older adults [16], people after surgery for degenerative cervical myelopathy [17], people after stroke [18], and people with Parkinson's disease [19,20], using different disturbance modalities and directions [1]. The practical design questions are the same ones the RPT had to answer: where on the body to apply the disturbance, in which direction, how large, how long and how often, how to keep it unpredictable, and how to keep the person safe when recovery fails.

6.2.4 Perturbation training in paediatric CP

In paediatric CP, robotic and treadmill-based interventions that include perturbations have been studied using a variety of mechanical arrangements and planes of motion [21,22]. Several findings from adjacent work shaped the RPT concept [1]. Studies of repeated waist-pull perturbations in people with cerebellar ataxia indicated that repetition is essential for drawing on residual motor-learning capacity and improving balance during steady walking [23]. In children with CP, gradually increasing the perturbation load during treadmill training has been studied as a way of promoting longer retention of locomotor adaptations [24]. With a cable-driven Tethered Pelvic Assist Device, frontal-plane pelvic perturbations changed pelvic motion in the sagittal and transverse planes as well as in the frontal plane, and increased activation of the gluteus medius, a key muscle for pelvic stability [25].

The original authors identify a gap in this work [1]: existing implementations are often limited to particular directions, stationary conditions, or non-standardized delivery, and controlled transverse-plane perturbations during dynamic gait, with simultaneous recording of muscle activation, are insufficiently described. The RPT was developed to fill this gap, delivering randomized transverse-plane waist pulls during treadmill walking with surface electromyography (sEMG) of the hip extensors and abductors. The original report also suggests wider applications (other neurological conditions, fall prevention in older adults, athletic training) [1], which are outside the scope of this book.

6.3 Design Requirements

The design requirements for the RPT can be reconstructed from the design rationale and features set out in [1]. Table 6.1 summarizes them. They follow from the clinical goals in Section 6.2 and from the constraints of working with children who have impaired balance.

Table 6.1. Design requirements for the Robotic Perturbation Trainer and how the published design addresses them (synthesized from [1]).

Requirement	Rationale	Implementation in the RPT [1]
Perturbations applied during walking, not only during standing	Falls in daily life occur mainly during locomotion; reactive gait responses must be trained in context	Integration with a treadmill; perturbations delivered during continuous treadmill walking
Perturbations in the transverse (horizontal) plane, in several directions	Transverse-plane waist pulls during gait are under-explored; multidirectional disturbances prevent adaptation to a single direction	Four cables at approximately ±45° and ±135° around the treadmill, giving front-left, front-right, back-left, and back-right pulls
Point of application near the CoM	Disturbing the trunk or pelvis near the CoM produces a whole-body balance challenge rather than a local limb displacement	Cables attached to a circular waist belt acting as the end-effector
Unpredictability of direction and timing	Reactive, not anticipatory, control is the training target	Pseudorandom selection of the cable for each event; randomized inter-perturbation interval

Requirement	Rationale	Implementation in the RPT [1]
Controlled, repeatable force magnitude	Dose must be defined, reproducible across sessions, and progressively scalable	Torque-mode motor control with current regulation; magnitude fixed within a trial and stepped up across sessions in a 65–85 N range
Cables must remain taut	Cable-driven mechanisms lose controllability when a cable goes slack	Baseline pretension on all cables (10 N in the implemented controller)
Force bounds suitable for children	Excessive forces risk injury and loss of confidence	Explicit lower and upper tension bounds in the tension-distribution formulation; hardware and software limits
Fall protection	Recovery failures are expected in a population with impaired balance	Body-weight support system and harness worn throughout training
Clinical practicality	Equipment must fit within a rehabilitation centre workflow	Compact integration of the RPT, treadmill, and BWS system into one platform

Two further requirements are implicit in [1]. The delivered force should be traceable from the intended vector to the motor commands so that dose can be documented, a property the original report attributes to its deterministic control pipeline [1]. The system should also accommodate a range of body sizes; the published study was limited to adolescents within a defined height range (Section 6.9.2).

6.4 Mechanical Design and Actuation

6.4.1 Overall architecture

The RPT is a cable-driven planar parallel manipulator (CDPPM) built around a treadmill [1]. Four rotary actuating units stand at the four corners of the treadmill, slightly above the level of the subject's hips. Seen from above, they are spaced at angular positions of approximately ±45° and ±135° relative to the walking direction. Each actuator turns a rigid arm of fixed length, 0.25 m. A tensioned steel cable runs from the tip of each arm through directional pulleys to a waist-worn belt or harness, which is the manipulator's end-effector. The child walks on the treadmill wearing this belt and also wears the harness of the BWS system, which provides fall protection.

The four cables are arranged diagonally, so that each pulls the waist toward one corner of the treadmill: front-right, front-left, back-right, or back-left. A single cable can therefore produce a diagonal pull with forward and lateral components, or with backward and lateral components. In the published controller (Section 6.6) only one cable delivers each perturbation, so the child experiences one of four diagonal pulls. In principle, the over-actuated four-cable layout can also generate a resultant force in any direction in the horizontal plane by combining tensions in several cables (Section 6.5.3).

6.4.2 Why a cable-driven parallel mechanism?

A walking person can be perturbed at the feet (moving belt or platform), through a rigid linkage at the pelvis, or through cables at the waist. The cable-driven option keeps the moving mass attached to the child small, essentially a belt and four cables, because the actuators are mounted on the treadmill frame. Walking is therefore minimally constrained between perturbations.

The main difficulty with cable mechanisms is that a cable can only transmit tension. If any cable goes slack, the mechanism loses its ability to control the end-effector in that direction, and a slack cable that suddenly re-tensions produces an uncontrolled jerk. Keeping every cable above a minimum tension at

all times is therefore a necessary condition for controllability in cable-driven robots [26]. The RPT meets this condition with a baseline pretension (Section 6.6.2). It also has more cables (four) than the number of degrees of freedom it controls in the plane (three: two translations and a rotation). This redundancy is what allows all cables to be kept taut while still generating a desired net force.

6.4.3 Actuators and drive electronics

Each actuating unit uses a CubeMars AK80-64 brushless DC motor with an integrated planetary gearbox [1]. Table 6.2 summarizes the specifications reported in the original paper.

Table 6.2. Actuation and drive hardware of the Robotic Perturbation Trainer (from [1]).

Item	Specification [1]
Actuator	CubeMars AK80-64 brushless DC motor, four units
Rated torque	48 Nm
Peak torque	120 Nm
Gear reduction	Planetary, 64:1
Position sensing	14-bit onboard encoder
Actuator arm length	0.25 m (constant)
Maximum cable force (from peak torque and arm geometry)	Up to 480 N
Motor controller	ODrive 24 V, version 3.6
Controller electronics	DRV8301 three-phase pre-driver IC; STM32F4 microcontroller (Arm Cortex-M4)
Cable	Tensioned steel cable routed via directional pulleys
End-effector	Circular waist belt with four attachment points at 90° intervals
Force verification (bench)	FUTEK LCM300 (250 lb) in-line load cells, one per cable

A torque T at the pivot produces a cable force T/d with $d = 0.25$ m, so the 120 Nm peak torque gives the 480 N maximum reported in [1]; the 48 Nm rated torque would give about 192 N (the author's arithmetic, not reported in [1]). Both are far above the 65–85 N clinical range (Section 6.7), so the actuators operate well away from saturation. Because the hardware can produce forces several times larger than appropriate for a child, the limits described in Section 6.8 are essential.

The publication does not give the treadmill model, the frame and pivot dimensions, the numerical belt radius, or the cable and pulley specifications of this configuration [1]; these are collected with the other unreported details in Section 6.9.7. The corresponding dimensions of the final multi-plane configuration are given in Section 6.10.2.

6.5 Kinematic and Static Model

This section develops the mathematical model that relates actuator commands to the forces applied to the child. The formulation follows the model published in [1] and is presented here with additional explanation for readers new to cable-driven robots. The notation follows the original paper where possible.

6.5.1 Geometry and coordinates

The RPT is modelled as a planar cable-driven parallel manipulator with three degrees of freedom: the horizontal position (x, y) of the belt centre and the belt's rotation θ about the vertical axis [1]. The rectangular treadmill frame provides the global reference frame. The four actuator pivots are fixed at its corners, at positions **A**_i, i = 1, …, 4. Each pivot carries a rigid arm of length d that rotates through an angle α_i. The cable leaves the arm tip and runs to the belt.

The belt is idealized as a rigid ring of radius p, with a local coordinate frame at its centre. The four cable attachment points **B**_1…**B**_4 are spaced at 90° intervals around the ring, with local offsets **r**_1 = (p, 0), **r**_2 = (0, p), **r**_3 = (−p, 0), and **r**_4 = (0, −p). The global position of each attachment point is found by rotating its local offset through θ and translating by the belt-centre position **b** = (x, y)^T:

$$\mathbf{B}_i = \mathbf{b} + \mathbf{R}(\theta)\,\mathbf{r}_i = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \mathbf{r}_i$$

6.5.2 Cable length and inverse kinematics

A distinctive feature of the RPT is that the physical cable has a fixed length. Unlike many cable robots, which wind cable onto a drum, the RPT changes the effective taut cable span by rotating the actuator arm. Rotating the arm moves the point at which the cable leaves the arm tip, and so changes the distance between that point and the belt [1]. The cable exit point (the moving anchor) lies on a circle of radius d about the pivot:

$$\mathbf{A}_i'(\alpha_i) = \mathbf{A}_i + d \begin{bmatrix} \cos\alpha_i \\ \sin\alpha_i \end{bmatrix}$$

The effective cable length l_i is the distance from the moving anchor to the belt attachment point:

$$l_i = \|\mathbf{B}_i - \mathbf{A}_i'(\alpha_i)\|$$

The inverse kinematic problem asks which arm angles give a desired belt pose. It is solved with the law of cosines [1]. Let **R**_i = **B**_i − **A**_i be the vector from the fixed pivot to the attachment point, with length L_i = ‖**R**_i‖ and direction β_i = atan2(R_iy, R_ix). The triangle formed by the pivot, the arm tip, and the attachment point gives

$$l_i^2 = L_i^2 + d^2 - 2\,d\,L_i \cos(\alpha_i - \beta_i)$$

and therefore

$$\alpha_i = \beta_i + \arccos\left(\frac{L_i^2 + d^2 - l_i^2}{2\,d\,L_i}\right)$$

This relation gives the four arm angles needed to produce a commanded set of cable lengths, and hence a desired belt pose [1]. In practice, the belt pose during training is determined largely by the child's own walking movement, not by the robot. The robot acts mainly as a force generator, not a position controller. The inverse kinematics nevertheless matters for understanding the workspace, the arm angles that occur as the child moves, and the direction in which each cable acts at any instant. (The arccos term has two solutions, corresponding to the two possible "elbow" configurations of the arm and cable. The published formulation takes the positive branch [1].)

6.5.3 Differential kinematics

The rates of change of the cable lengths relate linearly to the rates of change of the belt pose and the arm angles through a Jacobian matrix [1]. With generalized coordinates $\mathbf{q} = [x, y, \theta, \alpha_1, \alpha_2, \alpha_3, \alpha_4]^\top$ and unit cable directions $\mathbf{u}_i = (\mathbf{B}_i - \mathbf{A}'_i)/l_i$, the relation is

$$\dot{\mathbf{l}} = \mathbf{J}\,\dot{\mathbf{q}}, \qquad \dot{\mathbf{l}} \in \mathbb{R}^4, \quad \mathbf{J} \in \mathbb{R}^{4\times 7}$$

Row i of $\mathbf{J}$ contains the components of $\mathbf{u}_i$ in the x and y columns. The θ column holds the projection of the attachment point's rotational velocity onto the cable direction. One arm-angle column is non-zero, the one belonging to cable i, with entry $d(u_ix \sin\alpha_i - u_iy \cos\alpha_i)$ [1]. The physical meaning of this structure is that each cable's length depends on the belt pose (which is shared by all four cables) and on its own arm angle only. The arms are mechanically independent of one another. The unit vectors $\mathbf{u}_i$ computed here are reused directly in the static tension analysis that follows.

6.5.4 Wrench and the structure matrix

The quantity of clinical interest is the force applied to the child, not the cable lengths. Each cable i pulls the belt along its unit direction $\mathbf{u}_i$ with tension f_i. Because the cable attaches at an offset $\mathbf{r}_i$ from the belt centre, it also exerts a moment about the vertical axis equal to $(\mathbf{r}_i \times \mathbf{u}_i)_z = r_ix \cdot u_iy - r_iy \cdot u_ix$ [1]. The net planar wrench on the belt, $\mathbf{F} = [F_x, F_y, M_z]^\top$, is therefore a linear function of the four tensions, $\mathbf{f} = [f_1, f_2, f_3, f_4]^\top$:

$$\mathbf{F} = \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} = \mathbf{A}\,\mathbf{f}, \qquad \mathbf{A} = \begin{bmatrix} u_{1x} & u_{2x} & u_{3x} & u_{4x} \\ u_{1y} & u_{2y} & u_{3y} & u_{4y} \\ (\mathbf{r}_1 \times \mathbf{u}_1)_z & (\mathbf{r}_2 \times \mathbf{u}_2)_z & (\mathbf{r}_3 \times \mathbf{u}_3)_z & (\mathbf{r}_4 \times \mathbf{u}_4)_z \end{bmatrix} \in \mathbb{R}^{3\times 4}$$

$\mathbf{A}$ is called the structure matrix. For the symmetric attachment geometry of the RPT, the moment row simplifies to $(p\,u_1y, -p\,u_2x, -p\,u_3y, p\,u_4x)$ [1].

6.5.5 Bounded tension distribution

With four tensions and three wrench components, $\mathbf{A}\,\mathbf{f} = \mathbf{F}$ has infinitely many solutions. The redundancy is used to keep each tension within a safe band [1]:

$$f_{\min} \le f_i \le f_{\max}, \qquad i = 1, \ldots, 4$$

The lower bound keeps every cable taut (Section 6.4.2); the upper bound caps the force any cable can apply to the child. A unique tension vector is selected as the minimum-norm solution subject to the lower bound [1]:

$$\min_{\mathbf{f}} \|\mathbf{f}\|_2^2 \quad \text{subject to} \quad \mathbf{A}\,\mathbf{f} = \mathbf{F}, \quad f_i \ge f_{\min}$$

This quadratic program selects, among all tension sets producing the desired wrench, the one that loads the cables, motors, and belt least. The original implementation solves it in MATLAB with lsqlin (identity coefficient matrix, zero target vector, $\mathbf{A}\,\mathbf{f} = \mathbf{F}$ as equality constraint and $f_i \ge f_\min$ as bounds) [1]; $f_\max$ can be added as a further bound in the same formulation, consistent with the paper's description of explicit upper and lower bounds suitable for children [1].

The original authors present this bounded tension distribution as a technical contribution that guarantees static equilibrium while avoiding slack cables and unbounded internal forces [1]. The published clinical controller (Section 6.6) uses a simpler single-cable scheme; the general formulation is the framework for future protocols that combine cable tensions to pull in arbitrary directions.

6.6 Sensing, Control, and Perturbation Timing

6.6.1 Control architecture

The RPT controller has three objectives [1]: to generate perturbations that are precisely defined in magnitude yet unpredictable to the child, to keep constant pretension in all cables, and to enforce the actuators' safety limits. It does this through a deterministic pipeline with three layers.

1. A high-level perturbation scheduler decides when the next perturbation occurs, from which direction, and with what magnitude.
2. A tension and torque computation layer uses the kinematic model to convert the intended force vector into four cable tensions and then into four arm torques.
3. A low-level motor control layer regulates each motor's current so that it produces the commanded torque.

Because each layer is deterministic, apart from the seeded random choices in the scheduler, the force applied in any perturbation can be traced from the intended vector through to the actuator commands [1]. This traceability is a practical advantage in a clinical study, because the dose delivered in each session can be reconstructed and reported.

6.6.2 Pretension management

Before any perturbation is delivered, all four cables are pretensioned to keep them taut. The implemented controller uses 10 N per cable. This prevents slack and gives the controller an initial tension margin [1]. The original paper also describes the baseline pretension as 10% of the maximum perturbation force in its general system description, and refers to "adaptive pretension management" as a design feature [1]. With a maximum perturbation of 85 N, 10% would be 8.5 N. The 10 N figure is the value set in the implemented controller and the one confirmed by bench validation (10.2 ± 0.7 N; Section 6.9.1), so it is the value that applied in the published study. The 10%-of-maximum rule is the one adopted in the final multi-plane configuration of the RPT, where the maximum perturbation is scaled to the participant's body weight (Section 6.10.2) [28].

Pretension means the child always feels a small inward pull from all four cables; by symmetry these largely cancel when the child is centred on the treadmill, but not exactly when the child drifts off-centre.

6.6.3 Single-cable perturbation law

For the clinical implementation, the original authors deliberately chose a simple controller that produces discrete perturbations from one cable at a time [1]. The robot is treated as a static force distributor. At each perturbation event, the controller selects one cable k and raises its tension by the perturbation magnitude f_pert, while the other three cables stay at pretension:

$$f_i = \begin{cases} f_{pre} + f_{pert}, & i = k \\ f_{pre}, & i \neq k \end{cases}$$

The intended horizontal perturbation force is **F**_des = F_pert **e**_k, where **e**_k is a unit vector along cable k's pull direction [1]. Because each cable has a known pull direction in the transverse plane, the extra tension produces a horizontal pull of magnitude F_pert on the belt in that direction. The original paper notes that because only one cable delivers the perturbation, the net moment about the belt is negligible. The child therefore experiences essentially a pure translational pull, not a twist [1]. This follows from

the cable acting approximately through the belt centre when the cable is roughly aligned with its attachment-point radius.

The single-cable law is a feasible special case of the framework in Section 6.5.5. For a first clinical implementation it is transparent (one perturbation, one direction), needs no online optimization, and is easy to verify against a single load cell.

6.6.4 From tension to motor current

The commanded cable tension *f*_k becomes an arm torque through the arm length, *T*_k = *d f*_k, and is sent to the actuator. The other motors are held at their pretension torques [1]. The ODrive controller then converts this output-side torque into a motor current reference. It divides by the 64:1 gear ratio to obtain the motor-side torque and divides again by the motor torque constant *k*_T (in newton-metres per ampere) [1]:

$$T_{motor} = \frac{T_k}{64}, \qquad I_{ref} = \frac{T_{motor}}{k_T}$$

The ODrive then regulates the phase currents so that the motor's electromagnetic torque matches *T*_motor. Throughout operation it monitors the encoder and currents to maintain control accuracy, and it enforces limits on current, velocity, and position [1]. In this torque-control mode the motor current is the control variable for cable force. This means the RPT does not need force sensors in its operational configuration. The load cells described in Section 6.9.1 were used to verify the current-based force estimate on the bench. The publication states that *k*_T is the supplier's value but does not give it numerically, nor the control-loop rate, the host computer and its interface to the ODrive, or whether the load cells remained installed during clinical sessions [1] (Section 6.9.7). The tension-distribution computation was implemented in MATLAB [1].

Because a current-based force estimate ignores gearbox and pulley friction and arm inertia, designers of similar systems should decide whether closed-loop load-cell control is needed or whether bench-verified current control is accurate enough.

6.6.5 Randomization of direction and timing

Unpredictability is central to perturbation training. If the child can predict the direction or timing of the next perturbation, they can prepare an anticipatory adjustment, and the training then targets anticipatory rather than reactive control. The RPT randomizes both direction and timing [1].

For direction, the cable index $k \in \{1, 2, 3, 4\}$ is drawn at each event from a discrete uniform distribution, using a Mersenne Twister pseudorandom number generator. The generator is seeded once at the start of the experiment [1]. Each of the four diagonal directions is therefore equally likely at every event, and a short sequence of past perturbations gives no information about the next one.

For timing, after each perturbation pulse the controller returns all cables to pretension and waits for a randomly determined inter-perturbation interval before triggering the next event [1]. In the clinical protocol, perturbations occurred every 15 to 18 s (Section 6.7). The original paper describes this combination as a deterministic scheduler paired with a pseudorandom event generator, so that the child cannot anticipate either the timing or the direction of perturbations [1].

Seeding once per experiment means that, if the seed is recorded, the sequence of directions can be reconstructed afterwards. The publication does not state whether seeds and event timestamps were

logged and synchronized with the sEMG recordings, or the distribution from which the 15–18 s interval was drawn [1].

6.6.6 Perturbation timing relative to the gait cycle

Some perturbation systems trigger disturbances at a specific gait event (e.g. heel strike), detected by foot switches, insoles, or motion capture, to standardize the biomechanical state at perturbation onset. The RPT as published in [1] does not do this: perturbations are time-based, at pseudorandom intervals, so they arrive at varying gait phases. This adds unpredictability but also variability in the biomechanical response.

Gait-phase timing was introduced in the final multi-plane configuration, where perturbations were delivered once per gait cycle in a cycle-locked protocol during its validation in healthy adults [28] (Section 6.10.2). Cycle locking makes the biomechanical state at onset repeatable, at the cost of predictability; the two approaches therefore suit different purposes, random timing for training reactive control and cycle-locked timing for characterizing responses.

6.6.7 Pulse shape

Each perturbation is a force pulse lasting 400 ms [1]. Within the pulse, the selected cable's tension rises from pretension to pretension plus *f*_pert, is held, and returns to pretension when the pulse ends. Bench validation (Section 6.9.1) characterized the rise time, overshoot, and return-to-baseline time of this pulse. A 400 ms duration is long enough for the pull to displace the child's CoM appreciably and to demand an active response, and short enough that the perturbation is felt as a discrete event and not a sustained push.

6.7 Perturbation Protocol and Progression

6.7.1 Session structure

The published implementation comprised ten training sessions over five weeks [1]. Each session lasted more than 1.5 h including preparation, calibration, and donning and doffing, of which 22–24 min on average was active walking (Table 6.7). One preliminary session covered information and consent, and assessments were performed before, at mid-point (after five sessions), and after the intervention [1].

Perturbations were applied at random from the four diagonal directions every 15–18 s, giving approximately 82–93 perturbations per session, or about 20–23 per direction [1].

6.7.2 Dose parameters and progression rules

Perturbation magnitude was the main progression variable: fixed within a trial, adjusted manually between trials within 65–85 N, and increased across sessions from the lower bound while endurance and comfort were monitored [1]. Treadmill speed (0.2–0.5 km/h) and active duration (10 to 23 min) were also progressed [1]. Table 6.3 summarizes the parameters.

Table 6.3. Perturbation protocol parameters of the published RPT implementation (from [1]).

Parameter	Value or rule [1]
Program length	10 training sessions over 5 weeks
Session duration (total, incl. preparation)	> 1.5 h

Parameter	Value or rule [1]
Active walking time per session	Increased from 10 to 23 min across sessions; average 22–24 min (see Table 6.7)
Treadmill speed	0.2–0.5 km/h, progressed across sessions
Perturbation directions	4 diagonal directions (front-right, front-left, back-right, back-left), pseudorandom uniform selection
Inter-perturbation interval	15–18 s, randomized
Perturbations per session	Approximately 82–93
Perturbations per direction per session	Approximately 20–23
Pulse duration	400 ms
Pretension	10 N per cable
Perturbation magnitude	65–85 N; fixed within a trial; increased across sessions from the lower bound
Body-weight support	Kept to a minimum, approximately 10–15% of body weight (average 12.3–12.5%; Table 6.7)
Assessments	Pre, mid (after 5 sessions), post

The original paper also describes the starting perturbation force as 10% of the participant's body weight, increased over sessions to an upper bound of 85 N [1]. For the two participants in the study (body masses 67 kg and 45 kg; Table 6.6), 10% of body weight corresponds to roughly 66 N and 44 N respectively (the author's arithmetic, using $g \approx 9.81$ m/s²). The first value agrees with the 65 N lower bound, but the second falls below it, and the reported mean magnitudes (68 N and 73 N; Table 6.7) show that the lighter participant in fact trained at the higher forces. The publication does not give the step size between sessions or the criteria for increasing or holding magnitude, speed and duration [1]. The final configuration of the RPT expresses perturbation magnitude as a percentage of body weight (10–50%) [28], which removes this ambiguity for future protocols.

6.7.3 Rationale for progression

The progression is consistent with work on graded perturbation loads in CP [24] and with PBT principles generally [15]: training starts at a manageable level and becomes harder as responses improve. Larger forces displace the CoM further, higher speeds leave less time for a corrective step, and longer durations add fatigue. Keeping BWS low (approximately 10–15% of body weight) means the child bears most of their own weight, while the harness remains a safety net.

The treadmill speeds used, 0.2–0.5 km/h (about 0.06–0.14 m/s), are very slow compared with typical overground walking. This reflects the participants' functional levels, the novelty of walking on a treadmill with cables attached, and the priority given to safety in the first implementation. As children become familiar with the system, higher speeds may be appropriate. Chapter 5 describes how comfortable treadmill speed was individualized in the program's BWS study.

6.8 Safety Architecture

Safety is a primary design driver for any device that deliberately disturbs the balance of a child with a neuromotor impairment. The RPT has safety measures at several levels [1], summarized in Table 6.4.

Table 6.4. Layered safety measures of the Robotic Perturbation Trainer (from [1]).

Level	Measure [1]	Hazard addressed
Hardware	Torque limits at the actuators	Excessive force on the child
Drive electronics	Current, velocity, and position limits enforced by the ODrive; continuous encoder and current monitoring	Runaway motion, overcurrent, arm over-travel
Control software	Maximum cable tension constraint; tension bounds in the distribution; velocity and acceleration bounds	Excessive or abrupt forces
Control software	Real-time monitoring of all actuator states	Undetected faults
Mechanical	Constant pretension to prevent cable slack	Uncontrolled snatch loads on re-tensioning
Protocol	Perturbation magnitude restricted to 65–85 N, far below actuator capability; magnitude fixed within each trial; monitoring of endurance and comfort	Overloading the participant
Fall protection	Body-weight support harness worn throughout	Falls when recovery fails
Clinical	Eligibility criteria excluding spinal or pelvic instability, unhealed fractures of the anterior or posterior superior iliac spine, recent orthopaedic surgery, and severe spasticity (Section 6.9.2)	Musculoskeletal injury from waist-belt loading

Two features stand out. The BWS harness and the RPT play complementary roles: the RPT creates the challenge and the harness catches the child if a response fails [1]. The eligibility criteria are themselves a safety layer, excluding conditions that make the pelvis or spine vulnerable to belt loading [1].

The original report states that all sessions were completed according to the predefined protocol without interruption and that no protocol deviations were recorded [1]. It does not describe an emergency-stop provision, the behaviour of the cables on power loss or communication fault, predefined stopping criteria, or a systematic adverse-event log. For a device of this kind these are essential elements of the risk file required for medical-device registration, which the program intends to pursue for the RPT (Section 6.10.5).

6.9 Validation and Results Reported in the Published Study

The original paper validated the RPT methodology in two stages [1]. The first was bench validation of the actuation system without a human participant. The second was implementation of the full protocol in two adolescents with CP, with assessment at three phases. Both are summarized here. In line with the original authors' interpretation, the two-participant data show the feasibility of the protocol and the behaviour of the measurement framework. They do not establish clinical efficacy [1]. All data in this section are published in [1].

6.9.1 Bench validation of the actuation system

For bench validation, a FUTEK LCM300 load cell (250 lb capacity) was installed in series with each of the four cables to measure cable tension in real time [1]. Perturbations were delivered as transient force pulses on a randomly selected cable, as in the clinical controller, without a human participant attached. Motor-side force was estimated from the ODrive phase currents and the supplier's torque constant (force = current × k_T ÷ arm length, with arm length 0.25 m) [1]. The commanded targets covered the operating range: pretension at 10 N and perturbations at 65–85 N, in each of the four pull directions, with ten repetitions per target-direction combination. Table 6.5 reports the results.

Table 6.5. Bench validation of the RPT actuation system (published in [1]).

Performance aspect	Metric	Result [1]
Force tracking (commanded vs. load-cell measured force, all targets and directions)	Mean absolute error	2.3 N
	Mean relative error	3.1%
	Root-mean-square error	2.8 N
Repeatability	Within-target SD across repetitions	≤ 1.6 N
Direction independence	SD across the four directions	≤ 2.0 N
Pretension maintenance (representative session)	Baseline tension per cable	10.2 ± 0.7 N
	Maximum observed drift	1.4 N
Pulse dynamics (400 ms pulse, 65–85 N peak)	Rise time to commanded peak	Approximatel y 100 ms
	Overshoot	< 6%
	Return to pretension after pulse end	Approximatel y 120 ms

Force errors of a few newtons are small relative to the 65–85 N perturbations, and the uniformity across directions matters clinically: a direction that systematically delivered more force would make any asymmetry in the child's responses partly a device artefact. A rise time of about 100 ms gives a sharp onset within the 400 ms pulse; an overshoot below 6% corresponds to at most about 5 N at 85 N, which the safety bounds should accommodate; and the return to pretension in about 120 ms gives the perturbation a clear end.

The bench test did not load the belt with a moving mass, so it characterizes the actuation chain rather than the force delivered to a walking person, which also depends on the child's movement, belt compliance and cable dynamics. The final configuration has since been operated with healthy adults walking on the treadmill (Section 6.10.2), but that study reports muscle responses rather than measured delivered force [28].

6.9.2 Participants

The published study enrolled a convenience sample of two adolescent males with CP [1]. The study was approved by the Nazarbayev University Institutional Review Ethics Committee Board (IRB No: 1081/21,052,025, as printed in [1]). Informed consent was obtained from all participants and their legal guardians [1]. Table 6.6 summarizes the participants.

Table 6.6. Characteristics of the participants in the published RPT implementation (from [1], Table 1).

Characteristic	AB-16	AR-17
Age (years)	16	17
Sex	Male	Male
Body mass (kg)	67	45
Height (cm)	165	163
CP subtype	Spastic dyskinetic	Spastic diplegic
GMFCS level	III	I
Assistive device	Wheeled walker	None
Orthosis	See note	See note
Ambulatory status	Assisted	Independent

Note: The original paper is internally inconsistent on orthosis use. Its Table 1 lists an ankle-foot orthosis (AFO) during the intervention for AB-16 and none for AR-17. Its narrative text states that AB-16 did not wear orthoses during the intervention and that AR-17 wore an AFO [1]. The point is listed for confirmation in Section 6.9.7.

According to [1], both participants were cognitively intact, able to follow instructions, and free of recent orthopaedic surgery or conditions compromising safety. Inclusion criteria were age 12–18 years; GMFCS I–III; intact cognition and ability to report pain; upper-limb strength of at least 3+ on manual muscle testing; Ashworth score ≤ 2; absence of consolidated fractures and contracture; general good health; height 160–195 cm; and shoe size ≥ 38 [1]. Exclusion criteria included GMFCS IV–V; cognitive impairment; systemic, cardiovascular, or respiratory disease; orthopaedic surgery within six months; Ashworth score > 2; heterotopic ossification restricting range of motion; spinal or pelvic instability; and unhealed fracture of the anterior or posterior superior iliac spine. A separate recruitment paragraph in [1] adds botulinum toxin injection within six months, uncontrolled epilepsy, and severe musculoskeletal deformity.

6.9.3 Outcome measures and analysis

The assessment framework was multimodal [1]. Functional mobility and balance were measured with five standardized clinical instruments: the 6-Minute Walk Test (6MWT, distance in metres), the 10-Meter Walk Test (10MWT, time in seconds), the Timed Up and Go Test (TUGT, time in seconds), the Berg Balance Scale (BBS, points), and the Gross Motor Function Measure (GMFM, percent). Surface EMG was recorded bilaterally from the gluteus maximus and gluteus medius [1]. These muscles were chosen because hip extensors and abductors are central to controlling the pelvis and trunk in the transverse and frontal planes, which is where the RPT perturbations act.

According to [1], each clinical measure was administered three times at each assessment phase by the same physiotherapist under standardized conditions, and is reported as mean ± SD across trials. Because there were only two participants, no inferential statistics were applied to the clinical measures. Instead, absolute and percentage changes between phases were calculated and interpreted against published minimal detectable change (MDC) and minimal clinically important difference (MCID) values for CP [1,27]. A change was regarded as real only if it exceeded the MDC, and as clinically meaningful only if it exceeded the MCID. For sEMG, where activation of each muscle was sampled over many gait cycles per phase, the Friedman test was used to detect differences between phases, followed by pairwise

Wilcoxon signed-rank tests with Bonferroni adjustment (α = 0.017). Given the sample size, the original authors interpret the EMG results descriptively [1].

The publication does not report the EMG hardware, electrode placement standard, sampling rate, filtering, normalization, the activation variables analysed, or whether EMG was recorded during perturbed treadmill walking or overground [1]. The processing pipeline used with the final configuration is fully specified (Section 6.10.2) [28] and is the natural reference for future reporting.

6.9.4 Training parameters achieved

Table 6.7 reports the training parameters each participant achieved, averaged over the ten sessions.

Table 6.7. Training parameters averaged over ten sessions (published in [1], Table 2).

Participant	Mean treadmill speed (km/h)	Mean active walking time (min)	Mean perturbation magnitude (N)	Mean total perturbations per session	Mean perturbations per direction	Mean BWS (% body weight)
AB-16	0.39	22	68	82	~20	12.5
AR-17	0.42	24	73	93	~23	12.33

The mean perturbation magnitudes, 68 N and 73 N, sit in the lower half of the 65–85 N range. This is consistent with progression starting at the lower bound and reaching higher magnitudes only in later sessions. AR-17, the independently ambulatory participant at GMFCS I, tolerated slightly higher average forces, speeds, and durations than AB-16 (GMFCS III), which is what would be expected from their functional levels. The original report states that all sessions were completed as planned without interruption, with no protocol deviations and no missing measurements at any planned time point [1].

6.9.5 Clinical outcomes

Tables 6.8 and 6.9 reproduce, in reorganized form, the phase-wise clinical results reported in [1]. For timed tests (10MWT, TUGT), a negative change means faster performance, which is an improvement.

Table 6.8. Clinical measures for AR-17 (spastic diplegic CP, GMFCS I) at each phase: mean ± SD, pre-to-post change, and interpretation against MCID (published in [1], Table 3).

Measure	Pre	Mid	Post	Change pre→post (abs., %)	MCID used in [1]	Interpretation in [1]
6MWT (m)	181 ± 74.95	238.5 ± 6.36	185.5 ± 81.31	+4.5 (+2.5%)	6–23 m	Improvement below the lower MCID threshold
10MWT (s)	15.79 ± 3.55	13.09 ± 0.26	15.60 ± 3.82	−0.19 (−1.2%)	Not established for paediatric CP	Clinical significance cannot be determined
TUGT (s)	17.31 ± 2.38	14.61 ± 1.43	16.30 ± 3.81	−1.01 (−5.8%)	Not established for paediatric CP	Clinical significance cannot be determined
BBS (points)	48.5 ± 2.12	50.5 ± 0.70	49.0 ± 2.82	+0.5 (+1.0%)	Not established for paediatric CP	Clinical significance cannot be determined

Measure	Pre	Mid	Post	Change pre→post (abs., %)	MCID used in [1]	Interpretation in [1]
GMFM (%)	86.35 ± 4.03	89.4 ± 0.288	86.55 ± 4.31	+0.2 (+0.2%)	0.1–3.0%	Change within reported MCID range

Table 6.9. Clinical measures for AB-16 (spastic dyskinetic CP, GMFCS III) at each phase: mean ± SD, pre-to-post change, and interpretation against MCID (published in [1], Table 4).

Measure	Pre	Mid	Post	Change pre→post (abs., %)	MCID used in [1]	Interpretation in [1]
6MWT (m)	220 ± 56.56	284.5 ± 34.64	244.5 ± 91.21	+24.5 (+11.1%)	6–23 m	Improvement exceeding upper MCID threshold
10MWT (s)	13.85 ± 0.77	13.2 ± 1.69	12.65 ± 0.91	−1.2 (−8.7%)	Not established for paediatric CP	Clinical significance cannot be determined
TUGT (s)	27.5 ± 10.60	17.5 ± 3.53	25.0 ± 14.14	−2.5 (−9.1%)	Not established for paediatric CP	Clinical significance cannot be determined
BBS (points)	33.5 ± 3.53	38.5 ± 3.53	36.0 ± 7.07	+2.5 (+7.5%)	Not established for paediatric CP	Clinical significance cannot be determined
GMFM (%)	66.38 ± 14.16	78.2 ± 2.54	68.19 ± 16.70	+1.81 (+2.7%)	0.1–3.0%	Change within reported MCID range

Note: MCID values for 6MWT and GMFM-88 in [1] are taken from Storm et al. [27]. The post-intervention GMFM value for AB-16 is given as 68.19 in Table 4 of [1] and as 68.18 in its text.

For AR-17 (spastic diplegic, GMFCS I), every measure was best at mid-point and moved back toward baseline by post-intervention [1]; the 6MWT was 57.5 m above baseline at mid-point but only 4.5 m above at post, below the MCID range used. His high baseline BBS (48.5) and GMFM (86.35%) left little room for improvement on these scales.

AB-16 (spastic dyskinetic, GMFCS III) also peaked at mid-point, but post-intervention values remained better than baseline on all five measures; his 6MWT gain of 24.5 m (11.1%) exceeded the upper end of the 6–23 m MCID range, and the original authors note that he showed the larger gains of the two [1]. Whether more affected children benefit more cannot be tested with two participants.

Several cautions apply. SDs are often large relative to the changes (e.g. AB-16's post TUGT of 25.0 ± 14.14 s); the mid-point peaks could reflect day-to-day fluctuation, fatigue, motivation, or practice as much as training; and MCIDs for 10MWT, TUGT, and BBS were unavailable for paediatric CP in [1]. Tables 6.8 and 6.9 should be read as the published record of a feasibility implementation, not as evidence of efficacy. The original paper itself is explicit on this point [1]. Chapter 10 discusses the program's controlled clinical evidence on gait and balance.

A further reporting issue affects the precision of these tables. Although [1] states that each measure was administered three times per phase, several SDs in its Tables 3 and 4 (for example 2.12, 0.70, 3.53, 7.07

and 14.14) are exactly the SD of two values that differ by a whole number (for example, two values 3 units apart give an SD of 2.12), which suggests that some phases were summarized from two trials.

6.9.6 Electromyographic findings

Bilateral sEMG of gluteus maximus and gluteus medius was recorded at all three phases [1]. Table 6.10 shows the Friedman test results.

Table 6.10. Friedman test results for gluteal muscle activation across the three phases (published in [1], Table 5).

Muscle	χ^2 (AR-17)	p (AR-17)	χ^2 (AB-16)	p (AB-16)
Gluteus maximus, right	22.06	< 0.005	12.18	< 0.005
Gluteus maximus, left	12.87	< 0.005	25.1	< 0.005
Gluteus medius, right	83.07	< 0.005	51.11	< 0.005
Gluteus medius, left	25.28	< 0.005	3.43	> 0.005

Activation differed significantly across phases in both gluteus maximus muscles and the right gluteus medius for both participants. The left gluteus medius gave different results in the two participants: a significant phase effect for AR-17 but not for AB-16 [1]. Pairwise Wilcoxon signed-rank comparisons with Bonferroni correction were also carried out [1], but their results are not tabulated in the publication. The direction of the changes (increase or decrease in activation) is also not reported.

The original authors describe these results as exploratory, intended to demonstrate feasibility and characterize muscle responses rather than establish efficacy [1]. Because the repeated observations in each test are gait cycles from one participant, the tests describe within-person variation and cannot be generalized. The gluteus medius and maximus are the main hip stabilizers in the frontal and transverse planes, and pelvic perturbation with the TPAD increased gluteus medius activity [25]; the RPT data show that changes in these muscles are measurable with this protocol, not that reactive control improved.

The significance threshold is also reported inconsistently: the methods specify a Bonferroni-adjusted α of 0.017 for pairwise comparisons, whereas Table 5 of [1] reports the Friedman results against $p < 0.005$. The Friedman results are reproduced here as published.

6.9.7 Details not reported in the publication

Several details needed to reproduce the published configuration, or to interpret its results fully, are not given in [1]. They are collected here so that they can be supplied in one place. **Values of *k*_T, control-loop rate, host software and host–ODrive interface, and whether load cells stayed installed in clinical sessions; (c) emergency-stop provision and cable behaviour on power loss or communication fault; (d) the magnitude progression rule and the inter-perturbation interval distribution, and whether seeds and event times were logged; (e) EMG hardware, placement, sampling, filtering, normalization, variables and recording condition, and the direction of EMG changes and pairwise Wilcoxon results; (f) which participant wore an AFO; (g) the number of trials per clinical measure per phase; (h) the BWS unit used and how its level was set and monitored; and (i) adverse events or discomfort reports.]**

6.10 Integration, Final Configuration, Clinical Use, and Next Steps

6.10.1 Integration with the treadmill and body-weight support

The RPT is one module of a combined station [1]: the treadmill keeps the child in a fixed location so the cable geometry stays within its workspace, the BWS harness provides fall protection and partial unloading, and the RPT acts through a separate waist belt. The original authors describe the combination as a compact, clinically applicable platform suited to paediatric CP [1]. In the final configuration (Section 6.10.2), a commercially available BWS safety jacket serves both as the fall-protection device and as the mechanical interface between the cables and the subject [28].

The program's own adaptive BWS system, described in Chapter 5, unloads the child through a suspension harness attached to a cable–pulley mechanism driven by a pneumatic cylinder, with pressure feedback and an in-line load cell and displacement sensor. Which BWS unit was used in the published RPT study is not stated in [1] (Section 6.9.7).

The BWS harness acts vertically and the RPT cables horizontally, but a suspension harness can also restrain horizontal trunk movement to some degree. Keeping BWS low, as in the published protocol (about 10–15% of body weight [1]), limits this interaction. In the program's BWS pilot (Chapter 5), the best-tested BWS level varied considerably between children. A future combined protocol could use that individualized-BWS framework to choose the support level and then apply RPT perturbations on top of it. This is a possible direction, not a reported result.

Each diagonal pull of the four-cable configuration has an anteroposterior component, which interacts with the moving treadmill belt, and a mediolateral component, which challenges lateral stability and the hip abductors.

6.10.2 Final configuration: the multi-plane cable-driven RPT

The four-cable device of Sections 6.4–6.9 perturbs only in the transverse plane. The final configuration of the RPT extends it to perturbations in all three anatomical planes without adding actuators, by making the height of the cable anchors adjustable [28]. It is the same device in its final form, not a separate system, and it is the configuration on which the program's subsequent perturbation work is based.

Architecture. Four independently actuated motor–pulley units are mounted at the corners of a rigid rectangular frame, 2.5 m × 1.5 m, surrounding a treadmill [28]. Each unit retains the CubeMars AK80-64 brushless motor of the published RPT but drives a concentric, 3D-printed three-spoke pulley of 0.20 m diameter instead of a rotating arm, so that cable length is changed by winding rather than by arm rotation; the manuscript states that this arrangement can generate cable tensions up to 1400 N [28]. (With the 120 Nm peak torque of Table 6.2 and a 0.10 m pulley radius, the static limit would be about 1200 N; the stated figure should be read as an upper bound of the hardware, far above any force used with people.) The motor–pulley units sit on vertically translatable carriages integrated into the frame columns. Steel cables run from the pulleys to four attachment points on the BWS safety jacket, which are modelled as lying on a circular ring of radius 0.15 m around the pelvis [28]. Because the cables now wind on pulleys, the arm-based inverse kinematics of Section 6.5.2 applies only to the earlier configuration; the wrench mapping of Sections 6.5.4–6.5.5 carries over, extended to three dimensions.

Model. A global frame is placed at the centre of the treadmill, with X anteroposterior, Y mediolateral and Z vertical. The motor anchors are at ($\pm 1.25, \pm 0.75, Z_m$) m, where Z_m is the adjustable carriage height, and the pelvic centre of mass is assumed at $Z_C = 1.0$ m [28]. With $\mathbf{u}_i$ the unit vector from

attachment point **B**_i towards anchor **A**_i and τ_i ≥ 0 the cable tension, the resultant wrench at the pelvis is

$$\mathbf{W} = \begin{bmatrix} \mathbf{F} \\ \mathbf{M} \end{bmatrix} = \sum_{i=1}^{4} \tau_i \begin{bmatrix} \mathbf{u}_i \\ \mathbf{r}_i \times \mathbf{u}_i \end{bmatrix} = \mathbf{G}\,\boldsymbol{\tau}$$

where **r**_i is the position of the attachment point relative to the pelvic centre and **G** is the wrench Jacobian [28].

Operating modes. Carriage height selects the operating mode [28]:

- *Planar (transverse) mode*, *Z*_m = *Z*_C = 1.0 m. All cables lie essentially in the horizontal plane, the rotational rows of the Jacobian vanish, and the robot produces pure translational perturbations in the *X*–*Y* plane. Resultant horizontal forces of about 90–100 N produced centre-of-mass accelerations of 1.4–1.6 m/s² without appreciable pelvic rotation. This mode reproduces the function of the published four-cable RPT.
- *Spatial (frontal and sagittal) mode*, *Z*_m = 0.6 m. Lowering the carriages introduces vertical cable components and non-zero moment arms, so the mechanism becomes a spatial cable-driven parallel robot that can also apply moments about the pelvic *X* and *Y* axes. Sequential actuation of left–right motor pairs produced roll moments up to 72 Nm (angular accelerations of about 18 rad/s²), and front–back actuation produced pitch moments of about 76 Nm (about 19 rad/s²).

Controllability. Proximity to singular configurations was assessed with the condition number κ = cond(**J**^T**J**) of the force Jacobian as a function of motor height [28]. κ peaks sharply at *Z*_m = 1.0 m, where the anchors are coplanar with the pelvic centre and rotational controllability is lost; as the carriages are lowered, κ falls steeply and the full wrench becomes controllable. The authors note that this singularity is the intended planar operating mode rather than an unsafe condition: in that mode the robot is deliberately restricted to translational pulls.

Pretension and dose. A baseline pretension equal to 10% of the maximum perturbation force is maintained in all cables to prevent slack and preserve force closure, and perturbation magnitudes are scaled between 10% and 50% of the subject's body weight [28]. Integration with the BWS system provides fall protection in all trials.

Table 6.11 compares the two configurations.

Table 6.11. The published four-cable configuration and the final multi-plane configuration of the Robotic Perturbation Trainer.

Feature	Four-cable configuration [1]	Final multi-plane configuration [28]
Status	Bench-validated; implemented in 2 adolescents with CP; published	Validated in 3 healthy adults; manuscript
Actuators	4 × CubeMars AK80-64, 64:1	4 × CubeMars AK80-64
Cable drive	Rotating arm, 0.25 m; fixed-length cable	Concentric pulley, 0.20 m diameter; winding cable
Anchor height	Fixed, slightly above hip level	Vertically adjustable carriages (e.g. 1.0 m planar, 0.6 m spatial)
Frame	Not reported	2.5 m × 1.5 m rectangular frame around the treadmill
Subject interface	Circular waist belt, 4 attachment points	Commercial BWS safety jacket; attachment ring radius 0.15 m

Feature	Four-cable configuration [1]	Final multi-plane configuration [28]
Perturbation planes	Transverse	Transverse (planar mode); sagittal and frontal, including vertical components (spatial mode)
Pretension	10 N per cable	10% of maximum perturbation force
Perturbation magnitude	65–85 N	10–50% of body weight (10% in the validation study)
Timing	Random, every 15–18 s, independent of gait phase	Once per gait cycle, cycle-locked (validation study)
Controllability analysis	Bounded minimum-norm tension distribution	Wrench Jacobian; condition number versus anchor height

Validation in healthy adults. The final configuration was evaluated in three healthy male adults (mean age 28.33 ± 8.39 years, body mass 71.33 ± 9.29 kg, height 171.33 ± 1.15 cm), one left-foot dominant and two right-foot dominant, who gave written informed consent [28]. Each walked on the treadmill at a constant 0.5 km/h through four stages: unperturbed baseline walking (Stage 1) and walking with perturbations in the sagittal (Stage 2), frontal (Stage 3) and transverse (Stage 4) planes, delivered once per gait cycle at 10% of body weight. Ground reaction force, sEMG and inertial data were recorded at 2 kHz with a Noraxon Ultium portable laboratory, and sEMG was recorded bilaterally from seven muscles: tibialis anterior, medial gastrocnemius, adductors, biceps femoris, gluteus maximus, gluteus medius and rectus femoris [28]. The manuscript does not state the ethics approval reference for this study.

The sEMG pipeline is fully specified [28]: a third-order Butterworth band-pass filter (20–450 Hz), full-wave rectification, and a third-order 5 Hz low-pass filter to obtain the linear envelope; segmentation into gait cycles from heel strikes detected in the ground reaction force (right-dominant participants) or from the knee flexion angle (left-dominant participant); and time normalization of each cycle to 0–100%. Five time-domain features (mean absolute value, root mean square, integrated EMG, waveform length and Wilson amplitude) were screened with L1-regularized logistic regression, sequential feature selection and leave-one-subject-out cross-validation, which retained mean absolute value, waveform length and Wilson amplitude. Baseline and perturbed stages were compared with the Wilcoxon signed-rank test with Benjamini–Yekutieli correction ($\alpha = 0.05$), and Cliff's δ was used as the effect size. Onset latency, burst duration and time of peak activation were detected with a local adaptive threshold based on the median and median absolute deviation of a preceding window, and mean and peak EMG amplitudes were expressed relative to baseline walking (100%).

The principal findings were as follows [28]:

- Frontal-plane perturbations evoked the largest responses. Gluteus medius and adductor longus activity rose in some cases to more than 400% of baseline, consistent with the role of the hip abductors and adductors in mediolateral stabilization and foot placement.
- A distal-to-proximal pattern emerged. Tibialis anterior responded early and consistently in all three planes, with amplitude increases of more than 250% of baseline in some conditions, and biceps femoris provided strong posterior-chain support, particularly with frontal and sagittal perturbations.
- Responses depended on limb dominance in a muscle- and plane-specific way. With sagittal perturbations, tibialis anterior and gluteus maximus showed *direct* dominance (larger effect sizes on the dominant limb); with frontal perturbations, gluteus medius and biceps femoris showed *inverse* dominance (larger effect sizes on the non-dominant limb); and with transverse perturbations the adductors showed inverse dominance. A third pattern, *side* dominance, in which the same limb responded more in all participants regardless of dominance, was also defined.

- Amplitude responses varied greatly between individuals. In the right-foot-dominant pair, for example, left gluteus medius mean amplitude during frontal perturbations was 2016.93 ± 2770.25% of baseline.

These results come from three healthy young adults in a single session, with cycle-locked perturbations and with gait cycles, not participants, as the units of statistical comparison. The authors themselves list the small sample, the healthy population, the acute protocol and the predictability of cycle-locked perturbations as limitations [28]. The study establishes that the final configuration can deliver plane-specific perturbations to a walking person and that the sEMG framework distinguishes plane-dependent and dominance-dependent responses. Because asymmetry is a defining feature of unilateral and many bilateral presentations of CP, the dominance analysis is directly relevant to the paediatric trial, but its findings in healthy adults cannot be transferred to children with CP.

6.10.3 Perturbation-training trial in children with cerebral palsy

The program has since conducted a perturbation-training trial in 25 children with CP, all different children, recruited at the National Center for Children's Rehabilitation (NCCR) in Astana under NU-IREC Approval No. 1081 (21 May 2025), the same approval that covers the published implementation [1]. The program application specified the Berg Balance Scale (BBS) as the primary outcome and a sample of 25 children to provide 80% power, within an explanatory parallel randomized design comparing RPT-based training with conventional care; the application also hypothesized that perturbation training would change activation in the hip adductors, hamstrings and gastrocnemius in spastic diplegia and in the hip flexors, quadriceps and hamstrings in dyskinetic CP.

No outcome data are reported here. Results are pending; the design and status of the trial are summarized in Chapter 10 (Section 10.5).

The published feasibility study suggests three considerations for analysing and extending this trial: additional assessment points and a follow-up to describe retention, given the mid-point peaks in [1]; balance outcomes with established psychometric properties in CP, given the missing paediatric MCIDs; and device-derived reactive-balance outcomes (for example, trunk displacement or step responses after each perturbation), which require synchronizing the perturbation event log with the data-acquisition platform of Chapter 9. The Balance Recovery Index described next is the program's first attempt at an instrumented balance outcome of this kind.

6.10.4 The Balance Recovery Index (method under development)

To complement clinical balance scales, the program is developing a composite instrumented measure, the Balance Recovery Index (BRI), as the balance counterpart of the Gait Recovery Index (GRI) of Chapter 8. The BRI is defined in a CEMRR hand-calculation document and implemented in the program's analysis scripts [29]. It draws on the same three sensor streams as the GRI: a pair of 16-sensor plantar-pressure insoles, hip and knee encoders, and hip and knee load cells. Each session is summarized over ten consecutive steps or gait cycles. The BRI is a weighted sum of five aspect scores, each scaled so that 1 represents balanced or normal performance:

$$BRI = 0.25 \cdot WDS + 0.20 \cdot PST + 0.25 \cdot SLS + 0.15 \cdot JTB + 0.15 \cdot DRB$$

Table 6.12 defines the components as implemented.

Table 6.12. Components of the Balance Recovery Index as implemented in the program's analysis scripts [29].

Component (weight)	Definition	Data source
Weight distribution symmetry, WDS (0.25)	$1 - \lvert \Sigma P_L - \Sigma P_R \rvert / (\Sigma P_L + \Sigma P_R)$, where ΣP is the summed mean pressure over the 16 sensors of each insole	Insoles
Postural stability, PST (0.20)	Coefficient of variation (CV) of the step-wise mediolateral centre of pressure, averaged over both feet, referenced to the child's own Session 1: $PST = (CV_S1 - CV)/(CV_S1 - 15)$, clipped to [0, 1]; PST = 0 at Session 1 and 1 at the normal CV of 15% (PST = 1 if $CV_S1 \leq 15\%$)	Insoles
Single-limb support, SLS (0.25)	Mean single-limb support as a percentage of stride (left single support = right swing time / left stride time, and vice versa), divided by the normal value of 40% and clipped to [0, 1]	Insoles (heel-strike and toe-off events)
Joint torque balance, JTB (0.15)	Mean over hip and knee of $1 - \lvert \tau_L - \tau_R \rvert / (\lvert \tau_L \rvert + \lvert \tau_R \rvert)$, with τ = (passive-calibration peak force − mean session peak force) × 0.25 m	Load cells
ROM balance, DRB (0.15)	Mean over hip and knee of $1 - \lvert \theta_L - \theta_R \rvert / (\theta_L + \theta_R)$, with θ the mean peak joint angle	Encoders

Four supplementary indices are computed alongside but are not part of the BRI [29]: a plantar pressure index (PPI), the forefoot share (sensors 9–16) of total pressure averaged over both feet, with a reference value of about 0.55; step-width variability, the CV of step width, with a reference of below 12%; mean step width, with a reference range of 0.10–0.12 m; and load acceptance rate, in percent of body weight per second, with a reference range of 4–6 %BW/s. The script reproduces the reference example of the hand-calculation document, which provides a check on the implementation of the formulae.

Several properties of the index follow directly from its construction and should be borne in mind when it is applied. Because PST is self-referenced, it is zero at every child's first session, so the baseline BRI cannot exceed 0.80 and part of any later rise is guaranteed by design; PST measures change within a child, whereas the other four components measure status. WDS, JTB and DRB are symmetry ratios that start close to 1 in many children, which leaves little room for improvement and makes them insensitive to training. The normal values (CV of 15%, single-limb support of 40%) and the weights are taken from the method document and have not been derived from data. The JTB term inherits the load-cell torque framing of the GRI (Chapter 8), whose accuracy depends on calibration and moment-arm estimation, and it presupposes that the joint encoders and load cells are worn during balance sessions. Finally, the BRI has not yet been tested for reliability, validity against the BBS, or responsiveness. It is therefore presented as a method under development.

6.10.5 Planned next-generation paediatric system

A dedicated paediatric Robotic Perturbation System is planned as the next generation of the device. It is to use three pneumatic actuators in a triangular arrangement and to be developed in Laboratory 507, Block S4, Nazarbayev University. As engineering context, the height (160–195 cm) and shoe-size (≥ 38) criteria of the published RPT study [1] effectively restricted it to adolescents, three tension elements are the minimum able to produce a horizontal force in any direction, and pneumatic actuation offers the inherent compliance that motivated its use in the program's BWS system (Chapter 5). None of its features has yet been built or tested.

All copyrights and patents arising from the program are owned by Nazarbayev University Research Administration (NURA). Patent applications for the RPT will be filed, and the RPT, like the BWS system, is to go through medical-device registration and the SK-Pharmacy single-distributor process that governs public procurement in Kazakhstan.

6.11 Limitations

Evidence. The published implementation involved two participants with different CP subtypes and GMFCS levels and no control condition [1]. It shows that the system can be used and the protocol completed as planned, but it cannot separate the effect of perturbations from treadmill walking, BWS, test familiarity, or natural fluctuation, and it gives no basis for claims of efficacy. The original authors call for larger and more diverse cohorts [1]. The final multi-plane configuration has been validated only in three healthy adults in a single session [28], and the results of the 25-child trial are not yet available.

Assessment. EMG in the published study covered only selected hip muscles and may miss responses in the trunk, ankle, or hip adductors; the original authors recommend more muscle groups and biomechanical measures [1]. The healthy-adult study extended recording to seven muscles per limb [28], but neither study reported direct measures of the reactive response (centre-of-mass displacement, margin of stability, stepping), and the clinical scales used are general measures that may be insensitive to reactive-balance change. The BRI is intended to fill part of this gap but is not yet validated.

Device and protocol. In the published study only single-cable pulls in four diagonal directions were used, perturbations were not linked to gait phase, force was controlled through motor current, and delivery to a walking person was not measured directly. Treadmill speeds were very low, and the eligibility criteria restricted use to adolescents of a specific size range. In the final configuration, cycle-locked perturbations make responses repeatable but predictable, and the trade-off between repeatability and unpredictability has to be resolved for each training protocol.

Reporting. Internal inconsistencies in [1] flagged in this chapter (orthosis use, starting magnitude rule, pretension definition, session duration ranges, number of trials per clinical measure, and EMG significance threshold) should be resolved in future reporting.

6.12 Summary

The Robotic Perturbation Trainer complements the assistive devices of Chapters 4 and 5 by deliberately challenging balance. In its published form it is a cable-driven planar parallel manipulator in which four geared brushless DC actuators at the treadmill corners pull a waist belt through pretensioned steel cables. A kinematic model relates arm angles to effective cable lengths, and a bounded minimum-norm tension distribution maps a desired horizontal wrench onto four cable tensions within paediatric safety limits. In the published clinical controller, one cable at a time delivers a 400 ms pulse of fixed magnitude (65–85 N), with pseudorandom direction and randomized timing every 15–18 s, independent of gait phase. Layered hardware, software, mechanical, and clinical safety measures and a body-weight support harness allow this challenge to be applied safely.

Bench validation showed force errors of a few newtons, direction-independent delivery, stable pretension, and sharp pulses (rise time about 100 ms, overshoot below 6%) [1]. A ten-session, five-week implementation in two adolescents with spastic diplegic and spastic dyskinetic CP was completed without protocol deviation; clinical measures generally peaked at mid-point with variable retention, the more affected participant's 6MWT gain exceeded the MCID used, and phase-dependent gluteal activation changes were observed, all interpreted as exploratory [1].

In its final configuration, the RPT mounts its four motor–pulley units on vertically adjustable carriages on a 2.5 m × 1.5 m frame, so that the same hardware delivers horizontal-plane perturbations when the anchors are level with the pelvis and spatial perturbations, including roll and pitch moments, when they are lowered [28]. A study in three healthy adults showed the largest muscle responses to frontal-plane perturbations, an early, distal-to-proximal response led by tibialis anterior, and muscle-specific dominance patterns [28]. A trial in 25 children with CP, with the BBS as primary outcome, has been conducted under NU-IREC Approval No. 1081; its results are pending and will be reported in Chapter 10, where the Balance Recovery Index under development will also be applied. Controlled trials with adequate samples, device-derived reactive-balance outcomes, and follow-up will be needed to establish whether robotic perturbation training improves balance and reduces falls in children with CP.

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Chapter 7. Socially Assistive Robot QTrobot for Bilingual Therapy in Kazakh and Russian

Abstract. Children with cerebral palsy (CP) often have difficulties with communication, cognition and social interaction as well as with movement, but rehabilitation in Kazakhstan has mostly been organised around motor goals. This chapter describes the socially assistive robot (SAR) system that program BR27199433 built on the commercial humanoid QTrobot AI@Edge (LuxAI S.A., Luxembourg) and localised for therapy in Kazakh and Russian. It sets out the rationale for SAR-mediated therapy, drawing on the program's published scoping review. It then describes the robot's hardware, sensing and software architecture and its two-tablet operating configuration; the integration of the ISSAI KazakhTTS speech synthesiser on the robot's onboard computer, the routing of Kazakh and Russian speech, and the rule for addressing each child in his or her own language; the culturally grounded therapy scenarios and session structure; the roles of robot, therapist and caregiver; and co-design with clinicians and educators. It catalogues the measurement instruments used across the program's studies: observational checklists, behavioural mapping, interval-based engagement coding, functional tasks, acoustic and perceptual speech measures, and narrative language measures. It closes with technical and practical lessons and the system's limitations. Clinical outcomes are reported in Chapter 11.

Keywords: socially assistive robot; QTrobot; cerebral palsy; Kazakh language; Russian language; speech synthesis; child–robot interaction; therapy scenario design; behavioural coding; outcome measurement

7.1 Rationale: Why Socially Assistive Robots for Children with Cerebral Palsy

7.1.1 Beyond motor rehabilitation

CP is usually defined by its effects on movement and posture. The everyday experience of affected children is broader than that. Many children with CP also have difficulties with speech and language, attention, working memory, processing speed, and social and emotional functioning, and these difficulties restrict participation in school, play and community life [1, 2]. A large share of children with CP also have dysarthria or other motor speech impairments, which make spoken communication effortful and hard for listeners to understand [1, 3]. Even so, follow-up and rehabilitation programs have tended to concentrate on physical function. Cognitive ability is often assumed rather than evaluated, and children with the most severe motor involvement are the least likely to receive formal cognitive assessment [1]. Evidence syntheses of CP interventions have argued for some time that rehabilitation should address communication, cognition and social development alongside motor goals [2, 4].

This broader agenda places two demands on a rehabilitation centre: communication and cognitive therapy needs many structured, repetitive practice opportunities, which take specialist time, and it must stay engaging over many sessions. Both pressures are acute in Kazakhstan. The pilot study cites national data showing that only a minority of children with registered disabilities are covered by specialised social services, with access further limited outside the major cities [2]. The program therefore examined SARs as a possible complement to the existing workforce.

7.1.2 What socially assistive robots offer

SARs help their users through social interaction rather than physical contact: they speak, gesture, show facial expressions and follow structured routines. The program's scoping review identifies several properties that suit paediatric rehabilitation [1]. A robot can repeat prompts, demonstrations and praise

without the fatigue a therapist accumulates over a clinical day. Its simplified, predictable social behaviour may be less demanding for children who find human interaction overwhelming. Its expressive face and gestures can arouse curiosity and support motivation, which drives adherence to therapy.

The scoping review followed the PRISMA-ScR framework, searched six databases for studies published between 2015 and 2025, and included 20 studies of SAR-based cognitive, speech, communication or engagement-focused rehabilitation for children with CP [1]. Table 7.1 lists the conclusions that shaped the program's system design. Three were especially influential. Humanoid platforms, most often NAO, dominated the evidence base. Most interventions were therapist-led or mixed-mode, and fully autonomous therapy was rare, which suggests that a practical SAR system for CP will for now be a tool the therapist operates. Outcome measures were heterogeneous, samples small and interventions short, so cross-study synthesis was difficult [1]. Trials and reviews cited in the program's papers point the same way. Robots can elicit communication attempts, visual regard and affect from young children with complex CP [5]. Robot-mediated sessions can support speech-language therapy [6, 7]. A meta-analysis of SARs for children with CP reached cautious but encouraging conclusions [8].

Table 7.1. Findings of the program's scoping review that informed the QTrobot system design (published; *J NeuroEng Rehabil*, doi:10.1186/s12984-025-01852-0) [1].

Review finding	Design implication adopted by the program
Humanoid robots, mainly NAO, dominate; animaloid and non-anthropomorphic robots are rarer	Use a child-sized humanoid with an expressive face; extend platform diversity beyond NAO
Most interventions are therapist-led (n = 10) or mixed-mode (n = 9); full autonomy is rare	Semi-autonomous scripted operation under continuous therapist control
Typical sessions last 20–40 min, 1–3 times per week, with heterogeneous protocols	Short, fixed-structure sessions adapted to the child's tolerance; a standardised module sequence
Outcome measures are heterogeneous; engagement is captured by coding, logs, ratings or usability scales	Develop explicit, documented coding instruments and report reliability
Children with severe CP (GMFCS/MACS IV–V) and multilingual children are under-represented; most speech-language work is single-language	Deliver content in Kazakh and Russian; build culturally specific scenarios
Speech and language outcomes rely on standardised tests or ASR error rates	Add instrumental acoustic and blinded perceptual speech measures (Section 7.7.6)

7.1.3 Gaps addressed by the program

The review also identified gaps that the program set out to fill. Nearly all speech-language SAR interventions were single-language, with little work on cross-lingual adaptation or multilingual deployment [1]. Commercial SAR platforms are designed mainly for English and major European languages. Kazakh is agglutinative and has few speech-technology resources; a dedicated Kazakh child-speech corpus appeared only recently [9, 10]. Social robots have been proposed as "cultural brokers" between children of different linguistic backgrounds [11], but Central Asia was absent from the SAR literature the pilot study surveyed [2]. Finally, speech outcomes in this field had never been measured with instrumental acoustic analysis or blinded listener judgements [3]. The localised QTrobot system and its measurement framework respond to these gaps.

7.2 The Program's QTrobot Studies

The system was developed and refined over several studies at the National Center for Children's Rehabilitation (NCCR), Astana, which receives roughly 300 children each month. In total, 170 different children took part in the program's social-robot studies. The studies differ in design, sample and maturity, and Chapter 11 reports their results. Table 7.2 lists them with their publication status, because the system descriptions in this chapter draw on all of them. In this chapter, "pilot study" refers to the seven-session feasibility trial and "longitudinal study" to the ten-session controlled study.

Table 7.2. QTrobot studies conducted under program BR27199433 and their publication status at the time of writing.

Study (short name used in this chapter)	Design	Publication status
Scoping review [1]	PRISMA-ScR review of 20 studies	Published, *J NeuroEng Rehabil* 2026;23:34, doi:10.1186/s12984-025-01852-0
Pilot study [2]	Single-group pre–post feasibility trial, seven scripted sessions	Published (early access), *IEEE Trans Med Robot Bionics*, doi:10.1109/TMRB.2026.3733187
Longitudinal study [12]	Ten-session protocol with parallel standard-care control group	Under review, *International Journal of Social Robotics* (SORO-D-26-00192)
Microgenetic study [13]	Qualitative microgenetic case series, interval coding	Under review, *IEEE Trans Cogn Dev Syst*
Speech study [3]	Single-group feasibility study of acoustic and perceptual outcomes	In preparation
Narrative study [10]	Single-group pre–post study of narrative language	In preparation
Engagement comparison [14]	Non-equivalent two-group comparison, robot vs tablet	In preparation
Pilot randomised trial (2025)	Two-arm pilot, 10 intervention vs 10 conventional-therapy controls	Results report in preparation (Chapter 11, Section 11.8.5)

The program's randomised trial of the QTrobot intervention is registered with the Australian New Zealand Clinical Trials Registry as ACTRN12625001214426. The registration was retrospective: the first child was enrolled before the trial was registered. The speech and narrative studies state that they were conducted within the larger project covered by this registration, but that they were not themselves randomised and that their outcomes were exploratory additions [3, 10]. All the studies were conducted under approval No. 1081 (21 May 2025) of the Institutional Research Ethics Committee (IREC) of Nazarbayev University.

7.3 The QTrobot Platform

7.3.1 Hardware and sensing

QTrobot is a commercial, child-sized humanoid robot made by LuxAI S.A. (Luxembourg) for educational and therapeutic work with children [15]. The program used the AI@Edge version, which pairs the robot's embedded Raspberry Pi board with an NVIDIA Jetson AGX Orin computer inside the robot [3, 15]. Table 7.3 consolidates the hardware descriptions given in the program's manuscripts and the manufacturer's specification. The robot has a liquid-crystal display for a face, which shows animated

expressions such as happiness, sadness, surprise and a neutral face. It also has two articulated arms and a movable head, which together give twelve degrees of freedom in the upper body for arm and head gestures [12, 13]. For perception, it carries a three-dimensional Intel RealSense depth camera for vision and gesture recognition and an array of four digital microphones for far-field voice capture. Onboard loudspeakers produce synthesised speech [12]. The pilot study notes that the camera and microphones allow the robot to sense where the child is, how the child moves and what the child says [2].

Table 7.3. QTrobot hardware characteristics as reported in the program's manuscripts.

Characteristic	Description	Source
Manufacturer	LuxAI S.A., Luxembourg	[3, 12, 13]
Model designation	QTrobot AI@Edge (RD-V3 AI@Edge configuration)	[3, 15]
Height and mass	Approximately 63 cm and approximately 5 kg	[12]
Face	Digital LCD screen with animated emotional expressions	[12, 13]
Actuation	Two articulated arms and a movable head; 12 degrees of freedom in the upper body	[12, 13]
Vision	3D Intel RealSense depth camera (perception and gesture recognition)	[12, 15]
Audio input	Four digital microphones, far-field capture	[12, 15]
Audio output	Onboard speakers driven by the Raspberry Pi board; built-in Acapela text-to-speech in multiple languages	[3, 12, 15]
Computing	Raspberry Pi 4B board for motors, display, sensors and audio, connected via ROS to an onboard NVIDIA Jetson AGX Orin computer running session-management software and the Kazakh speech-synthesis container	[12, 15]

The physical design matters clinically as well as technically. Because QTrobot is small and has a simplified, cartoon-like face, its social signals are easier to read than a human's. Its behaviour is predictable from one session to the next. The program's papers argue that this predictability lowers the social-processing load for children with developmental difficulties [2, 12]. Earlier work with the same platform, cited by the longitudinal study, found that children with autism attended to QTrobot for longer than to a human partner and showed fewer stereotyped behaviours during robot interaction [16]. The program was among the first to take this platform beyond the autism literature into CP rehabilitation [12].

7.3.2 Software stack and control architecture

As used in the program, the robot's software has three layers. The lowest is the embedded controller (the Raspberry Pi board), which drives the motors, the face display, the sensors and the loudspeakers. It communicates through the Robot Operating System (ROS) with the onboard Linux computer (the Jetson AGX Orin of the AI@Edge version), which runs the session-management software and the robot's speech service [12, 15]. This architecture supports two modes of operation: autonomous execution of pre-programmed behaviours, and teleoperation, in which a supervising therapist triggers specific behaviours in real time from a dedicated interface [12]. The program added one component to this layer, a speech router for Kazakh, described in Section 7.4.2.

The top layer is the content layer, where therapy scripts are written. The research team at the Center of Excellence in Medical Robotics and Research (CEMRR) wrote all scripts in LuxAI's graphical (visual) programming tool. The tool lets authors sequence speech, gestures and tablet activities without writing low-level code [2]. Each script combines robot utterances, synchronised gestures (for example clapping, waving, nodding, other hand and head movements, and blowing kisses), facial-expression changes, and the images and response options shown on the child's tablet [13]. Pre-recorded audio was not used: the robot generated all speech with text-to-speech (TTS) at run time [13]. Section 7.4 describes the language-specific speech pathway. Because the Kazakh voice runs on the robot itself (Section 7.4.2), a session does not depend on a network connection to an external speech server.

7.3.3 The two-tablet configuration and the division of labour

The robot was always used with two tablets, a feature of the LuxAI educational configuration [2]. The *learner's tablet* sat directly in front of the child. It showed story pictures, emotion cards, sorting tasks and answer options, and the child responded by touching it. The *educator's tablet* was held by the therapist and used to control the session: to select the script for the day, start and advance activities, repeat a step, or slow the pace when a child needed more time [2]. With this arrangement the therapist could manage the session without leaving the child's side or interrupting the child's attention.

The microgenetic study describes the division of responsibilities most precisely. It splits each task cycle into stimulus, response and feedback, each handled by a different agent [13]. The robot provided the social layer: greetings and farewells, narration of the module theme, and every task question spoken aloud in the child's language. The tablet provided the task layer: it showed the pictures and options the question referred to and recorded touches, but it never spoke, gestured or gave feedback. A tablet touch was scored automatically. A spoken or gestured answer was judged by the therapist, who pressed a correct or incorrect control on the control tablet; automatic speech recognition was not used because the children's speech varied so much [13]. The robot always delivered the feedback, and the therapist, not the robot, re-prompted a child who did not respond or responded ambiguously [13].

This book calls the operating mode *semi-autonomous*, as most of the program's papers do [3, 10, 13]. The robot generated all of its behaviour from pre-scripted repertoires, and the team member at the control tablet only launched and paced modules and judged non-tablet responses, without changing content [13]. The engagement-comparison manuscript describes the same arrangement as "Wizard-of-Oz", because in its sessions one therapist supported the child while a second operated the robot from the control tablet [14]. The Wizard-of-Oz label usually implies that a hidden human makes the robot's moment-to-moment conversational decisions [17]. Here the operator was visible, paced a fixed script and judged responses within it, so "semi-autonomous" describes the mode more accurately. Whether the child-facing therapist and the operator were the same person or two people varied with staffing (Section 7.3.4).

7.3.4 Room set-up and recording

All sessions took place in a dedicated room at the centre, arranged to feel welcoming and to reduce the clinical atmosphere that can make children anxious about evaluation [13]. The robot stood on a table facing the seated child, with the learner's tablet in front of the child. The therapist sat beside the child with the control tablet, and a high-definition camera recorded the scene [13]. Sessions were usually scheduled in the morning (08:00–12:00), around each child's other rehabilitation appointments [13].

Robot sessions were not delivered by one person. Normally four to five adults from the program's research team conducted the sessions; the team included educators and therapists, who handled the child-facing role, robot operation and recording. One or two NCCR clinicians were present during the trials. Parents were involved throughout: they gave consent, could stay in the room to keep the child comfortable [12], and in the early sessions often helped the child with the tablet [2]. Every child was addressed in his or her own language, Kazakh or Russian (Section 7.4.3). The video recordings, stored securely with access limited to the research team, were the main data source for most behavioural instruments [2, 12]. Audio for the speech and narrative assessments was recorded separately (Sections 7.7.6 and 7.7.7).

7.4 Localisation for Kazakh and Russian

7.4.1 The linguistic context

Kazakh and Russian are both used as clinical languages at NCCR [12]. Children arrive with different home languages, and the clinical team works in both. Robots that speak only one language, or that switch unpredictably between languages, would not fit this setting. In the pilot study most children were primarily Kazakh-speaking and a minority primarily Russian-speaking [2]. In the longitudinal study, three-quarters of the intervention group received the intervention in Kazakh [12]. The speech and narrative studies included both Kazakh- and Russian-speaking children [3, 10]. Every script and module therefore had to work equally well in both languages, and the robot needed a natural-sounding voice in each.

7.4.2 Speech synthesis and language routing

Each language had its own speech pathway. Russian used the robot's built-in Acapela voice [3, 12]. QTrobot had no adequate built-in Kazakh voice [10], so the program integrated KazakhTTS, the open-source Kazakh text-to-speech system developed at the Institute of Smart Systems and Artificial Intelligence (ISSAI) of Nazarbayev University [3, 12]. KazakhTTS was built with the ESPnet speech-processing toolkit and trained on an open corpus of professionally recorded Kazakh speech, first released in 2021 and later extended with more speakers, data and topics as KazakhTTS2 [39, 40]. The program's engineers packaged the ISSAI model in a Docker container and installed it on the robot's Jetson AGX Orin computer, so Kazakh speech is synthesised on the robot itself; the audio is played through the Raspberry Pi board's loudspeakers, the same output path used by the Acapela voice. The narrative manuscript's description of the Kazakh voice as a custom system developed by the research team [10] refers to this local deployment and integration of the ISSAI model.

The integration is registered as Republic of Kazakhstan copyright certificate No. 74308, *Kazakh speech-synthesis routing system for QTrobot*. Its core is a router that takes over QTrobot's speech service. Every utterance that a script sends to the speech service passes through the router. Kazakh text is sent to the ISSAI voice in the Docker container, and all other text is passed to the built-in Acapela voice. Because the router sits behind the robot's standard speech interface, scripts written in LuxAI's authoring tool reach the Kazakh voice through the same speech calls as the Russian one. The Kazakh and Russian

versions of a module can therefore share their structure, gestures, facial expressions and tablet events, while the wording of each version is written separately (Section 7.4.4). Synthesis latency and the naturalness of the Kazakh voice have not been formally measured in the program (Section 7.9).

Using synthesised speech had a consequence that affected dialogue design. The microgenetic study notes that the robot's voice pitch was not varied to convey emotion. Affective tone therefore had to come from the screen face, gestures and wording [13]. In practice, script authors could not count on prosody to signal praise, surprise or sympathy. Each emotionally loaded line had to be paired with a matching facial expression and gesture. This multimodal redundancy was written into the scripts from the start.

7.4.3 Language assignment rule

The program used a simple, consistent rule for language: children were addressed in their own language. Each child's language of delivery was set by the family's or the child's stated preference, Kazakh or Russian, and every session for that child was conducted entirely in that one language [10, 12]. The robot greeted the child by name in the preferred language at the start of each session [12]. Assessment tasks were also given in that language [3, 10]. The program did not mix languages within a session. This rule kept each child's experience consistent and made speech and narrative samples interpretable. Its cost is that the system was not used to support children's use of two languages within a session, an application suggested by the "cultural broker" literature [11].

The same rule applied to the eight children whose 65 robot sessions were analysed in both the microgenetic and the engagement-comparison studies: the robot spoke Kazakh or Russian according to each child's preferred language [13]. The engagement-comparison manuscript's statement that its robot sessions were conducted in Kazakh [14] should be read in that light.

7.4.4 Parallel authoring rather than translation

The scripts were not translated word for word. The narrative study reports that the Kazakh and Russian versions of each module had the same narrative content and meaning, but each was written separately in its own language to keep the phrasing natural and age-appropriate [10]. This matters because Kazakh is agglutinative and Russian is fusional. A literal translation can produce sentences that are grammatical but sound unnatural. Sentence length in words is also not comparable across the two languages, which has implications for measurement (Section 7.7.7). The narrative study acknowledges that the two language versions were not formally checked for equal length and linguistic complexity [10], so future work should include such a check.

7.4.5 Dialogue design without speech recognition

The children's speech ranged from sounds and single words to fluent sentences, and many had dysarthria [3, 10, 13]. The program therefore did not make the dialogue depend on automatic speech recognition (ASR). Dialogue was scripted and branched only on whether the response, scored by the tablet or by the therapist, was correct [13]. Feedback phrases were written in advance for each module and were mostly positive. Correct answers drew praise, often with clapping or a blown kiss. Incorrect answers drew a short, reassuring acknowledgement, usually followed by a brief explanation of the correct answer [13]. The robot also performed the routine social parts of the session: a greeting, a song with gestures to imitate, a culturally appropriate farewell and a clear closing cue [12]. These routines gave each session a predictable frame. The microgenetic study recorded children returning the robot's greetings and imitating its gestures, and one child performed one of the robot's routines before the robot did, apparently remembering it from an earlier session [13].

Avoiding ASR made the system more robust and inclusive. A child who could answer only by touch, gesture or gaze could still take part fully. It also kept a human therapist involved at every decision point that required interpreting speech. The scoping review notes that ASR adapted to dysarthric speech has been demonstrated technically but not yet integrated into clinical SAR trials [1]. Kazakh child-speech resources for building such ASR are only beginning to appear [9].

7.5 Therapy Content and Scenario Design

7.5.1 Design principles

The scripts and modules followed four principles stated in the program's manuscripts. *Cultural grounding*: stories and situations came from Kazakh and Central Asian folklore and everyday life in Kazakhstan [2, 12]. *Multi-domain targeting*: each script addressed communication, cognition and/or social-emotional development through storytelling, emotion recognition, turn-taking, sorting, role-play, sequencing, memory and moral reasoning [2, 12]. *Comparability*: in the pilot study the scripts made broadly similar demands, without a planned increase in difficulty, and the scripts at the two assessment points shared a task structure [2]. *Standardisation*: every child received the same scripts in the same order, so that sessions could be compared across children and trajectories analysed [2, 12].

The longitudinal study organised module development around four "integration dimensions": linguistic patterns, communication modalities, cultural scenarios and emotional climate. It also required each module to include at least one song with movement, a narrative or storytelling component, and one or more structured activities aimed at the session's primary behavioural domains [12].

7.5.2 The seven-script pilot set

The pilot study used seven scripts, delivered on seven consecutive days [2]. Table 7.4 lists them. Their content was validated by expert review from specialists in rehabilitation and special education [2]. The set mixes folk tales (*The Wise Donkey of Bukhara*, *The Greedy Fox and the Magic Well*, *Aldar Köse and the Rich Man's Coat*) with role-play of everyday situations (the market, the hospital, the kitchen, the yurt). One script explicitly includes greeting in Kazakh as part of a hospitality scenario.

Table 7.4. Therapeutic scripts of the seven-session pilot study (published) [2].

Session	Script	Principal activities
1	The Wise Donkey of Bukhara — story and emotion matching	Listen to the story; match emotion cards to story events
2	Going to the Market — role-play and coin sorting	Pretend shopping with the robot; match coins to prices
3	The Greedy Fox and the Magic Well — story and cause–effect	Identify the fox's actions and link them to outcomes
4	Going to the Hospital — role-play and emotion cards	Name body parts and feelings; act out a doctor visit
5	In the Kitchen — cooking role-play and food sorting	Sequence cooking steps; sort foods into groups
6	Aldar Köse and the Rich Man's Coat — story and sorting	Sort characters by need; explain choices
7	Visiting the Yurt — role-play and hospitality sorting	Greet in Kazakh; sort items for guests and others

7.5.3 The ten-module protocol

For the longitudinal, microgenetic, speech and narrative studies, the pilot set was extended to ten modules [12, 13]. Three new modules were added: *The Swan Mother* (protector matching and role-play built on a Kazakh symbol of maternal care), *Nauryz* (counting ingredients, sequencing and a memory task set during the spring festival, including preparation of the festive dish köje), and *The Brave Batyr and the Lost Horse* (a map-navigation game and retelling of a heroic legend) [12, 13]. In the longitudinal study's account, modules 1, 3, 6, 8 and 10 were built on folklore narratives, and modules 4, 5, 7 and 9 on everyday functional and social contexts [12]. Table 7.5 gives the protocol as specified in the longitudinal study, including the behavioural domains each module mainly targeted.

Table 7.5. The ten-module QTrobot protocol (under review) [12]; module order as in the longitudinal and microgenetic studies [13].

Module	Theme	Primary target domains	Key activities
1	The Wise Donkey of Bukhara	Initiating joint attention, communication, familiarisation	Story comprehension, emotion matching, greeting routine
2	Going to the Market	Initiating and responding to behavioural requests, communication, numeracy	Shopping role-play, coin sorting, turn-taking dialogue
3	The Greedy Fox and the Magic Well	Cognition, moral reasoning	Cause–effect game, prediction, emotion-sequence matching
4	Going to the Doctor	Activities of daily living, communication, emotion recognition	Naming body parts, emotion-face game, turn-taking, role-play
5	In the Kitchen	Activities of daily living, cognition, vocabulary	Food classification, sequencing, expressing preferences
6	Aldar Köse and the Rich Man's Coat	Initiating and responding to social interaction, communication, moral reasoning	Sorting game, cause–effect, moral discussion
7	Visiting the Yurt	Responding to social interaction, communication, social imitation, daily living	Hospitality sorting, role-play as host, greetings
8	The Swan Mother	Responding to joint attention and social interaction, imitation	Protector matching, role-play, prediction tasks
9	Nauryz Celebration	Cognition, communication, turn-taking, daily living	Ingredient counting, sequencing, memory recall
10	The Brave Batyr and the Lost Horse	Initiating social interaction and behavioural requests, communication, narrative recall	Map navigation, story retelling, farewell celebration

The narrative study gives the same ten modules in a different order. *In the Kitchen* is second, *The Greedy Fox* is last, and *The Brave Batyr* is a pure story-retelling module in which the child is asked to tell the story back to the robot [10]. The microgenetic manuscript, which reports the order actually followed by its eight children, agrees with the longitudinal study [13], and the speech manuscript does not list the order [3]. The narrative manuscript also lists the key comprehension questions for each module. Examples include "Who needs the coat? Why does the shepherd need a coat?" for the Aldar Köse module

and "What do you think we should learn from the fox?" for the Greedy Fox module [10]. These questions show how each story was linked to inferential and moral reasoning prompts.

7.5.4 Session structure and dosage

Every session had three phases [12]. In the *opening phase* (about two to three minutes), the robot greeted the child by name, sang a thematic song with gestures to copy, and introduced the day's story or activity. The longitudinal study argues that this predictable warm-up is especially important for children with CP, who may need extra time to settle into new activities [12]. The *main activity phase* took up most of the session: the child worked through the module with the robot, and the therapist added prompts and encouragement without taking over the robot's instructional role. In the *closing phase* (about one to two minutes), the robot praised the child's participation, said a culturally appropriate goodbye and signalled the end of the session [12].

In the pilot study, the therapist gave each child an introduction before the first session. It explained that they would listen, respond and do simple tasks with the robot, encouraged the child to look at the robot and answer in words or gestures, and stressed that there were no right or wrong answers [2]. In the microgenetic cohort, the first session was used only for familiarisation. Children met the robot and the session format, and no data were collected [13].

Session length was adjusted to the child's tolerance rather than fixed. Table 7.6 gives the durations reported across the studies. Sessions were consistently much shorter than the 20–40 minutes typical of the studies in the scoping review [1]. This reflects the attentional and fatigue profile of the children. The engagement-comparison draft notes that sessions were designed to last no more than about ten minutes so that fatigue would not cause disengagement [14].

Table 7.6. Session dosage reported across the program's QTrobot studies.

Study (status)	Sessions planned	Reported session duration	Schedule
Pilot (published) [2]	7	Approximately 10–15 min	Seven consecutive days
Longitudinal (under review) [12]	10	Approximately 6 to 15 min or more, depending on the child	Within regular attendance over a ten-week study period (Sept–Nov 2025)
Microgenetic (under review) [13]	10 (first for familiarisation)	Mean 6.1–7.2 min per child; individual sessions 4–11 min	Familiarisation 24 Sept 2025; then near-daily within 11 working days (25 Sept–9 Oct 2025)
Speech and narrative (in preparation) [3, 10]	10	6–12 min	Two weeks
Engagement comparison (in preparation) [14]	Up to 10	Target ≤ about 10 min	Not specified
Pilot randomised trial, 2025 (results pending)	10	Not yet reported	Three weeks

7.5.5 Roles of robot, therapist, educator and caregiver

The system was designed to support, not replace, the therapist, as the scoping review recommends [1, 2]. The *robot* was the social agent and narrator; the narrative study argues that its consistent model of storytelling and questioning makes a retelling task comparable across children [10]. The *therapist* was the clinical decision-maker, who chose and paced the module, judged non-tablet responses, re-prompted,

helped physically with the tablet, and decided when to slow down or stop [13, 14]. In the longitudinal study the therapist also completed the observational checklist immediately after each session [12]. *Educators* in the research team contributed to script content and to documenting procedures, and one or two *NCCR clinicians* attended the sessions. The *caregiver* could stay. The pilot study observed parents giving substantial help early on and stepping back as children became more independent [2], in line with a systematic review of parental involvement in robot-mediated interventions [18]. It recommends an explicit protocol for gradually reducing parents' physical help while keeping them emotionally available [2].

The therapy content is registered as intellectual property: RK copyright certificate No. 74309 covers the Kazakh- and Russian-language scripts for robot-assisted therapy for children with CP. Like the other copyrights arising from program BR27199433, it is owned by Nazarbayev University Research Administration (NURA). The QTrobot therapy content will not be commercialised.

7.6 Co-Design with Clinicians and Educators

The scripts were developed with the people who would deliver and interpret the sessions. For the pilot study, the research team wrote the scripts with guidance from the centre's experts, and specialists in rehabilitation and special education reviewed them for content validity [2]. For the ten-module protocol, specialists in special education and child development wrote the greetings, instructions, songs, stories and reinforcement phrases together with the research team, and the study's first author and the supervising therapist developed the modules [12]. Measurement tools were co-designed in the same way. A specialist in special education and early childhood development chose the functional tasks used in the longitudinal study [12]. A psychologist and a specialist in inclusive education wrote the engagement codebook [14]. The microgenetic study's coding protocol was piloted on three sessions and revised before full data collection [13].

The NCCR setting supported this collaborative approach. NCCR's multidisciplinary team includes paediatric neurologists, physiotherapists, occupational therapists, speech therapists, psychologists and special-needs teachers, and the centre combines medical, psychological, pedagogical and social approaches to rehabilitation [2]. The SAR sessions were added to each child's individually prescribed program without replacing any part of it [13]. Because of this, clinical staff saw the robot as one tool within familiar routines rather than as a separate research activity. In the pilot study, therapists were able to run the educator interface after minimal training [2].

The program planned this work as a participatory design process with three elements: engaging stakeholders (families, therapists and educators) early in the design, developing the robot interventions iteratively, and refining them through usability testing and clinical sessions [41]. Between January and August 2025, the team gathered information on needs and preferences from 35 families, 7 therapists and 3 teachers; NCCR therapists worked with educators from Nazarbayev University to document the procedures used in the sessions [41]. An initial library of lessons was designed between January and March 2025 around two areas, cognitive and communication skills (storytelling, guided question-and-answer, memory games) and social skills (turn-taking, emotion recognition, cooperative play), and a first set of five Kazakh and Russian scripts with greetings, turn-taking exercises, imitation games and guided tasks was implemented on the robot between March and June 2025 [41].

Usability testing with children, families and therapists followed between July and September 2025. It examined how easily the robot could be set up, how stably the scripts ran and whether the clinical rooms suited the sessions, and feedback was collected through observation notes, parental questionnaires and therapist debriefings [41]. The refinements made in September–October 2025 included simplified

instructions and additional visual cues for children with lower verbal capacity, breaks and transitional activities to reduce fatigue, more varied activities to sustain attention, and feedback wording in which the robot never calls a child's answer "wrong" but encourages another try; the session schedule was also aligned with the therapists' existing routines [41]. These changes are consistent with the reassuring corrective phrases recorded in the microgenetic study (Section 7.4.5) [13] and with the lessons from the pilot study described in Section 7.8.

7.7 Measurement Instruments

The program used a family of instruments designed to capture different aspects of what happens during and after robot-mediated sessions. This section describes the instruments. Their results are reported in Chapter 11. Table 7.7 gives an overview.

Table 7.7. Measurement instruments used across the program's QTrobot studies.

Instrument	Construct	Unit and scale	Rater and timing	Study (status)
Structured observational checklist, pilot version	Communication, cognition, social skills	Item ratings 0–3 (not observed, rare, sometimes, often)	Synchronous observer plus asynchronous psychologist	Pilot (published) [2]
Behavioural mapping (narrative)	Individual behavioural trajectory	Qualitative description per session	Research observer; centre psychologist	Pilot (published) [2]
Adapted SRS-2 observational checklist, 11 domains	Social skills sub-domains, communication, cognition, activities of daily living	Item frequency 0–3; domain sums	Therapist, immediately after each session	Longitudinal (under review) [12]
Structured functional task assessment	Comprehension, accuracy, verbal communication, prompt dependency	Three tasks × four domains, 0–2 each (max 24)	Pre and post, both groups	Longitudinal (under review) [12]
Interval-based behavioural mapping protocol with WISC-V-informed profiling	Engagement; domain-relevant cognitive behaviour	10-s intervals; engagement 1–5; domain ratings 1–5	Retrospective video coding	Microgenetic (under review) [13]
Segment-level engagement codebook	Engagement (initiative × substantiveness)	10-s segments; 1–5 with decision algorithm	Retrospective video coding	Engagement comparison (in preparation) [14]
Acoustic word analysis	Duration, F0, F1, F2, intensity	Single-word tokens	Annotator plus automated extraction	Speech (in preparation) [3]
Blinded listener identification	Word intelligibility	Closed-set identification, correct/incorrect	Five blinded native listeners	Speech (in preparation) [3]
Picture-narration analysis	Narrative micro- and macrostructure	Utterance and word counts; 7 story-grammar elements	Transcriber plus second rater	Narrative (in preparation) [10]

Instrument	Construct	Unit and scale	Rater and timing	Study (status)
WISC-V, formally administered (Kazakhstan adaptation)	Full-Scale IQ and index scores	Standard scores	Trained assessor, baseline and post-intervention	Pilot randomised trial, 2025 (results pending) [41]

7.7.1 Structured observational checklists derived from the SRS-2

The pilot study's structured observational checklist was the program's first behavioural instrument [2]. Its items were adapted from the Social Responsiveness Scale, Second Edition (SRS-2) [19] and covered three domains: communication (verbal and non-verbal cues), cognition (attention, memory, problem-solving) and social skills (joint play, imitation, emotional expression, engagement). Six behavioural outcomes were defined operationally. *Eye contact* was gaze directed at the robot or instructor. *Motor response* was any purposeful movement in response to a robot prompt, such as pointing, reaching, using the tablet or clapping. *Vocal response* was any audible verbalisation in reply, including unclear attempts at speech. *Emotional expression* covered social smiling and imitation of the robot's emotions. *Attention* was sustained orientation to the robot or tablet without redirection. *Initiative and engagement* covered child-initiated acts such as spontaneous greeting or unprompted speech [2]. Behaviours were rated as rare, sometimes or often, and the item-level analysis added a "not observed" level to give a 0–3 code [2]. Engagement was treated as multidimensional, covering both the quality and the quantity of participation [2, 20].

The longitudinal study developed this into an eleven-domain instrument [12]. Items again came from the SRS-2, originally a parent- and teacher-report measure normed on autistic populations, and were recast as observational frequency codes (0 = never, 1 = rare, 2 = sometimes, 3 = often). The team added items on cognitive engagement, functional task participation and activities of daily living (ADL) to reflect NCCR's holistic rehabilitation goals [12]. Table 7.8 gives the domain structure. The facilitating therapist completed the checklist immediately after each session to reduce recall bias [12]. The authors state that the adapted instrument was not validated as a standalone psychometric tool, with no evidence of construct, criterion or convergent validity [12].

The paper form of the checklist shows how the codes are generated. Each item is first marked as observed or not observed (Yes/No), and an observed behaviour is then marked as occurring rarely, sometimes or often, with a free-text comment field; "No" corresponds to code 0 and the three frequency boxes to codes 1–3. The social-skills section is organised under the seven sub-domain headings of Table 7.8 and is followed by an "Interaction and ADL" section and separate Communication and Cognition sections. The items are concrete and anchored to the robot setting: under initiating joint attention, for example, "makes eye contact with SAR and instructor", "alternates gaze between SAR and instructor's eyes" and "points with extended index finger to SAR/picture/poster before tester points"; under initiating behavioural requests, "extends arm toward out-of-reach SAR" and "combines eye contact with a reaching gesture"; under social imitation, "imitates or repeats gestures, emotions, actions or behaviours demonstrated by the SAR". The ADL section includes self-control during structured play, appropriate posture for interaction, sitting or standing without support and use of assistive devices, and the Cognition section includes sustained attention, memory for the previous task, cause and effect, and retelling a story or answering questions.

Two properties of the form matter for interpretation. First, some items in the Communication domain describe difficulties rather than abilities ("unclear speech", "demonstrates delayed speech or response", "does not attempt to speak or engage verbally"), and one item under responding to social interaction records looking at the instructor *instead of* the robot. The manuscripts do not report reverse-scoring of these items, so a higher domain sum does not uniformly mean better function. Second, some items depend on the robot's state (for example, eye contact "when the SAR is inactive" under initiating behavioural requests), so their frequency can change as a child learns the session routine, independently of any change in the underlying skill. Both points bear on the declining sub-domains reported in Chapter 11 (Section 11.3.6).

Table 7.8. Domain structure of the adapted observational checklist used in the longitudinal study (under review) [12].

Domain	Items	Score range
Initiating joint attention (IJA)	8	0–24
Responding to joint attention (RJA)	2	0–6
Initiating behavioural requests (IBR)	5	0–15
Responding to behavioural requests (RBR)	2	0–6
Initiating social interaction (ISI)	3	0–9
Responding to social interaction (RSI)	6	0–18
Social imitation	2	0–6
Social skills total	28	0–84
Activities of daily living (ADL)	12	0–36
Communication	17	0–51
Cognition	10	0–30

Because this instrument was scored at every session, the longitudinal study could model trajectories over sessions rather than only compare pre and post. Its primary model was a random-intercept linear mixed-effects model, fitted separately for each domain, in which *i* indexes the child and *j* the session [12, 21]:

$$y_{ij} = \beta_0 + \beta_1 \,\mathrm{Session}_{ij} + u_{0i} + \varepsilon_{ij}$$

Here β_1 is the mean change per session, u_{0i} is a child-specific random intercept for baseline differences, and ε_{ij} is residual error. To check whether change was non-linear, a quadratic term in session number was added, and piecewise models with a breakpoint at Session 5 were also fitted [12]. Chapter 11 reports the estimates. The point to note here is that the instrument and the analysis were designed together: frequent, short sessions produced dense repeated measures that suited growth-curve modelling.

7.7.2 Behavioural mapping

The pilot study also used behavioural mapping as a main qualitative data source [2]. For every session, each child's verbal and non-verbal reactions, attention, imitation of the robot, emotional reactions and

task completion were described in narrative form. A research team member observed live (synchronous observation), and a psychologist from the centre later reviewed the video independently (asynchronous observation) [2]. Agreement between the two was checked on checklist items only; the narrative maps were treated as complementary accounts [2].

7.7.3 Structured functional task assessment

In the longitudinal study, a structured functional task assessment was the one outcome measured in both the intervention group and the standard-care control group [12]. It used three object-sorting tasks: shapes, vegetables, and coloured balls sorted according to a card. Each task was scored in four domains (comprehension, accuracy, verbal communication and prompt dependency) from 0 (no response or not attempted) through 1 (partial completion with prompting) to 2 (independent or near-independent completion), for a maximum of 24 [12]. Because it was given before and after the intervention period without the robot, it provides an outcome independent of the robot.

7.7.4 Interval-based behavioural mapping and WISC-V-informed profiling

The microgenetic study built a finer-grained instrument for observing cognitive behaviour within and across sessions [13]. Its design rests on three ideas. The first is the microgenetic method, which observes the same children intensively and at short intervals to capture *how* change happens rather than only *whether* it happens [22]. The second is Fredricks and colleagues' model of engagement as behavioural, emotional and cognitive [23]. The third is Vygotsky's zone of proximal development, which supports separating independent, scaffolded and non-responsive performance [24].

The coding unit was a 10-second interval, short enough to separate the robot's prompt, the child's response and the robot's feedback [13]. For each interval the coder recorded a behavioural category, a specific behaviour descriptor (for example "counts coins with hands"), the robot's concurrent action, a free-text description of the child's response, and an engagement rating. The free text covered verbal and non-verbal behaviour, facial expression, gaze direction and emotional cues [13]. All coding was manual, with no automated detection or affect-recognition software. Gaze frequencies were obtained afterwards by searching the descriptors with a predefined dictionary of gaze verbs and target nouns, and are descriptive indicators rather than eye-tracking measurements [13].

Engagement in each interval was rated on a five-point scale with behavioural anchors. 1 = disengaged: no attention or response. 2 = low: minimal, passive focus with delayed reactions. 3 = moderate: partial interaction, with correct responses mainly when prompted. 4 = high: active, quick responding with positive affect. 5 = peak: absorbed and enthusiastic, with self-initiated actions [13].

The coded record was then interpreted through the five index domains of the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V): verbal comprehension, visual-spatial processing, fluid reasoning, working memory and processing speed [25]. The domains served only as an organising framework; the test was not given and no norms were applied [13]. Each domain was linked to observable indicators. Examples are receptive accuracy for verbal comprehension, accurate matching and sorting for visual-spatial processing, predictions and fairness judgements about story characters for fluid reasoning, multi-step sequences for working memory, and the delay between prompt and response for processing speed [13]. Fatigue was an interpretive label, applied when markers such as yawning, slumping posture, longer delays and more need for prompting built up late in a session [13].

One researcher wrote a report for each session, including pairwise statements comparing domains. A second used these statements to place each child's domains on an ordinal 1–5 scale from "critical weakness" to "dominant strength", and the two finalised the ratings by consensus. Each domain's course

over the sessions was then classified as increase, plateau or decrease [13]. The authors state that the resulting profiles are descriptive, not diagnostic or psychometric [13].

7.7.5 Segment-level engagement codebook with decision algorithm

The engagement-comparison study produced a separate coding scheme, the *Engagement Level Codebook*, written by a psychologist and a specialist in inclusive education as a universal instrument for a child with CP interacting with a robot–tablet system [14]. It was applied to the same robot-session videos and to sessions with a tablet application delivering the same content. It also uses 10-second segments and a 1–5 scale, but defines the levels differently and adds an explicit decision algorithm. The codebook rests on two axes: the source of initiative (prompted by the robot or therapist, or initiated by the child) and substantiveness (a confirmed content contribution versus mere presence or a mechanical button press). Levels explicitly do not depend on correctness, loudness or intelligibility, facial expressiveness on its own, utterance length or emotional valence [14].

Each level is defined by worked sub-categories (Table 7.9). Level 1 (disengaged) requires that attention be fully occupied by an unrelated stimulus and that the child not return to the task even when prompted. Level 2 (low) requires a clearly observable marker of disengagement while presence is maintained, such as averted gaze, standing up, seeking contact with the therapist instead of the task, or loss of focus after a distraction. Level 3 (moderate) is sustained presence without a confirmed content contribution; its eight sub-categories include navigational presses ("next"), incomplete attempts, "I don't know" with no further attempt, isolated agreement, a questioning echo of the adult's word, unintelligible vocalisation whose relevance cannot be established, affect without action, and fleeting undirected imitation. Level 4 (high) is a confirmed content contribution prompted by a question; its ten sub-categories include a content-based button press regardless of correctness, a verbal or non-verbal answer of any length, an action performed on request, an honest "I don't know" given as an answer, a humorous or negative but on-topic response, and an attempt that fails only because of motor limitation. Level 5 (peak) is a content contribution initiated by the child or substantively exceeding what was asked, for example answering before the question is finished, commenting during narration, spontaneous metacommentary, holding to a correct answer against an adult's misleading prompt, or a spontaneous demonstration addressed to the adult.

The rules are applied in a fixed order [14]. A segment with no observable action (only "thinking" or "getting ready") defaults to level 3. An explicit disengagement marker gives level 2 (partial) or 1 (complete), and this check precedes any evaluation of a response. If an action is present, an echo of a word the adult just said gives level 3, any answer to a question from robot or therapist gives level 4, and a contribution made without a question, before the question is completed or substantively beyond it gives level 5. A purely navigational press is level 3. Three rules are tailored to children with CP. A failed motor attempt with visible, directed intent scores at least level 4, so that physical limitation is not scored as low motivation. An isolated "yes" or nod with no confirming action scores no higher than 4 and usually 3, and if a child agrees with almost every question in a session, all isolated "yes" answers in that session are coded conservatively to guard against acquiescence. Consistently selecting the same option regardless of content is flagged as a possible automatised motor pattern and is not credited as a content press. A content press made under substantial hand-over-hand help scores 3 or 4 depending on the child's independence. Coders also kept unscored notes on the nature of affect, the degree of scaffolding, ambiguous cultural gestures, signs of fatigue, the child's stable communicative profile, perseveration and therapist behaviour (for example scripted praise or pre-empting the child's answer). Segment scores were averaged within sessions and then within children, and the proportion of segments at levels 4–5 was reported as "high-engagement time" [14].

Table 7.9. Engagement Level Codebook: level definitions and principal decision rules [14].

Level	Label	Definition	Typical examples
1	Disengaged	No orientation to robot or tablet; attention fully on an unrelated stimulus	Does not return to the task after a direct prompt
2	Low engagement	Brief, unstable attention with a clear observable marker of disengagement	Gaze averted; stands up; seeks contact with the therapist instead of the task
3	Moderate engagement	Sustained presence without a confirmed content contribution	"Next" press; questioning echo; isolated "yes"; smile without action; unintelligible vocalisation
4	High engagement	Confirmed content contribution prompted by a question or instruction	Content-based press (correct or not); answer of any length; failed attempt with visible intent
5	Peak engagement	Content contribution initiated by the child or substantively beyond the question	Answers before the question ends; comments during narration; corrects an adult's misleading prompt

Two engagement instruments applied to the same videos need careful handling. They share labels and a time unit but differ in anchors and in how disengagement is ranked against response. The engagement study itself shows that its rule order can lower scores in robot sessions, where the child's gaze must move between robot, tablet and an operating therapist [14]. Scores from the two instruments should not be pooled or compared directly; Chapter 11 discusses the implications.

7.7.6 Acoustic and perceptual speech measures

The speech study added a two-layer objective speech outcome, combining acoustic analysis with blinded listener identification of the same single words [3]. Speech was elicited immediately before the first session and directly after the last by asking the child to describe the same coloured scene in the dominant language. The scene showed a grandmother, a boy, a girl and a dog under a tree with a kite caught in it, with a yurt and mountains behind. It was generated with an image-generation tool, checked for cultural appropriateness, and was not part of the intervention modules [3].

Audio was recorded with a wireless lavalier microphone system (Hollyland Lark M2; 48 kHz, 24 bit) clipped near the child's chest, with noise cancellation off, and saved as WAV files in Audacity [3]. A custom Python tool based on Parselmouth 0.4.7, which exposes the algorithms of Praat 6.1.38, supported manual word segmentation and automated measurement [3, 26, 27]. A native-speaking researcher marked the boundaries of every recognisable word and recorded the word, language and notes. The tool then saved the clip and its spectrogram and computed word duration, mean F0, mean F1 and F2, and mean intensity [3]. Because formant estimation in children's speech depends on analysis settings [28], pitch and formant measures were computed both with default settings (pitch 75–600 Hz, formant ceiling 5500 Hz) and with child-appropriate settings (120–650 Hz, 8000 Hz) [3]. Acoustic analysis of this kind is well established for dysarthric speech [29].

Intelligibility was operationalised as word identification by blinded listeners [3, 30]. Five adult native speakers fluent in Kazakh and Russian, unfamiliar with the children and blind to diagnosis, time point and study aims, rated every clip independently. Clips were anonymised and presented in one randomised order. Listeners chose from a closed set of 58 target-word glosses common to both languages (chance about 1.7%) or typed a free response [3]. Exact matches, inflected forms and translation equivalents were scored correct; synonyms, related words and blanks were scored incorrect. When a child produced a different word from the intended one, the clip was scored against the word actually spoken [3].

The protocol included an audio-quality audit that future users should keep. Listeners could flag clips as "not recorded in full", giving an exclusion criterion set blind to the results, and an automatic check of clip time stamps found overlapping clips, which were then kept, relabelled or excluded by explicit rules [3]. Section 7.8 explains why this matters.

The main analysis unit was the *matched word pair*: the same word from the same child in the same language at both time points. For the secondary analysis, all retained ratings were modelled with a mixed-effects logistic regression. Time point was the fixed effect, with crossed random intercepts for child (c), word (w) and listener (l) [3]:

$$\text{logit}P(Y_{cwl} = 1) = \beta_0 + \beta_1 \,\text{Time} + a_c + b_w + d_l$$

Listener agreement on the binary correct/incorrect outcome was summarised with pairwise percentage agreement and Fleiss' kappa, interpreted against standard benchmarks [3, 31].

7.7.7 Narrative language measures

The narrative study measured story language in the same intervention cohort, using its own picture-narration task given before and after the intervention. Children were shown a culturally grounded picture of a rural Kazakh landscape and asked to talk about what they saw [10]. Each session was recorded as a separate audio file on a dedicated recorder. One team member transcribed the recordings and a second checked every transcript against the audio. The child's utterances were then separated from those of the interviewer, parent and robot [10].

Two levels of analysis were used, following standard frameworks for narrative language samples [32, 33]. The *microstructural* measures were the number of utterances, mean length of utterance in words (MLU), the length of the longest utterance, the number of different words (NDW) and the type–token ratio (TTR) [10]. NDW and TTR depend on sample length, and recent work questions their clinical validity [34]. The samples were too short for length-controlled alternatives, so these two measures were reported only as descriptive counts [10]. The longest utterance was kept as an indicator of maximal syntactic capacity that is less affected than MLU by many short answers to follow-up prompts [10]. The *macrostructural* analysis coded seven story-grammar elements (setting, character, initiating event, internal response, attempt or plan, consequence and resolution) as present (1), partly present (0.5) or absent (0), giving a composite score of 0–7, following the story-grammar tradition [10, 35]. Cohesive ties were classified as causal, temporal, additive or adversative. Each piece of content was also coded as spontaneous or prompted, so that the child's dependence on the interviewer's help could be tracked [10]. For reliability, a blinded second rater re-coded the story-grammar elements for a subset of children, and a second analyst independently reproduced all measures for the whole sample [10].

The narrative study flags two limitations of the instrument that come directly from the bilingual system design. First, a single-scene picture limits how many higher-order story-grammar elements can be elicited, especially the resolution, whatever the child's ability [10]. Second, word-based measures such

as MLU do not count equivalent syntactic units in agglutinative Kazakh and fusional Russian. The authors recommend morpheme-based measures for future bilingual work [10].

7.7.8 Formal cognitive assessment with the WISC-V

The observational instruments above were complemented in the program's randomised work by a formal, standardised cognitive test. In the 2025 pilot randomised trial (10 intervention and 10 control children), outcomes were assessed with the WISC-V in the version adapted for use in Kazakhstan, with Full-Scale IQ (FSIQ) as the planning outcome, together with qualitative behavioural observations by clinical therapists [41]. Baseline WISC-V subtests were administered from October 2025 to establish the participants' cognitive profiles [41]. The same test is the planned outcome of the registered QTrobot trial, with baseline and post-intervention assessment in both arms (Chapter 3, Section 3.5.7). Unlike the WISC-V-informed profiles of Section 7.7.4, which borrow only the test's domain structure, this use yields normed standard scores. Its limitation in this population is the one that motivated the microgenetic method: the test's motor and speed demands can underestimate the ability of children with CP [13, 25].

7.7.9 Reliability procedures

Every study included some form of reliability check, although the procedures differed. Table 7.10 summarises them. The figures are given as properties of the instruments in their first use, labelled by the publication status of their source. They are not clinical outcomes.

Table 7.10. Reliability procedures reported for the program's instruments.

Instrument (status)	Procedure	Reported agreement or consistency
Pilot checklist (published) [2]	Synchronous observer vs asynchronous psychologist, Sessions 1 and 4; KR-20	97.9% and 95.8% agreement; KR-20 0.32 (floor effects at baseline) and 0.79
Adapted SRS-2 checklist (under review) [12]	Independent blind rater, 31 of 277 sessions; ICC(A,1) [36]; Cronbach's alpha	Overall ICC 0.520; good for ADL, cognition and communication; poor-to-moderate for social-skills sub-domains; $\alpha = 0.761$ across domains
Interval coding (under review) [13]	Independent coder, 34 of 65 sessions; Cohen's kappa	$\kappa = 0.71$ (81.8% agreement) over 1,158 observation pairs
WISC-V-informed profiles (under review) [13]	Blind re-derivation of all 40 ratings	Quadratic-weighted $\kappa = 0.64$; 27.5% exact agreement
Trajectory classifications (under review) [13]	Independent audit of all 40 classifications against the written syntheses	38 of 40 agreed ($\kappa = 0.90$); both discrepancies were transcription errors and were corrected
Engagement codebook (in preparation) [14]	Independent raters, 34 of 65 robot and 30 of 69 tablet sessions; weighted kappa	
Listener identification (in preparation) [3]	Five listeners; Fleiss' kappa	$\kappa = 0.518$ (moderate)

Instrument (status)	Procedure	Reported agreement or consistency
Story-grammar coding (in preparation) [10]	Blind second rater on a subset; full independent replication	Weighted $\kappa = 0.80$ (subset) and 0.79 (full sample)

The pattern matters for future users of the system. Instruments that coded concrete, task-bound behaviours, such as ADL, cognition, communication and story elements, reached good agreement. Agreement was weaker for instruments that required inferences about brief social behaviours from video, such as the social-skills sub-domains, or ordinal synthesis across many observations, such as the domain profiles [12, 13].

7.8 Technical and Practical Lessons

Across the studies, the authors recorded lessons about running the system that do not appear in outcome tables but matter to anyone replicating it. They fall into four groups.

Platform reliability and data capture. Technical problems were few but affected data completeness. Some microgenetic-cohort sessions were lost to recording failures and robot connectivity problems [13], and the engagement study attributes some unusable recordings to camera malfunctions [14]. More fundamentally, the tablet application did not store item-level logs, so accuracy and response latency had to be estimated from 10-second video intervals [13]. Logging stimulus onset, touch time and correctness on the tablet, as the microgenetic study recommends [13], would turn the learner's tablet into a measurement instrument at almost no cost. On the positive side, the pilot study reported no serious technical difficulties and successful delivery of the bilingual scripts [2], and the longitudinal study notes that no infrastructure beyond the robot and a trained therapist was needed [12]. Running the Kazakh voice on the robot's own computer (Section 7.4.2) also removed any dependence on the centre's network for speech.

Speech and audio. Extracting single words from spontaneous child speech was the weakest link of the speech pipeline: nearly one clip in five was excluded after the audit because words had been cut or clip boundaries overlapped [3]. The damage was not neutral. A damaged clip is almost never identified, so damaged pre-test clips depress the baseline and can create false improvement [3]. The listener flag and the time-stamp overlap check caught these problems cheaply. Energy-based automatic segmentation could not reproduce the manual boundaries in this dysarthric material, so segmentation remains a manual cost [3]. The study also recommends calibrated recording conditions (fixed microphone distance or a reference tone) and a short fixed word list repeated at both time points to guarantee matched pairs [3]. On the output side, the TTS voice does not vary pitch for emotion, so affect must be carried by the face, gestures and wording [13].

Scenario and session design. The pilot study's behavioural mapping produced several design lessons [2]. Some children were distressed on first entry and settled with repeated exposure, and novelty generally gave way to structured engagement within two to three sessions, so early sessions should emphasise comfort and routine over task demands. The later dedicated familiarisation session reflects this [13]. The touchscreen itself had to be learned: some children first touched it at random or relied on a parent, which argues for explicit orientation to the response method before cognitive tasks begin [2]. A thermometer item in the hospital role-play, requiring children to identify and label feelings or temperature readings on cards, was a consistent sticking point; the authors suggest visual scaffolding, a simpler instruction or moving the item later in the session [2]. The longitudinal study suggests refreshing the protocol with new or harder activities around Sessions 8–9, where gains tended to level off [12], and

the fixed module order, which confounds session number with content, should be counterbalanced in future [13].

People and roles. The system cannot be separated from the people around it. A typical session involved four to five adults from the research team, one or two NCCR clinicians and often a parent (Section 7.3.4), which is a substantial staffing commitment for a session of about ten minutes. When the facilitating therapist also completed the ratings, as in the longitudinal study, the arrangement matched resource-limited practice but ruled out blinding [12]; its authors suggest that more autonomous robot operation could reduce therapist burden [12, 37]. The lead therapist changed partway through the microgenetic cohort, which may have affected later sessions [13]. In the engagement study, format was confounded with the therapist's role [14]. Manual video coding was labour-intensive in every study, and the pilot study points to automated engagement detection, facial-expression and gaze analysis as ways to reduce this burden [2, 38].

7.9 Limitations

The system and its evidence base have limitations that should be stated plainly.

Platform and localisation. QTrobot is a commercial platform, and the program's innovations sit in its content and speech layers, not in its hardware. Kazakh speech depended on integrating an open-source TTS model trained on adult professional voices [39, 40]. Its synthesis latency, prosodic range and naturalness have not been measured in the program, and no child or parent evaluated the Kazakh voice directly; neither voice varied pitch to express emotion [13]. Language assignment was fixed for each child, so the system's possible use in bilingual sessions was not explored. The program's manuscripts also describe the operating arrangement in different terms (semi-autonomous or Wizard-of-Oz), which this book resolves in favour of "semi-autonomous" (Section 7.3.3).

Interaction design. The dialogue was fully scripted and did not use speech recognition. This made it robust and inclusive, but the robot could not respond to what children actually said except through the therapist. The robot did not adjust content to performance during the session. Personalisation depended entirely on the therapist's pacing. The scoping review lists personalisation as a priority for the field [1].

Measurement. Most behavioural instruments were developed or adapted by the program. The adapted SRS-2 checklist was not psychometrically validated [12]. The WISC-V-informed profiles are interpretive, not normed [13]. Two different five-point engagement scales were applied to overlapping video material [13, 14]. Several instruments relied on one primary coder, and reliability was often checked on a subset of sessions. Standard functional classifications (GMFCS, MACS, CFCS) and formal dysarthria severity ratings were not consistently available in the centre's records [2, 3, 10]. This limits how far the cohorts can be compared with international CP samples. Speech recording conditions were not calibrated between sessions, and the same assessment picture was used at both time points [3, 10].

Generalisability. All deployments took place at one national rehabilitation centre, mostly in short series of sessions. Whether the system works the same way in regional clinics, schools or homes, or over months rather than weeks, has not been tested.

7.10 Summary

This chapter described the SAR system that program BR27199433 developed to extend rehabilitation for children with CP into communication, cognition and social interaction. Its rationale comes from the program's published scoping review, which found SARs feasible and engaging but identified gaps in

multilingual work, autonomy and measurement [1]. The system pairs the commercial QTrobot humanoid with a two-tablet configuration in which the robot carries the social layer, the learner's tablet the task layer, and the therapist controls pacing and judges spoken or gestured responses. Localisation was the main technical contribution: Russian uses the robot's built-in Acapela voice, Kazakh uses the ISSAI KazakhTTS (ESPnet) model running in a Docker container on the robot's Jetson AGX Orin, a router registered under RK copyright certificate No. 74308 sends each utterance to the right voice, and each child is addressed in his or her own language with scripts written in parallel in both languages. Therapy content grew from a seven-script pilot set to a ten-module protocol built on Kazakh and Central Asian folklore and everyday situations, developed with 35 families, 7 therapists and 3 teachers and refined through usability testing; the Kazakh and Russian scripts are registered under certificate No. 74309. The accompanying instruments cover observed behaviour, engagement, functional tasks, formal cognitive assessment with the WISC-V, speech acoustics and intelligibility, and narrative language. The main practical lessons are to log task events on the tablet, audit audio quality, allow time for settling in and for learning the response method, calibrate recording conditions, and reduce the manual coding burden. Chapter 11 reports the clinical findings obtained with this system.

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Part III. Software and Data Platforms

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Chapter 8. Gait Analysis Pipeline and the Gait Recovery Index

Abstract. This chapter describes the gait analysis pipeline developed at the Center of Excellence in Medical Robotics and Research (CEMRR), Nazarbayev University, to convert the sensor data recorded during robot-assisted treadmill training on the Gait Rehabilitation Robot into clinically interpretable measures of gait and of the child's own motor contribution. The pipeline combines three sensor streams — joint encoders on the robot's hip and knee drives, Futek load cells in series with the four joint actuators, and a pair of 16-sensor plantar pressure insoles — and derives from them temporal and spatial gait parameters, symmetry indices, stride-time variability, a support measure based on double-limb stance, and a load-cell-based measurement of the patient's joint torque contribution. These are normalized into five aspect scores (symmetry, stability, support, efficiency and joint strength) and combined into a weighted composite, the Gait Recovery Index (GRI). The chapter gives every formula, normalization constant and weight exactly as specified in the program's technical documents and analysis scripts, works through a complete ten-cycle hand calculation from raw data to GRI, and describes the software that implements the calculations: a clinical dashboard and the Gait Analysis and Rehabilitation Advisory System (GARAS), which adds Gaussian-process recovery curves, mixed-effects responder classification, Shapley-value attribution of change and a rule-based recommendation engine, and which has been run on data recorded at the National Center for Children's Rehabilitation (NCCR). The chapter closes with a critical discussion of the assumptions built into the index and of the validation work that remains before it can be used as a clinical outcome measure.

Keywords: gait analysis; cerebral palsy; robot-assisted gait training; plantar pressure insoles; gait events; symmetry index; stride-time variability; patient torque fraction; composite index; Gait Recovery Index; clinical decision support; GARAS

8.1 Introduction

8.1.1 Why a device-integrated gait analysis pipeline

A gait rehabilitation robot is, by construction, also a measuring instrument. Its joint encoders record the angular trajectory of the hips and knees in every step, its load cells measure the forces exchanged with the limbs, and when it is combined with instrumented insoles it can detect the instants at which each foot strikes and leaves the treadmill belt. Over a course of sessions this produces a dense longitudinal record of how a child walks while in the robot. Clinical outcome measures such as the six-minute walk test (6MWT), the 10-metre walk test or the Gross Motor Function Measure, which are used in the program's gait trial (ACTRN12626001203347; Chapter 4), are administered only at baseline and after the intervention and say little about how a child's walking changes from session to session. A pipeline that summarizes each session in a small number of interpretable numbers can therefore complement conventional assessment by showing the trajectory of change and by indicating which aspect of gait is limiting progress at a given time.

The technical data sheet of the Gait Rehabilitation Robot describes the post-session analysis of logged data along four gait domains — symmetry, stability, support/balance and propulsion efficiency — as the basis for therapist-oriented recommendations [1]. The CEMRR pipeline formalizes that idea, adds a fifth domain based on the patient's own joint torque contribution, and combines the domains into a single index. The underlying motivation is the assist-as-needed philosophy developed by the team for robotic gait orthoses [2]: if the goal of therapy is for the patient to take over progressively more of the work of walking from the robot, then the patient's share of the joint torque is itself an outcome worth tracking.

8.1.2 Status of the material in this chapter

The material in this chapter is at an early stage of development, and its status must be understood precisely. Table 8.1 summarizes it.

Table 8.1. Sources and status of the material reported in this chapter.

Component	Source	Status
Sensor configuration, formulas, constants, weights	CEMRR 10-cycle hand-calculation document [3]; CEMRR pipeline software documentation [4]; analysis script gri_cemrr.py [5]	Unpublished technical documents and code
Earlier design using motor-current torque estimation	Gait report software, part I [6]	Unpublished working document with a fictitious worked example; superseded
Worked example (Section 8.9)	Hand-calculation document [3]	Simulated reference dataset used to verify the software; not a recording from a participant
Clinical dashboard	Pipeline software documentation [4]	Documented in simulation and CSV-replay mode
GARAS (copyright certificate No. 74083)	GARAS software description [9]	Run on NCCR data; no patient results reported in this chapter
Validity, reliability and responsiveness of the GRI	—	Not yet established; validation analyses outlined in Section 8.11

No measurement from a child in the program trial is reported in this chapter. Trial outcomes are reported, as they become available, in Chapter 10.

8.2 Sensing

The pipeline is defined around three sensor types, each of which plays a distinct role [3,4]. Their contributions are summarized in Table 8.2 and described below.

Table 8.2. Sensor streams used by the CEMRR gait pipeline.

Sensor	Quantity	Number and placement	Role in the pipeline
Joint encoders	Joint angle (degrees); peak flexion per cycle	Four: hip and knee, left and right, one per drive	Kinematic component of step length; joint range of motion
Futek load cells	Force (N) between actuator and limb; peak per cycle	Four: in series with each joint actuator	Patient joint torque contribution and Patient Torque Fraction (joint strength)
Plantar pressure insoles	Pressure at 16 sites per foot, expressed as % body weight	Two insoles, 16 sensors each in a 4 × 4 grid; 200 Hz	Gait event detection (heel strike, toe-off); all temporal parameters; loading distribution

Sources: [3,4].

8.2.1 Joint encoders

Each of the four joint drives of the Gait Rehabilitation Robot carries an angle encoder [7]. The pipeline uses the peak flexion angle of each joint within each gait cycle: θ_hip,L, θ_hip,R, θ_knee,L and θ_knee,R [4]. The hip angle is used to estimate the kinematic part of step length (Section 8.4.3); the knee angle is reported as a descriptor of joint range of motion and is displayed in the dashboard, but does not enter the GRI [3,4]. Encoder accuracy is specified by the manufacturer as ±1.0° zero offset and at most ±2.0° error over the range [7].

It is worth noting a property emphasized in the program's earlier design notes: the encoder measures angle but not ground contact, so it cannot by itself determine when a step begins or ends [6]. Every temporal parameter therefore depends on the insoles.

8.2.2 Load cells and the passive calibration trial

Four Futek load cells, fitted as standard on the Gait Rehabilitation Robot, measure the force exerted by the robot at each joint [3,4,9]. They are placed in series with the actuators, so that the measured force is the force transmitted between the robot and the limb segment [3]. Two recordings are required. In a *passive calibration* trial, the robot moves the child's legs while the child is fully relaxed and makes no effort; the peak force recorded at each joint in this condition, F_passive, represents the force the robot must supply to move a passive limb through the prescribed pattern [3,4]. In a training session, the peak force F_session is recorded in each cycle. If the child actively contributes to the movement, the robot needs to supply less force, and F_session falls below F_passive [4]. The difference, multiplied by the moment arm at which the load cell acts, gives the joint torque contributed by the patient (Section 8.7).

The program's pre-assessment form makes the passive calibration a mandatory step before a child's first training session, noting that without it the strength score cannot be computed [8]. The hand-calculation document highlights an advantage of load cells over motor-current estimation: because the force is measured directly at the joint, no motor torque constant is needed [3].

8.2.3 Instrumented insoles

Each foot carries an insole with 16 pressure sensors arranged in a 4 × 4 grid that covers the toe, ball, midfoot and heel regions; sensors 13–16 are the heel sensors [4]. The insoles are sampled at 200 Hz and each reading is expressed as a percentage of body weight [3,4]. The insoles are the backbone of the pipeline: they provide the heel-strike and toe-off events on which the temporal parameters, the double-support measure and the cadence all depend [6]. They also provide the plantar pressure maps and the bilateral loading information shown to therapists and, as biofeedback, to patients [1,4].

8.2.4 An alternative: torque from motor current

An earlier design of the pipeline, documented in an unpublished program working document [6], did not use load cells. Instead, joint torque was estimated from the current drawn by each motor through a torque constant, $\tau = k_t \cdot I$, and the patient's contribution was obtained as the difference between a passive reference torque and the torque estimated during the session [6]. That document worked through a fictitious example with an assumed torque constant of 0.8 N·m/A. The current pipeline replaces motor-current estimation with direct load-cell measurement [3,9], and the load-cell configuration is the one fitted to the robot used in the NCCR trial. The motor-current approach requires no additional hardware, but it is sensitive to the accuracy of the torque constant, to back-electromotive force and to friction and inertia in the drive train, which the load-cell approach avoids by measuring at the joint [9]. Early observations of the robot's controller, made before the load cells were integrated, treated the torque

delivered to the limb as unmeasured; with the load cells in place, the patient's joint torque contribution is measured directly in every session.

8.3 Signal Processing and Gait Event Detection

8.3.1 Gait events

Two events per foot are detected from the insole signals [3,4]. A heel strike (HS) is detected when the summed signal of the heel sensors (13–16) crosses a threshold of 5% of maximum pressure on a rising trend. A toe-off (TO) is detected when the total insole signal falls below a 5% threshold. The documents describe the threshold slightly differently: the hand-calculation document and the GARAS specification use 5% of maximum pressure for both events [3,9], the dashboard documentation defines the toe-off threshold as 5% of body weight [4], and the earlier design notes define a single threshold of 5% of the body-weight-normalized maximum pressure [6]. This book follows the GARAS definition, which is the one implemented in the software applied to NCCR data. The difference between the definitions is small in practice, but a single definition, together with any filtering or debouncing applied to the raw insole signals, should be fixed in the trial's analysis plan so that event detection is reproducible.

Within a recording of n gait cycles of the left (reference) limb, there are n + 1 left heel strikes, which delimit n complete strides [3]. Right heel strikes and both toe-offs are indexed to the same cycles.

8.3.2 Per-cycle data structure

After event detection, each gait cycle is summarized by one record. The pipeline software documentation defines a comma-separated file format for this purpose, which serves both for replaying stored sessions and as the interface to the laboratory acquisition system [4]. Its columns are listed in Table 8.3.

Table 8.3. Per-cycle session data format.

Column(s)	Content
cycle_number	Integer, from 1
hs_L_start, hs_L_end	Left heel strike at the start of the cycle and at the start of the next cycle (s)
hs_R, hs_R_end	Right heel strike within the cycle and its next occurrence (s)
to_L, to_R	Left and right toe-off (s)
theta_hip_L, theta_hip_R, theta_knee_L, theta_knee_R	Peak flexion angles (degrees)
f_hip_L, f_hip_R, f_knee_L, f_knee_R	Load-cell forces during the session (N)
p_L_1 … p_L_16, p_R_1 … p_R_16	Insole sensor pressures (% body weight)

Source: [4].

The design choice to reduce each cycle to peak angles and peak forces, rather than to retain the full time series, keeps the calculations transparent enough to be reproduced by hand, which was an explicit aim of the program's documentation [3]. It also discards information — for example, the timing of peak force within the cycle, or the shape of the joint angle trajectory — that the earlier design notes suggested could reveal spasticity (Section 8.7.3).

8.4 Spatiotemporal Parameters

8.4.1 Temporal parameters

For cycle i of the left limb, stride time, stance time and swing time are computed from consecutive events [3,4]:

$$t_{stride,L}(i) = HS_L(i+1) - HS_L(i)$$

$$t_{stance,L}(i) = TO_L(i) - HS_L(i), \qquad t_{swing,L}(i) = HS_L(i+1) - TO_L(i)$$

The same formulas are applied to the right limb with HS_R and TO_R. By construction, stance and swing times sum to the stride time, which provides a simple check on the event sequence [3]. Stance and swing are also expressed as percentages of the stride.

8.4.2 Double support and the double support ratio

In each stride there are two periods during which both feet are on the ground: one after the right heel strikes and before the left toe leaves the ground, and one after the left heel strikes again and before the right toe leaves. The hand-calculation document and the software documentation define the double-support time of cycle i as the overlap of the two stance phases that begin within that cycle [3,4]:

$$t_{ds,1}(i) = \min\big(TO_L(i),\, TO_R(i)\big) - \max\big(HS_L(i),\, HS_R(i)\big)$$

and the double support ratio (DSR) as the mean double-support time divided by the mean left stride time:

$$\mathrm{DSR} = \frac{\overline{t}_{ds}}{\overline{t}_{stride,L}} \times 100\%$$

This formula captures only the first of the two double-support periods. The analysis script used for the cohort demonstration therefore adds the second period, which spans the next left heel strike and the right toe-off [5]:

$$t_{ds,2}(i) = \max\big(0,\, TO_R(i) - HS_L(i+1)\big), \qquad \mathrm{DSR}_2 = \frac{\overline{t_{ds,1} + t_{ds,2}}}{\overline{t}_{stride,L}} \times 100\%$$

The script header records this as an agreed deviation from the hand-calculation document, noting that the single-period formula halves DSR relative to the normal reference of about 20% [5]. The distinction matters, because the support score of the GRI compares DSR with that reference (Section 8.8.3). In the worked example of Section 8.9, the single-period DSR is 12.43% while the two-period DSR is 19.59%.

8.4.3 Cadence

All heel strikes of both feet are pooled and sorted in time; the intervals between consecutive heel strikes are step times, and cadence in steps per minute is [3,4]:

$$\mathrm{Cadence} = \frac{60}{\overline{t}_{step}} \ \mathrm{steps/min}$$

8.4.4 Step length and stride length

Step length on a treadmill cannot be measured directly from foot displacement, because the feet do not progress relative to the laboratory. The pipeline estimates it as the sum of a kinematic component, derived from the peak hip flexion angle and the leg length L_leg, and a belt component equal to the distance the belt travels during the step [3,4]:

$$L_{kin} = 2\,L_{leg}\sin\left(\frac{\theta_{hip}}{2}\right), \qquad L_{belt} = v_{belt}\,t_{step}$$

$$L_{step} = L_{kin} + L_{belt}, \qquad L_{stride} = L_{step,L} + L_{step,R}$$

The left step time is taken as the interval from the left heel strike to the following right heel strike, and the right step time as the interval from that right heel strike to the next left heel strike [3]. Leg length is measured at pre-assessment from the greater trochanter to the lateral malleolus [8].

The kinematic component treats the leg as a rigid link of length L_leg swinging through the peak hip angle, so that 2·L·sin(θ/2) is the chord subtended by that angle. Because the belt speed is the same for both feet, and in steady walking the two step times are similar, the belt component contributes almost equally to both sides and the step-length asymmetry arises mainly from the difference in hip angles [6]. The physical interpretation of adding the two components is discussed among the limitations in Section 8.11.

8.5 Symmetry Indices

Two symmetry indices are computed from the session means of the left and right values, each expressed relative to the mean of the two sides [3]:

$$\mathrm{SI}_{step} = \frac{\left|\overline{L}_{step,L} - \overline{L}_{step,R}\right|}{\left(\overline{L}_{step,L} + \overline{L}_{step,R}\right)/2} \times 100\%$$

$$\mathrm{SI}_{stride} = \frac{\left|\overline{t}_{stride,L} - \overline{t}_{stride,R}\right|}{\left(\overline{t}_{stride,L} + \overline{t}_{stride,R}\right)/2} \times 100\%$$

A value of zero indicates perfect symmetry. The stride-time index is expected to be very small on a treadmill with a robot enforcing the rhythm, because both legs must complete a stride in the same time to remain on the belt; in the worked example it is 0.03% [3]. The step-length index is the more informative of the two and is the one used in the GRI. In hemiplegic CP, the affected side typically takes the shorter step [8], and step-length asymmetry is therefore the principal target of training in that group.

8.6 Variability

Stride-to-stride variability is quantified by the coefficient of variation (CV) of stride time for each limb, using the sample standard deviation [3,4]:

$$\mathrm{CV}_L = \frac{s\left(t_{stride,L}\right)}{\overline{t}_{stride,L}} \times 100\%, \qquad s(x) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

and likewise for the right limb. Higher CV indicates less consistent, and by implication less stable, walking. The documents use a threshold of 3% to separate normal from elevated variability [3,4].

Because the treadmill and the robot both impose a rhythm, stride-time CV measured in the robot reflects the child's ability to remain entrained to an external pace rather than the self-selected variability of overground walking; this distinction is important when comparing values with published norms.

8.7 Patient Joint Torque and the Patient Torque Fraction

8.7.1 Human torque

From the passive and session forces at each joint j, and the moment arm r at which the load cell acts, the pipeline defines the torque contributed by the patient as the reduction in the torque the robot must supply relative to the passive condition [3,4]:

$$\tau_{passive,j} = F_{passive,j}\, r, \qquad \tau_{session,j} = F_{session,j}\, r$$

$$\tau_{human,j} = \tau_{passive,j} - \tau_{session,j} = \left(F_{passive,j} - F_{session,j}\right) r$$

In the reference configuration, r = 0.25 m [3]. A positive value indicates that the patient is assisting the motor, which is the desired behaviour; a negative value indicates that the patient is resisting it, which GARAS flags as possible spasticity [3,9].

The pipeline and GARAS treat this quantity as a direct measurement of the patient's joint torque contribution, obtained from the Futek load cells rather than inferred from motor current [3,9]. Two qualifications apply. First, a load cell in series with the actuator measures a joint-reaction force, so the accuracy of the derived torque depends on the calibration of the load cells and on the estimate of the moment arm at which they act. Second, the subtraction of session from passive values assumes that the passive mechanical properties of the limb and the inertial demands of the movement are the same in the calibration trial and in the session, so that the change in robot force reflects the patient's own effort. Changes in speed, range of motion, body-weight support or cuff fit between calibration and session would weaken that assumption, which is why the passive calibration should be repeated whenever these settings change (Section 8.11).

8.7.2 Patient Torque Fraction

The Patient Torque Fraction (PTF) normalizes the patient's contribution by the passive requirement, using the session mean of the per-cycle peak forces [3,4]:

$$\mathrm{PTF}_j = \frac{F_{passive,j} - \overline{F}_{session,j}}{F_{passive,j}}$$

PTF is 0 when the patient contributes nothing and the robot supplies the full passive requirement, and approaches 1 as the patient takes over the work [4]. Because the moment arm cancels, PTF does not depend on r. As a patient recovers, PTF is expected to increase toward 1 [4].

8.7.3 Spasticity signature

The earlier design notes proposed that the sign of the instantaneous human torque within the gait cycle could reveal spasticity: negative values during the swing phase, when the robot is flexing the knee or hip and spastic muscles resist the velocity-dependent stretch, were described as the characteristic signature of CP spasticity, and a per-joint spasticity measure tracked across sessions was suggested as evidence that therapy reduces involuntary muscle activation [6]. In a fictitious example the notes showed positive human torque at the affected hip during stance and negative values during mid-to-terminal swing, confined to the affected side [6]. The current pipeline works with per-cycle peak forces and does

not compute a within-cycle spasticity measure. GARAS retains two related indicators at session level: each joint is labelled as assisting, passive or showing possible spasticity according to the sign of τ_human, and a Joint Stiffness Index, $JSI_j = |\Delta\tau_human,j| / |\Delta\theta_j|$ in N·m per degree, relates the change in patient torque to the change in peak joint angle between consecutive sessions; a JSI above 0.08 N·m/° triggers a recommendation for physiotherapist assessment [9]. Neither indicator has been validated against clinical measures of spasticity such as the Modified Ashworth Scale, and both should be regarded as screening flags.

8.7.4 Loading index

The dashboard also computes an Adaptive Loading Index (ALI) from the total forces under the left and right feet [4]:

$$\mathrm{ALI} = 1 - \frac{|F_L - F_R|}{F_L + F_R}$$

ALI equals 1 when the load is perfectly balanced between the feet and 0 when all the load is on one foot; the software documentation gives an expected range of 0.65–0.80 for hemiplegic CP [4]. ALI is displayed for biofeedback but is not a component of the GRI.

8.8 The Gait Recovery Index

8.8.1 Structure

The GRI combines five aspect scores, each mapped to the interval [0, 1], into a weighted sum [3,4,5]:

$$\mathrm{GRI} = 0.25\,S + 0.15\,V + 0.20\,B + 0.20\,E + 0.20\,\mathrm{STR}$$

where S is the symmetry score, V the stability score, B the support score, E the efficiency score and STR the joint strength score. The weights sum to 1, so the GRI also lies in [0, 1]. The documents interpret GRI = 1 as full recovery toward normal gait [4]. In the analysis script, every component score is clipped to [0, 1] [5]. The component definitions and constants are given in Table 8.4 and explained below.

Table 8.4. Definitions of the five GRI aspect scores and their normalization constants.

Score	Underlying measure	Definition	Constants
S — Symmetry	Step-length symmetry index	S = 1 − SI_step length / SI_baseline	SI_baseline = 20.54%
V — Stability	Mean stride-time CV of both limbs	V = 1 − [(CV_L + CV_R)/2] / CV_baseline	CV_baseline = 4.2%
B — Support/balance	Double support ratio	B = 1 − (DSR − DSR_normal) / (DSR_baseline − DSR_normal)	DSR_normal = 20%; DSR_baseline = 36%
E — Efficiency/propulsion	Belt speed, cadence, stride length	E = (v_belt/v_normal + cadence/cad_normal + L_stride/L_stride,normal) / 3	v_normal = 0.90 m/s; cad_normal = 110 steps/min; L_stride,normal = 1.40 m
STR — Joint strength	Patient Torque Fraction	STR = mean of PTF over the four joints	—

Sources: [3,4,5]. All scores clipped to [0, 1] in the analysis script [5].

8.8.2 Symmetry, S

$$S = 1 - \frac{\mathrm{SI}_{step}}{\mathrm{SI}_{baseline}}, \qquad \mathrm{SI}_{baseline} = 20.54\%$$

S equals 1 for perfect step-length symmetry and 0 when the asymmetry equals the baseline value [3,4]. The software documentation describes SI_baseline as the value from Session 1 [4], and the hand-calculation document describes all scores as normalized relative to a Session 1 baseline and a normal reference, with 0 meaning the same as baseline and 1 meaning the normal level [3]. In the analysis script, however, 20.54% is applied as a fixed constant to every child and every session, an approach that the script records as agreed [5]. Under this convention, a child whose step-length asymmetry exceeds 20.54% receives S = 0 regardless of how severe the asymmetry is.

8.8.3 Stability, V

$$V = 1 - \frac{\overline{\mathrm{CV}}}{\mathrm{CV}_{baseline}}, \qquad \overline{\mathrm{CV}} = \frac{\mathrm{CV}_L + \mathrm{CV}_R}{2}, \quad \mathrm{CV}_{baseline} = 4.2\%$$

V equals 1 when stride time is perfectly regular and 0 when the mean CV reaches 4.2% [3,4].

8.8.4 Support, B

$$B = 1 - \frac{\mathrm{DSR} - \mathrm{DSR}_{normal}}{\mathrm{DSR}_{baseline} - \mathrm{DSR}_{normal}}, \qquad \mathrm{DSR}_{normal} = 20\%, \quad \mathrm{DSR}_{baseline} = 36\%$$

A DSR at or below the normal reference of 20% gives B = 1 after clipping, and a DSR of 36% or more gives B = 0 [3,4]. The rationale is that children with impaired balance prolong the period in which both feet are on the ground, so a reduction of DSR toward the normal value indicates improved single-limb support. A DSR below normal is not penalized, which is a deliberate simplification: an abnormally short double-support period could itself indicate a hurried, unstable gait.

8.8.5 Efficiency, E

$$E = \frac{1}{3}\left(\frac{v_{belt}}{v_{normal}} + \frac{\mathrm{cad}}{\mathrm{cad}_{normal}} + \frac{L_{stride}}{L_{stride,normal}}\right)$$

with v_normal = 0.90 m/s, cad_normal = 110 steps/min and L_stride,normal = 1.40 m [3,4]. In the analysis script each of the three ratios is clipped to [0, 1] before averaging [5]. E rewards walking faster, with a higher cadence and longer strides, relative to the reference values.

8.8.6 Joint strength, STR

$$\mathrm{STR} = \frac{1}{4}\left(\mathrm{PTF}_{hip,L} + \mathrm{PTF}_{hip,R} + \mathrm{PTF}_{knee,L} + \mathrm{PTF}_{knee,R}\right)$$

STR is the mean of the four Patient Torque Fractions [3,4]. It is the only component that draws on the load cells and the only one intended to reflect the patient's own neuromuscular contribution rather than the gait pattern produced jointly by patient and robot. The earlier design notes argued that joint strength deserves a weight equal to symmetry and efficiency, because it addresses the question clinicians and parents most want answered: whether the nervous system is recovering, or the robot is merely compensating for an unchanged deficit [6].

8.8.7 Weights and their rationale

The weights and the rationale given for each in the hand-calculation document are reproduced in Table 8.5.

Table 8.5. GRI weights and stated rationale.

Weight	Aspect	Value	Rationale stated in the source [3]
w_S	Symmetry	0.25	Primary impairment in hemiplegic CP and main therapeutic target
w_V	Stability	0.15	The treadmill enforces rhythm, so lower weight than spatial indices
w_B	Support/balance	0.20	Loading equality, directly targeted by BWS and insole biofeedback
w_E	Efficiency	0.20	Functional walking output, meaningful to patients and carers
w_STR	Joint strength	0.20	Neurological recovery, measured directly by the load cells
Σw	—	1.00	Weights sum to 1

The weights are expert-assigned rather than derived from data; the GARAS specification describes them as reflecting the relative clinical importance of each aspect in paediatric CP, with symmetry weighted highest as the primary impairment and stability weighted lowest because it is partly enforced by the treadmill [9]. The rationale given for w_B in the hand-calculation document refers to loading equality, whereas B is computed from the double support ratio rather than from left–right loading; loading equality is captured by ALI, which is not in the index. In this book B is interpreted as a measure of support time (double-limb stance), consistent with its formula. Because the weights are not derived from data, conclusions drawn from the GRI should be checked for sensitivity to alternative weightings when trial data are analysed.

8.8.8 Interpretation bands

The dashboard colors each aspect score green above 0.70 ("within normal range"), amber between 0.40 and 0.70 ("progressing, needs attention") and red below 0.40 ("significantly below normal") [4]. The GRI gauge is accompanied by a plain-language status — symmetric, progressing, or rehabilitation required — together with the percentage value [4]. GARAS uses slightly different bands for the GRI itself (green at or above 65%, amber at or above 35%, red below 35%) [9]. These bands are heuristic display conventions; they have not been calibrated against clinical outcome measures, and a single set should be adopted before the index is used in reporting.

8.9 Worked Example: Ten Gait Cycles from Raw Data to GRI

This section reproduces, in condensed form, the hand calculation that serves as the reference for the software [3]. Its purpose is didactic and for verification: every intermediate value can be checked, and the software documentation states that every software result has been verified against the document values [4]. The example describes a child with left hemiplegic CP walking on the treadmill at 0.50 m/s, with body weight 32 kg, leg length 0.62 m and load-cell moment arm 0.25 m, over ten gait cycles [3]. The data are a simulated reference set; they are not a recording from a program participant, and every value in Sections 8.9.1–8.9.7 is simulated.

8.9.1 Input data

Table 8.6 lists the peak joint angles per cycle and Table 8.7 the peak load-cell forces with the passive reference values.

Table 8.6. Worked example (simulated data — not patient results): peak joint flexion angles per gait cycle (degrees).

Joint	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Hip L	24.2	23.8	24.5	24.1	23.9	24.3	24.6	24.0	23.7	24.4
Hip R	36.1	36.4	35.9	36.3	36.0	36.5	36.2	36.1	36.3	36.0
Knee L	51.2	50.8	51.5	51.0	50.9	51.3	51.6	51.1	50.7	51.4
Knee R	58.4	58.7	58.2	58.6	58.3	58.8	58.5	58.4	58.6	58.3

Source: [3].

Table 8.7. Worked example (simulated data — not patient results): peak load-cell force per cycle and passive reference (N).

Joint	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	F_passive
Hip L	3.2	3.5	3.1	3.4	3.3	3.6	3.2	3.5	3.3	3.4	5.1
Hip R	2.8	3.0	2.9	2.8	3.1	2.9	3.0	2.8	3.0	2.9	4.6
Knee L	2.4	2.6	2.3	2.5	2.4	2.7	2.4	2.5	2.3	2.6	4.0
Knee R	2.0	2.1	2.0	2.2	2.1	2.0	2.2	2.1	2.0	2.1	3.7

Source: [3].

The insole-derived event times comprise eleven left heel strikes (0.000, 1.284, 2.571, 3.856, 5.143, 6.428, 7.715, 9.000, 10.289, 11.574 and 12.861 s), eleven right heel strikes beginning at 0.642 s, and ten toe-offs per foot beginning at 0.800 s (left) and 1.380 s (right) [3]. The mean plantar pressures at the sixteen sensor sites are also tabulated in the source, ranging from 5.9% to 14.2% of body weight on the left and from 3.0% to 15.8% on the right [3].

8.9.2 Temporal parameters

For cycle 1, the left stride time is 1.284 − 0.000 = 1.284 s, left stance 0.800 s and left swing 0.484 s; the right stride time is 1.926 − 0.642 = 1.284 s, right stance 1.380 − 0.642 = 0.738 s and right swing 0.546 s; and the first double-support period is min(0.800, 1.380) − max(0.000, 0.642) = 0.158 s [3]. Repeating the calculation over all ten cycles gives the means in Table 8.8. The affected left limb spends 62.2% of the stride in stance, compared with 57.4% on the right, the expected pattern of prolonged stance on the affected side in hemiplegia [3].

Pooling the 22 heel strikes of both feet gives 21 step times with a mean of 13.4990/21 = 0.6428 s, so the cadence is 60/0.6428 = 93.34 steps/min, or 84.9% of the reference value of 110 [3].

8.9.3 Step and stride length

For the left step in cycle 1, L_kin = 2 × 0.62 × sin(12.10°) = 0.2599 m; the left step time is 0.642 s and the belt component is 0.500 × 0.642 = 0.3210 m, so the left step length is 0.5809 m. For the right step, L_kin = 2 × 0.62 × sin(18.05°) = 0.3842 m and, with the same belt component, the right step length is

0.7052 m. The stride length is 1.2861 m [3]. Over ten cycles, the mean left and right step lengths are 0.5795 m and 0.7080 m and the mean stride length is 1.2875 m [3].

8.9.4 Symmetry, variability and support

The step-length symmetry index is |0.5795 − 0.7080| / 0.6437 × 100 = 19.96%, while the stride-time symmetry index is only 0.03% [3]. The sample standard deviation of the left stride times is 0.001524 s, giving CV_L = 0.1185%; for the right limb CV_R = 0.0902% [3]. The mean double-support time from the single-period formula is 0.1598 s and DSR = 0.1598/1.2861 × 100 = 12.43% [3]. Applying the two-period definition of Section 8.4.2 to the same events, the analysis script obtains a mean second double-support period of 0.0921 s and a total DSR of 19.59% [5].

8.9.5 Torque and joint strength

For the left hip, the mean session force is 3.350 N; the human torque is (5.1 − 3.350) × 0.25 = 0.4375 N·m and PTF = 1.75/5.1 = 0.3431 [3]. The corresponding values for the other joints are shown in Table 8.8. The mean of the four PTF values is STR = 1.5287/4 = 0.3822 [3].

Table 8.8. Worked example (simulated data — not patient results): summary of calculated parameters.

Parameter	Left (affected)	Right	Reference used in source
Stride time (s)	1.2861	1.2857	~1.15
Stance time (s, % stride)	0.8000 (62.2%)	0.7380 (57.4%)	~60%
Swing time (s, % stride)	0.4861 (37.8%)	0.5477 (42.6%)	~40%
Step length (m)	0.5795	0.7080	—
Stride length (m)	1.2875		1.40
Stride-time CV (%)	0.1185	0.0902	< 3
Step-length SI (%)	19.96		0
Stride-time SI (%)	0.03		0
DSR, single-period / two-period (%)	12.43 / 19.59		20
Cadence (steps/min)	93.34		110
τ_human hip (N·m)	0.4375	0.4200	—
τ_human knee (N·m)	0.3825	0.4050	—
PTF hip	0.3431	0.3652	→ 1
PTF knee	0.3825	0.4378	→ 1

Sources: [3]; two-period DSR from [5].

8.9.6 Aspect scores and GRI

With these parameters, the five aspect scores are as follows [3]:

$$S = 1 - \frac{19.96}{20.54} = 0.0283$$

$$V = 1 - \frac{(0.1185 + 0.0902)/2}{4.2} = 1 - \frac{0.1044}{4.2} = 0.9752$$

$$B = 1 - \frac{12.43 - 20}{36 - 20} = 1.4734 \;\rightarrow\; 1.0000 \text{ (clipped)}$$

$$E = \frac{1}{3}\left(\frac{0.50}{0.90} + \frac{93.34}{110} + \frac{1.2875}{1.40}\right) = \frac{2.3237}{3} = 0.7746$$

$$\text{STR} = \frac{1.5287}{4} = 0.3822$$

Hence:

$$\text{GRI} = 0.25(0.0283) + 0.15(0.9752) + 0.20(1.0000) + 0.20(0.7746) + 0.20(0.3822) = 0.5847$$

With the two-period DSR of 19.59%, B is still clipped to 1.0000, and the script reproduces the same GRI of 0.5847 [5].

8.9.7 Reading the example

The worked example illustrates how the composite should be read: by its components rather than its total. A GRI of 0.58 conceals a sharply uneven profile. Stability and support are near their maxima, efficiency is good, joint strength indicates that the child supplies a little under 40% of the passive torque requirement, and symmetry is near zero because the step-length asymmetry (19.96%) is almost as large as the normalization baseline (20.54%). The program documents use such profiles to suggest the next therapeutic emphasis [3,6]. The earlier design notes, for instance, reasoned from their own fictitious profile, in which joint strength was the lowest component, that training should shift toward resistance-mode work to challenge voluntary torque generation while preserving gains in symmetry and balance [6]. In the deployed software, GARAS, such recommendations are generated by a rule-based expert system with twelve recommendation categories, each triggered by explicit numerical thresholds on the computed parameters (Section 8.10.5) [9]. They are not produced by a language model. They remain hypotheses generated by the index for a therapist to consider, not validated clinical rules.

8.10 Clinical Dashboard and Report Software

8.10.1 Purpose and architecture

Two applications implement the calculations. The first, the CEMRR gait pipeline dashboard described in Sections 8.10.1–8.10.4, was built to visualize the calculations cycle by cycle at the treatment station. The second, GARAS (Section 8.10.5), extends the same calculations into a longitudinal analysis and recommendation system and is the software that has been applied to data recorded at NCCR.

The CEMRR gait pipeline dashboard implements the calculations of Sections 8.4–8.8 and displays the results in a dashboard intended for use at the treatment station [4]. It is written in Python 3.12 with a PyQt6 user interface, pyqtgraph for charts, and numpy and scipy for numerical work, and it is packaged with PyInstaller as a standalone executable [4]. The architecture follows a model–view–controller pattern in which the calculation and simulation core is separated from the user-interface panels [4].

As documented, the dashboard runs in simulation mode, generating randomized data based on the reference child of the worked example, and replays recorded sessions from CSV files in the format of Table 8.3 [4]. The documentation describes the path to a live connection: the CSV loader is to be replaced by a serial or data-acquisition reader, the joint angles read directly from the encoders, and the animation driven by detected heel strikes rather than by a timer, with the calculation logic and display panels unchanged [4].

8.10.2 Display panels

The dashboard comprises several panels [4]. A sagittal-plane stick-figure animation shows both legs walking, with the affected leg in red and the unaffected leg in green, phase badges for stance, swing and double support, heel-strike and toe-off labels at the moment of each event, the knee angle beside each knee, and a timeline bar indicating the current phase of each leg. Five circular gauges show the aspect scores S, V, B, E and STR, updated after each completed gait cycle and colored according to the bands of Section 8.8.8. A large semicircular gauge shows the GRI from 0 to 100% with a plain-language status line.

A pressure-map tab places the 16 sensors of each insole inside an anatomical foot outline, colored from dark blue (low) through green to red (high), with a weight-distribution bar that shifts toward the more heavily loaded foot in real time and a numerical ALI. A live-charts tab provides four time-series views — joint angles, load-cell forces, temporal parameters and spatial parameters — updated each cycle; the documentation notes that these are most informative when compared across sessions, when convergence of the affected-side traces toward the unaffected side indicates improvement [4]. A session-data tab tabulates all computed parameters in groups (temporal, spatial, symmetry and variability, torque and strength, GRI components), with color coding of values outside normal ranges [4].

8.10.3 Session control and sample data

The operator starts, pauses and resets a session, or loads a CSV file for replay [4]. In simulation mode, all panels update every 3 s as each new cycle is completed [4]. Three sample files are bundled: one reproducing the hand-calculation reference data at 0.50 m/s; one simulating the same child after six weeks of therapy, with improved range of motion, a belt speed of 0.65 m/s and better symmetry; and one simulating a severe hemiplegic case with stiff-knee gait (38° peak knee flexion) at 0.35 m/s [4]. The documentation states that the last two were parameterized from published therapy-outcome and clinical reference values. All three files are simulations for software testing and demonstration and are not patient data.

8.10.4 Relationship to the device software

The robot's own operator software logs joint angles, torques, step symmetry and cadence and can export CSV files [1,7]. The CEMRR dashboard and GARAS are separate applications that consume such exports, combined with insole and load-cell data, in the formats of Table 8.3 and Section 8.10.5 [4,9]. Both rely on the three sensor streams sharing a common time base, because every per-cycle record pairs insole events with encoder angles and load-cell forces from the same cycle. Chapter 9 describes the program's data platform.

8.10.5 GARAS: Gait Analysis and Rehabilitation Advisory System

GARAS (Republic of Kazakhstan copyright certificate No. 74083) was developed at CEMRR under program BR27199433 in 2025–2026 [9]. It accepts the raw signals of the four joint encoders, the four Futek load cells, the two 16-sensor insoles and the treadmill belt speed, either by manual entry or as a multi-session CSV file, and processes them in seven sequential stages [9]:

1. *Stage 0 — ingestion and validation:* completeness and unit checks, session numbering and linkage to the child's earlier sessions.
2. *Stage 1 — feature extraction:* gait events and the ten spatiotemporal parameters of Sections 8.4–8.6.
3. *Stage 2 — aspect scores and GRI:* the five scores and the composite of Section 8.8, with a principal-component projection of the five scores into a two-dimensional "gait fingerprint" whose distance from Session 1 serves as a supplementary trajectory measure.

4. *Stage 2B — recovery curves:* a Gaussian-process regression with a squared-exponential kernel fitted to each aspect score and to the GRI as functions of session number, giving a smooth recovery curve with a 95% interval; a plateau flag is raised when the posterior mean changes by less than 2.5% over the last five interpolation points.
5. *Stage 2C — responder classification:* a linear mixed-effects growth model across children, GRI ≈ β_0 + (β_1 + u_{1i})·k (in the current implementation the group slope is estimated by pooled least squares and each child's slope deviation u_{1i} is computed from it), in which each child's slope is compared with the group slope β_1; children with a slope above 1.25·β_1 are classified as fast responders and those below 0.65·β_1 as slow responders.
6. *Stages 3–4 — trajectory profile and attribution:* identification of the weakest, strongest and plateaued aspects, the ALI and JSI, and a Shapley-value (SHAP-style) decomposition of each session-to-session change in GRI, φ_aspect = w_aspect·Δscore, which identifies the aspect that drove the change.
7. *Stages 5–6 — recommendations and reports:* a rule-based expert system with twelve recommendation categories, each triggered by explicit thresholds — for example on DSR (body-weight support adjustment), the speed ratio (treadmill speed progression), step-length SI (symmetry biofeedback), stride-time CV, PTF and STR (assistance or resistance mode), ALI (plantar loading), JSI (joint stiffness alert), GP plateau status (programme escalation) and responder class — with each recommendation assigned a High, Medium or Low priority; and output as a text report, CSV and JSON files and an interactive dashboard.

Because the score decomposition is linear, the "SHAP" values are exact weighted differences rather than estimates from a machine-learning model, which makes them easy to audit. The recommendation rules encode the clinical experience of the CEMRR rehabilitation team and are intended to be revised as evidence accumulates [9]; they are decision support for the therapist, not autonomous prescriptions. The user interface is browser-based, runs offline without transmitting data, and is fully trilingual: all labels, recommendation texts and status badges can be switched at run time between Kazakh (the default), Russian and English [9].

GARAS has been run on data recorded from children at NCCR. Its outputs on those data are not reported in this chapter: the design and status of the program's gait trial are reported in Chapter 10.

8.11 Limitations and Validation Roadmap

The GRI is a promising organizing idea, but several aspects of its current definition require scrutiny before it is used as an outcome measure in a publication of clinical results.

Normalization constants. The baselines (SI 20.54%, CV 4.2%, DSR 36%) are fixed constants inherited from the reference dataset and applied to every child [5]. The software documentation and hand-calculation document describe them as Session 1 values [3,4], which suggests that a child-specific baseline was originally intended. The two approaches answer different questions: a fixed baseline places every child on a common scale, while a child-specific baseline measures change relative to that child's own starting point but makes values incomparable between children. The worked example itself is internally ambiguous on this point, since its own step-length SI (19.96%) differs from the SI_baseline it is normalized by (20.54%). The choice should be made explicitly and justified.

Reference values. The normal references used in E (0.90 m/s, 110 steps/min, 1.40 m) and the support reference in B (20%) [3,4] are program reference values pending validation; they are not drawn from an age-matched normative dataset. The 20% figure for double support is of the order of the total double-limb support time (two periods of roughly 10% each) described for typical adult walking [10], which supports the two-period definition of DSR. The pre-assessment form gives different reference values for adolescents aged 13–18 — a comfortable speed of approximately 1.0–1.3 m/s and a cadence of

approximately 100–115 steps per minute [8] — and the GARAS specification describes its references as age-matched [9]. These values should be reconciled, and replaced by published age- and sex-specific norms, before the GRI is used to report trial results.

Treadmill step length. On a treadmill in steady walking, the distance the belt travels during a step is itself an estimate of step length relative to the belt. Adding a kinematic chord to this belt displacement, as the current formula does, yields stride lengths of about 1.29 m at a belt speed of 0.50 m/s and a stride time of 1.29 s in the worked example [3], whereas the belt moves only about 0.64 m per stride at that speed. The two components may be measuring overlapping quantities, and the efficiency ratio for stride length and the symmetry index both inherit any bias. The formula should be validated against the overground footprint measurements collected at pre-assessment, and the belt term alone should be considered as the estimate of treadmill step length if the comparison favours it.

Efficiency and therapist settings. The speed term of E uses the belt speed, which is set by the therapist rather than chosen by the child. E therefore partly measures the treatment prescription rather than the child's capacity, and any progression protocol that raises belt speed will raise E mechanically.

Patient torque measurement. The load-cell measurement of the patient's joint torque contribution is a joint-reaction measurement whose accuracy depends on load-cell calibration and on the moment-arm estimate. PTF also assumes that the passive calibration remains a valid reference throughout training, which may not hold if speed, range of motion, body-weight support or cuff fit change. The magnitudes in the worked example (forces of 2–5 N and human torques below 0.5 N·m at a 0.25 m moment arm) are small, and real values will depend on where the load cells are mounted and how they are calibrated [3]. Repeating the passive calibration periodically, and at every change of settings, and recording the calibration date with each session would make the measure more robust.

Variability under external pacing. With both treadmill and robot imposing a rhythm, stride-time CV is likely to be very low (0.09–0.12% in the worked example [3]), so V may be close to 1 for most children and carry little information.

Double support definition. The single-period and two-period definitions of DSR differ by a factor of about 1.6 in the worked example (12.43% versus 19.59%). The two-period definition used in the analysis script [5] is physically more appropriate, and the documentation should be updated accordingly.

Weights and aggregation. The weights are expert-assigned [3]. Composite indices are sensitive to weighting and to the clipping of components, and a sensitivity analysis is advisable.

Validation. Before the GRI is used as a trial outcome, three properties should be established. Test–retest reliability can be estimated from repeated sessions at unchanged settings, using intraclass correlation and the standard error of measurement, from which a minimal detectable change follows. Convergent validity can be examined by correlating the GRI and its components with the clinical measures collected in the gait trial — the 6MWT (the primary outcome), 10MWT, TUG, GMFM-88 and the Paediatric Berg Balance Scale — and with the sEMG, IMU and insole gait parameters. Responsiveness can be examined by relating change in the GRI to change in these measures between baseline and post-intervention. The trial's design, which collects both the robot-derived data and the clinical measures in the same children, provides the opportunity to do so; the recommendations generated by GARAS should be evaluated in the same way before they are relied on clinically.

8.12 Summary

The CEMRR gait pipeline converts the data available during robot-assisted treadmill training — joint encoder angles, load-cell forces and plantar pressure insole signals — into a coherent set of gait descriptors. Heel strikes and toe-offs detected from the insoles yield stride, stance, swing and double-support times and cadence; encoder hip angles, leg length and belt speed yield step and stride length; and the comparison of session load-cell forces with a passive calibration yields the patient's joint torque contribution and the Patient Torque Fraction. Five normalized aspect scores — symmetry, stability, support, efficiency and joint strength — are combined into the Gait Recovery Index, GRI = 0.25·S + 0.15·V + 0.20·B + 0.20·E + 0.20·STR. A ten-cycle worked example, reproduced in this chapter, takes illustrative raw data through every step to a GRI of 0.5847 and shows that the composite is best read through its components. A dashboard application implements the calculations with gauges, plantar pressure maps and session tables, and GARAS, which has been run on NCCR data, adds Gaussian-process recovery curves, mixed-effects responder classification, Shapley-value attribution of change and a twelve-category rule-based recommendation engine in a trilingual interface. Several assumptions — fixed normalization constants, reference values, the treadmill step-length formula, the use of belt speed in efficiency, and the stability of the passive calibration — need to be resolved, and the reliability and validity of the GRI need to be established against the clinical measures collected in the program's trial before the index is used to report clinical results.

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Chapter 9. Clinical Data Acquisition, Rehabilitation Platform and VR Training Software

Abstract. The devices described in Part II produce useful data only if those data can be captured, synchronised, linked to clinical information and stored safely. This chapter describes the software layer that the program built around the devices and the clinic. It covers the NCCR Rehabilitation Platform for managing clinical and sensor data; the head-mounted virtual-reality (VR) training program developed under contract for use with the Gait Rehabilitation Robot and first used with children in a 2025 pilot study; the rule-based methods developed for removing direct identifiers from, and extracting structured clinical variables out of, Russian-language clinical records containing Kazakh names; and the data-governance arrangements that support the program's plan for an open, de-identified dataset. The program's software outputs are protected by Republic of Kazakhstan copyright certificates obtained in June 2026. Where technical details have not yet been documented for publication, this is stated.

Keywords: clinical data platform; multimodal sensor data; data synchronisation; de-identification; virtual reality; exoskeleton training; cybersickness; data governance; open data

9.1 Why the Program Needed Its Own Data Layer

Robot-assisted rehabilitation generates data from several sources that were never designed to work together. In the program these included the joint encoders and Futek load cells of the Gait Rehabilitation Robot (Chapter 4), the load-cell, pressure and cable-displacement sensors of the body-weight support system (Chapter 5), the cable-tension and motor signals of the Robotic Perturbation Trainer (Chapter 6), wearable sensors (surface EMG, inertial measurement units and plantar-pressure insoles, recorded in the 2025 pilots with the Noraxon Ultium portable laboratory and Medilogic insoles), video and audio recordings of the social-robot sessions (Chapter 7), and the clinical assessments recorded by therapists at NCCR. Each source has its own sampling rate, clock, file format and identifier scheme.

Three practical problems followed. First, signals had to be aligned in time so that, for example, a gait event detected by an insole could be matched with the joint angle and the muscle activity at the same moment. Second, sensor data had to be linked to the child's clinical profile (diagnosis, CP subtype, GMFCS level, assessment scores) without exposing the child's identity. Third, NCCR clinical records are mostly written in Russian and contain Kazakh personal names. Off-the-shelf de-identification tools, built largely for English, do not specifically address these records. Chapter 1 noted that standardised functional classifications were often missing or recorded only in free text, which made structured extraction necessary as well as de-identification.

The program addressed these problems with several software products: the gait analysis pipeline and GARAS (Chapter 8), the NCCR Rehabilitation Platform, a VR training program for use with the Gait Rehabilitation Robot, and a pipeline for de-identification and structured extraction of clinical records. The registered products are listed in Table 9.1.

Table 9.1. Republic of Kazakhstan software copyright certificates obtained under program BR27199433 (June 2026).

Certificate No.	Software	Described in
74083	GARAS gait analysis and rehabilitation recommendation system	Chapter 8
74149	VR-based exoskeleton training program for patients with CP	Section 9.3
74396	NCCR_Rehabilitation_Platform_2025	Section 9.2

Certificate No.	Software	Described in
74308	Kazakh speech-synthesis routing system for QTrobot	Chapter 7
74309	Kazakh and Russian scripts for robot-assisted therapy for children with CP	Chapter 7

All copyrights arising from the program are owned by Nazarbayev University Research Administration (NURA).

9.2 The NCCR Rehabilitation Platform

9.2.1 Purpose and scope

The NCCR Rehabilitation Platform, registered as NCCR_Rehabilitation_Platform_2025 (certificate No. 74396), is the program's software for bringing together the clinical and sensor data generated in rehabilitation sessions at NCCR. Its role in the program follows from the problems set out in Section 9.1: to hold each child's pseudonymised clinical profile and assessment results alongside the session records and sensor files from the devices, so that the analyses reported in Chapters 5, 6, 8, 10 and 11 can draw on linked, consistently identified data. The program's calendar plan records that a synchronised dataset combining clinical and instrumental data was collected at NCCR in 2025 and integrated into a single normalised dataset for feature extraction and the evaluation of measures such as the Berg Balance Scale and the Gross Motor Function Measure.

9.2.2 Data organisation

A data model suitable for rehabilitation research separates four layers: the participant (pseudonymous study code, demographic and clinical profile), the assessment (date, assessor, instrument and score), the session (device, settings such as belt speed and BWS level, duration, adverse events) and the signal (raw and processed sensor streams linked to the session). The program's datasets follow this principle in their identifiers: study codes, such as ABWS1–ABWS7 in the body-weight support pilot (Chapter 5), do not correspond to clinical record numbers. The clinical variables used across the program's studies include GMFCS, MACS and CFCS levels; the 6MWT, 10MWT and TUG; GMFM-88; the Paediatric Berg Balance Scale; and, in the social-robot studies, WISC-V and observational engagement codes (Chapters 3, 10 and 11).

9.2.3 Integration with the analysis software

The gait analysis software of Chapter 8 accepts session data as structured CSV files: the dashboard replays per-cycle records, and GARAS imports multi-session files with one row per session [1]. These file-based interfaces allow session data held for a child to be analysed without manual re-entry and make each analysis reproducible from the stored files. Data-quality checks of the kind GARAS applies at ingestion — completeness of required fields, unit checks and session linkage [1] — are a minimum; checks for sensor dropout and synchronisation error between streams should be added before the trial analyses.

9.2.4 Status

A copyright certificate protects the platform's code as a literary work. It is not evidence of validation, and the platform's outputs have not been reported in a peer-reviewed publication.

9.3 VR-Based Exoskeleton Training Program

9.3.1 Rationale

Repetitive treadmill training in a gait robot is effective only if the child stays engaged for the whole session, and engagement is a recurring difficulty in paediatric rehabilitation (Chapters 2 and 11). Virtual-reality environments can turn stepping into a goal-directed task, give immediate feedback on performance and add a cognitive component to motor practice. The program's application set out to build a VR system that would work with its robotic devices, provide cognitive interaction alongside physical rehabilitation, and be tested with children (program Task 8). The research team had earlier built a proof-of-concept mixed-reality system on the Microsoft HoloLens 2 to run alongside a gait rehabilitation robot; the program's system was developed for current head-mounted displays of the Meta Quest family (Meta Quest Pro and Meta Quest 3S), with Unity, the XR Interaction Toolkit and the Mixed Reality Toolkit (MRTK).

9.3.2 Development and architecture

The VR program (certificate No. 74149) was developed for NURA under contract by Vexor LLP and delivered in 2025, with exclusive rights to the results transferred to NURA [2]. It is a head-mounted application built on Unity 2022 LTS with the Universal Render Pipeline, using the XR Interaction Toolkit for tracking and interaction and MRTK 2.8 or later, with Windows Device Portal access, as the basis for mixed-reality extensions and voice commands [2]. The software is organised in layers: an input layer that accepts movement from hand controllers, a development simulator or the treadmill; a translation layer that converts every input into a common forward-speed and direction format; a locomotion layer that moves the user's viewpoint; and the interactive scenes [2]. Because the treadmill is treated as one input source among several, the virtual walking speed can follow the belt speed (parametric synchronisation over 0.1–2.0 m/s is specified) without changes to the locomotion logic [2].

9.3.3 Scenes and tasks

The program provides five interactive environments — an aul (Kazakh village), a school with classroom and corridor, a park, a home and a playground — with a library of more than 50 interactive objects and a single set of interaction mechanics (select, activate, collect) used across all scenes [2]. Culturally adapted assets include a yurt that serves as a landmark, start and finish point and "mission station", and a set of five types of Kazakh ornament (*oyu*) that serve as target objects [2]. The sessions are designed as cognitive–motor dual tasks: the child walks continuously while periodically making decisions. Three end-to-end scenarios were demonstrated at acceptance: *Navigation and Selection* (moving to a checkpoint, selecting and confirming a target, receiving feedback); *Collecting Objects by Rule* (sequentially collecting five to ten ornaments of a specified type, with error recording and hints); and *Guided Route* (navigating forks by following arrows) [2]. Difficulty is scaled parametrically through speed, number of targets, number of forks, frequency of hints, selection rules and visual density, and calmer scenes (home and park) are provided as low-sensory-load options [2]. Voice-command structures were implemented in Kazakh and Russian [2].

9.3.4 Data logging and integration with the robot

Every session event is logged with a timestamp, an anonymised participant identifier, a session identifier, the scene, the event type and its parameters — for example target selected or confirmed, wrong target, item collected, checkpoint passed, wrong turn, route completed, hint shown and safety stop — and exported as CSV or JSON for analysis of reaction time, accuracy, errors and stage duration [2]. The logs use pseudonymous identifiers only, consistent with the de-identification requirements of

randomised trials. An integration layer with the gait robot was prepared to stream joint angles, velocities, torque and force, device states and safety events, to place VR events and exoskeleton parameters on a common timeline, and to allow the level of robotic assistance to be linked to the context of the scene (for example, increased support in difficult sections) [2]. The contractor's report describes this layer as ready at the interface level, and recommends that an exchange protocol with the treadmill and robot be agreed, that performance be validated on the target headset over 10–15 minutes of continuous use, and that thresholds and response times for safety stops be documented and tested (a response time below 100 ms to safety events is specified) [2].

9.3.5 Use in the program

The VR program was used with children in the program's 2025 pilot study combining the Gait Rehabilitation Robot with VR-based gait training at NCCR, in which five children received the combined intervention and five control children received conventional manual therapy, with the 6MWT as the primary outcome. The pilot was intended mainly to estimate an effect size for planning a larger trial (Chapter 3).

9.3.6 Safety of head-mounted VR during treadmill walking

A head-mounted display removes the child's view of the treadmill, the robot and the room. Three hazards therefore need explicit management when it is used during robot-assisted treadmill walking. The first is cybersickness, a form of motion sickness caused by mismatch between visual and vestibular cues, which is most likely when virtual movement does not match the belt speed. In a study of 50 children aged 4–10 years playing a 3D game in a head-mounted display for 60 minutes, paediatric simulator-sickness scores rose modestly but significantly, three children stopped within the first ten minutes (two with symptoms consistent with mild motion sickness), and postural stability worsened on average by 9% after exposure, although this change did not reach statistical significance [3]. The second hazard is loss of balance or a fall, both during walking with occluded vision and immediately after the headset is removed. The third is the added strain of a headset on children with limited head and trunk control. In the program's set-up these risks are mitigated by the overhead harness and body-weight support system and by the gait robot's own safety layers (Chapters 4 and 5); by synchronising virtual speed to the belt; by using short exposures, calm scenes and low visual density at first; by stopping the session at the first sign of discomfort; and by observing the child after the headset is removed. Children with photosensitive epilepsy should be screened before exposure. These measures are precautions, not evidence of safety, and adverse events and symptoms should be recorded systematically in any trial of the combined intervention.

9.4 De-identification and Structured Extraction of Clinical Records

NCCR clinical documents are predominantly Russian-language texts that contain Kazakh personal names, national individual identification numbers (IIN, 12 digits) and home addresses. Before such documents can be used for research, direct identifiers must be removed and key clinical variables extracted into structured fields. As part of program BR27199433, the team developed a rule-based pipeline for this purpose, which is being prepared for publication as a methods paper [4]. The pipeline works on PDF documents and comprises three methodological components and a supporting step [4]. The first removes three predetermined classes of direct identifier — patient names, IINs and home addresses — from the documents; its rules handle Kazakh-specific characters and the declined forms that Kazakh names take in Russian sentences. The second extracts clinical classifications and scale scores, such as GMFCS and MACS levels, from free text in a way that tolerates the visually identical Cyrillic and Latin characters (homoglyphs) that occur within abbreviations in these records, without

globally converting Cyrillic text, which would corrupt genuine Russian words. The third infers the patient's sex category from the document's patient-directed grammatical-gender conventions, with explicit caveats where Russian grammatical gender does not reflect the patient's sex. A final step reconciles duplicate records by exact identifiers before the structured output is written. Validation used a synthetic document corpus and independent manual review of a sample of real documents during method development; the accuracy figures will be reported in the publication.

In this book, "de-identification" refers specifically to the removal of these three classes of direct identifier. It is not a comprehensive anonymisation of all potentially identifying information, such as dates, telephone numbers, institutions, relatives' names or rare diagnoses, and documents processed in this way remain personal data to be handled under the program's ethics approval.

9.5 Data Governance and Open Data

Data handling in the program followed the approvals of the Nazarbayev University Institutional Research Ethics Committee (NU-IREC), including Approval No. 1081 of 21 May 2025 for the body-weight support pilot, the perturbation-training trial and the QTrobot studies, and the approval for use of the Gait Rehabilitation Robot in the gait trial (Chapter 3). Consent and assent forms were available in English, Kazakh and Russian. Participants were identified in research datasets by study codes that do not correspond to clinical record numbers, and video recordings were stored with access restricted to the research team (Chapter 3). The processing of participants' personal data is subject to the Law of the Republic of Kazakhstan "On Personal Data and Their Protection" [5].

The program plans to deposit a de-identified dataset in a public repository so that its analyses can be reproduced and extended. In September 2026 a protocol amendment was submitted to NU-IREC to allow this, together with revised consent, assent and recruitment forms; the amendment has been conditionally approved. The choice of repository and licence is under consideration. Raw video and audio recordings, which could identify children, will not be shared.

9.6 Limitations

The software products described in this chapter have not yet been described in peer-reviewed publications, and their validation has not been reported. A copyright certificate protects code as a literary work; it is not evidence of clinical validity. The VR program's integration with the gait robot is specified at the interface level, and its effects on engagement, gait and cognition in children have not yet been reported. Any use of the platform's or the analysis software's outputs for clinical decisions would require verification and, depending on intended use, classification and registration as medical-device software (Chapter 13).

9.7 Summary

The program built a data layer to connect its robotic devices, wearable sensors and clinical records. It comprises the NCCR Rehabilitation Platform for managing linked clinical and sensor data; a head-mounted VR training program, developed under contract by Vexor LLP, with five culturally adapted environments, dual-task decision-making scenarios, pseudonymised event logging and an interface layer for the gait robot, which was used in the 2025 Gait robot + VR pilot; and a rule-based pipeline for removing direct identifiers from, and extracting clinical variables out of, Russian-language records containing Kazakh names. A de-identified dataset is planned for public release under a conditionally approved ethics amendment. Five software copyright certificates, owned by NURA, protect the program's software.

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Part IV. Clinical Evidence and Translation

Chapter 10. Clinical Evidence for Robot-Assisted Gait and Balance Rehabilitation

Abstract. This chapter brings together the clinical evidence the program has produced on gait and balance, and states plainly what is published, what is in manuscript form, and what is still pending. Two studies have been completed and analysed: an exploratory pilot of individualized body-weight support (BWS) in seven children and adolescents with cerebral palsy (CP), reported in a manuscript in preparation, and a ten-session implementation of the Robotic Perturbation Trainer (RPT) in two adolescents with CP, published in *MethodsX*. Two larger studies are under way or awaiting analysis: the registered two-arm trial of robot-assisted gait training in adolescents aged 13–18 years (ACTRN12626001203347), in which 25 children have been enrolled and robot-assisted sessions began on 19 October 2026, and a perturbation-training trial in 25 children with CP. The chapter summarizes the completed studies, describes the design and current status of the two trials, and outlines how their results will be analysed and reported, including with the Gait Recovery Index (GRI) and Balance Recovery Index (BRI). It closes by comparing outcome measures across studies and stating what the evidence does and does not yet support.

Keywords: cerebral palsy; robot-assisted gait training; body-weight support; perturbation-based balance training; feasibility study; randomized controlled trial; outcome measures; Gait Recovery Index; Balance Recovery Index

10.1 Scope and Status of the Evidence

Table 10.1 lists the program's gait and balance studies and their status at the time of writing (October 2026). Only one clinical result in the table has passed peer review. The BWS pilot is reported in a manuscript in preparation; the 2025 pilot trials of the Gait Rehabilitation Robot have been completed but their results report has not yet been finalized; and the registered gait trial and the perturbation-training trial have not yet reported. The healthy-adult validation of the final RPT configuration is included for completeness, although it is an engineering study rather than clinical evidence. Earlier clinical programs with the gait robot, described in the device documentation (Chapter 4), are not included because no methods or quantitative results have been formally reported.

Table 10.1. The program's studies of gait and balance devices and their status.

Study	Device	Design	Participants	Main outcomes	Status	Details
Individualized BWS pilot	Adaptive BWS (fixed-level mode)	Prospective single-arm; within-participant sweep of 7 support levels, then 3–5 training sessions at the selected level	7 children and adolescents with CP, 10–17 years, GMFCS I–II (6 completed training)	Plantar-pressure gait metrics across support levels; 6MWT, 10MWT, TUG, OMNI exertion pre–post	Completed; manuscript in preparation [1]	Chapter 5; 1

Study	Device	Design	Participants	Main outcomes	Status	Details
						0.2
RPT implementation	Robotic Perturbation Trainer (four-cable) with BWS	Two single-case implementations; 10 sessions over 5 weeks; pre, mid and post assessment	2 adolescent males with CP, 16 and 17 years, GMFCS III and I	6MWT, 10MWT, TUGT, BBS, GMFM; gluteal sEMG	Published, *MethodsX* 2026 [2]	Chapter 6; 10.3
Multi-plane RPT validation	Robotic Perturbation Trainer (final configuration)	Single-session, four-stage protocol: baseline and sagittal, frontal and transverse perturbations	3 healthy adults	sEMG temporal and amplitude features	Completed; manuscript [4]	Section 6.10.2
Gait robot pilot trial (2025)	Gait Rehabilitation Robot	Two-group pilot	6 intervention, 6 control	6MWT	Completed; results report pending	Section 10.4.3
Gait robot and VR pilot	Gait Rehabilitation Robot	Two-group pilot; control = conventional manual therapy	5 intervention, 5 control	6MWT	Completed; results report pending	Sectio

Study	Device	Design	Participants	Main outcomes	Status	Details
trial (2025)	with VR					n10.4.3
Registered gait trial	Gait Rehabilitation Robot	Explanatory parallel two-arm RCT; robot-assisted vs conventional gait rehabilitation	25 enrolled, 13–18 years, GMFCS I–III	6MWT (primary); 10MWT, TUG, GMFM-88, PBS; sEMG, IMU, insoles; GRI	Registered, ACTRN12626001203347 [3]; robot sessions in progress since 19 October 2026	Section10.4
Perturbation-training trial	Robotic Perturbation Trainer	See Section 6.10.3	25 children with CP	BBS (primary)	Conducted under NU-IREC No. 1081; results pending	Section10.5
Phase-synchronized BWS mode	Adaptive BWS (phase-synchronized mode)	Under development	None reported	—	No participant data reported	Section5.4.3

Abbreviations: 6MWT, 6-Minute Walk Test; 10MWT, 10-Metre Walk Test; TUG(T), Timed Up and Go Test; BBS, Berg Balance Scale; PBS, Paediatric Berg Balance Scale; GMFM, Gross Motor Function Measure; OMNI, OMNI Rating of Perceived Exertion Scale; RCT, randomized controlled trial.

The BWS pilot, the RPT implementation and the perturbation-training trial were conducted under Nazarbayev University Institutional Research Ethics Committee (NU-IREC) Approval No. 1081 (21

May 2025). Use of the Gait Rehabilitation Robot in the registered gait trial received NU-IREC conditional approval on 14 October 2026, and the conditions have been met.

10.2 Individualized Body-Weight Support: What the Pilot Showed

The BWS pilot asked a methodological question: can a support level be chosen for each child from their own gait data, rather than set by a fixed rule? Seven children and adolescents with CP (10–17 years, GMFCS I–II) walked on the treadmill at seven support levels from 0% to 30% of body weight in 5% steps, in fixed ascending order, while plantar pressure was recorded with 64-sensor insoles at 100 Hz and surface EMG at 2000 Hz. A multidomain score built from plantar-pressure measures of temporal symmetry, temporal variability, centre-of-pressure behaviour and loading symmetry was used to select the best-tested level for each child (Section 5.6) [1].

Three findings stand out. First, the selected level varied widely, from 5% to 30% of body weight, in children of broadly similar functional level. This is the main argument against a single prescribed level. Second, the selection was robust for five children but uncertain for two, for whom two or more levels scored within 5 points of each other or the bootstrap often failed to reproduce the primary choice. A clinical method therefore needs to report the certainty of its recommendation, not only the recommendation. Third, gait at the selected level differed from unsupported walking mainly through a reduction in stride-time variability, which fell in all seven children; changes in symmetry were inconsistent in direction [1].

Six participants then trained for three to five 15-minute sessions at their selected level; the seventh (ABWS7) completed the selection assessment but was unable to attend training or the post-assessment. After training, four of six completed the comfortable-speed 10MWT faster and five of six the TUG faster, but 6MWT distance fell in five of six, with a median change of −50 m [1]. The manuscript does not establish why endurance declined; fatigue from a concentrated rehabilitation period, the timing of assessments and the short training dose are all possible explanations. Assessor blinding was not reported. With six participants, no control group and no inferential testing, these pre–post changes describe the cohort and cannot be attributed to the intervention [1].

10.3 Perturbation-Based Balance Training: What the Published Implementation Showed

The published RPT study demonstrated that a cable-driven trainer could deliver randomized transverse-plane perturbations of 65–85 N to adolescents walking on a treadmill with body-weight support, for ten sessions, without protocol deviations or missing assessments [2]. Bench testing showed force errors of a few newtons and consistent delivery in all four directions (Section 6.9.1).

Clinically, both participants performed best at the mid-point assessment. The participant with spastic diplegia at GMFCS I returned close to baseline by the end of training on most measures, while the participant with dyskinetic CP at GMFCS III remained better than baseline on all five measures at post-test, with a 6MWT gain of 24.5 m that exceeded the upper bound of the MCID range used [2,5]. Gluteal muscle activation changed significantly across phases in most muscles tested. The authors of the original paper interpret all of these results as exploratory evidence of feasibility, and the large between-trial standard deviations reinforce that reading [2].

The RPT has since been rebuilt in its final, multi-plane configuration and evaluated in three healthy adults (Section 6.10.2) [4]. That study characterizes plane-specific and dominance-specific muscle responses; it contributes to the design of paediatric protocols but is not clinical evidence in CP.

10.4 The Registered Gait Trial

10.4.1 Design

The program's main test of robot-assisted gait training is an explanatory, parallel, two-arm randomized controlled trial at the National Center for Children's Rehabilitation (NCCR), Astana, registered with the Australian New Zealand Clinical Trials Registry as ACTRN12626001203347 [3]. It compares robot-assisted gait training with the Gait Rehabilitation Robot against conventional (manual) gait rehabilitation.

Participants. Children and adolescents with CP aged 13–18 years at GMFCS levels I–III are eligible if they are cognitively able to report pain, have upper-limb strength of at least 3+ on manual muscle testing and a Modified Ashworth score of 2 or less, have no unconsolidated fractures or fixed contractures, and are in good general health. In the 2025 pilot, height of 160–195 cm and shoe size of 38 or more were applied as device-fit criteria (Chapter 4).

Intervention. The intervention group receives 10 sessions of 20 minutes of robot-assisted gait training. Program documents prepared earlier described other schedules (ten 30-minute sessions in the program application; three to four sessions a week for eight to ten weeks in the ethics protocol); the dose adopted for the trial is ten 20-minute sessions. Session delivery details are described in Chapter 4.

Outcomes. The primary outcome is the 6-Minute Walk Test (6MWT), measured at baseline and after the intervention. Secondary outcomes are the 10-Metre Walk Test (10MWT), the Timed Up and Go (TUG) test, the 88-item Gross Motor Function Measure (GMFM-88), the Paediatric Berg Balance Scale (PBS), instrumented gait parameters from surface EMG, inertial sensors and pressure insoles, and the Gait Recovery Index (Chapter 8). The NCCR pre-assessment (Section 4.11.2) adds footprint-based step and stride length, step width and cadence, and a passive calibration on the robot that is required to compute the joint-strength component of the GRI.

Allocation. Allocation follows a computer-generated sequence.

10.4.2 Current status

Enrolment began on 10 September 2026, and 25 children have been enrolled. Until NU-IREC approved use of the Gait Rehabilitation Robot (conditional approval on 14 October 2026, with the conditions since met), only pre-assessment was carried out, in children staying in Astana and registered with NCCR. Robot-assisted sessions began on 19 October 2026 and are continuing. Seven children living in Astana have been recruited for follow-up assessments after the end of the intervention, which will provide a first, limited view of retention. Participant flow and outcomes will be reported following the CONSORT 2010 statement [6].

10.4.3 Sample size

The program application set a target of 23 participants, based on the 6MWT with 80% power. The 2025 pilot trials provide effect-size estimates for a formal calculation, which are presented, with corrections to the arithmetic in the program's working documents, in Chapter 3. For a two-sided test at $\alpha = 0.05$ with 80% power (constant $2(1.96 + 0.84)^2 = 15.68$), the gait robot pilot (6 vs 6; between-group difference $\delta = 44$ m, pooled $\sigma = 62.5$ m) gives 31.6, that is 32 children per group, or 37 per group allowing for 15% attrition. The gait robot and VR pilot (5 vs 5; $\delta = 50.3$ m, $\sigma = 61$ m) gives 23.06, that is 24 per group, or 28 per group with attrition. The results of these pilots will be reported when the pilot results report is finalized.

With 25 children enrolled, the current phase is therefore an explanatory, feasibility-scale trial, consistent with the program's reduced pilot-sampling strategy. It can estimate effects and their uncertainty, test procedures and instruments, and inform the design of a confirmatory trial, but a confirmatory comparison of robot-assisted and conventional gait training on the 6MWT would need the larger numbers above.

10.4.4 How the trial addresses the limitations of the pilots

The completed studies share four limitations: very small samples, no concurrent control group, unreported or absent assessor blinding, and short follow-up. The registered trial addresses the control-group limitation by design and enlarges the sample, although not to confirmatory size, and the seven children recruited for follow-up assessments will begin to address retention. It also provides the first opportunity to test the instrumented indices of Chapter 8 against established clinical measures in real patients. Whether the GRI tracks change in the 6MWT, GMFM-88 or walking speed is an empirical question that the trial data can answer.

10.5 The Perturbation-Training Trial

The program's second trial applies perturbation-based balance training with the RPT in 25 children with CP, all different children, under NU-IREC Approval No. 1081. The Berg Balance Scale (BBS) is the primary outcome; the program application specified 25 children to provide 80% power on this outcome. The design as implemented, the study dates, and the RPT configuration and perturbation mode used are described in Section 6.10.3, where the outstanding details are listed. Results are pending. Like the gait trial, this phase is too small to be confirmatory, and the absence of an established minimal clinically important difference for the BBS in paediatric CP (Section 6.9.5) will complicate the interpretation of individual change.

10.6 Measurement Across the Gait and Balance Studies

The studies used overlapping but not identical outcome batteries (Table 10.2). This reflects their different questions, but it limits comparison between devices. A core set of measures used in every study (for example 10MWT, 6MWT and TUG, with GMFCS recorded for every participant) would allow pooled analysis in future.

Table 10.2. Outcome measures used in the gait and balance studies.

Measure	BWS pilot	RPT study	Gait trial
6MWT	Yes	Yes	Yes (primary)
10MWT	Yes (comfortable and fast speed)	Yes	Yes
TUG / TUGT	Yes	Yes	Yes
Berg Balance Scale	No	Yes (BBS)	Yes (Paediatric BBS)
GMFM	No	Yes	Yes (GMFM-88)
Perceived exertion (OMNI)	Yes	No	
Surface EMG	Yes	Yes (gluteal muscles)	Yes
Plantar pressure	Yes	No	Yes

Measure	BWS pilot	RPT study	Gait trial
IMU	Specified in later protocol (WaveX)	No	Yes
Gait Recovery Index	No	No	Yes

In both completed studies, the interpretation of change was hampered by the absence of established minimal clinically important differences for several tests in paediatric CP. The RPT paper interpreted 6MWT and GMFM changes against published, distribution-based MCID ranges [5] but could not do so for 10MWT, TUGT or BBS [2]. The registered trial and the perturbation trial should prespecify which thresholds they will use, and report between-group differences with confidence intervals rather than relying on thresholds for individual children.

10.7 What the Gait and Balance Evidence Supports

Taken together, the completed studies support three modest conclusions. The BWS system and the RPT can be used safely and acceptably with children and adolescents with CP in a routine rehabilitation setting in Astana; all RPT sessions were completed as planned, and six of the seven BWS participants completed training. The response to a given device setting differs markedly between children, which supports individualizing support and challenge rather than prescribing fixed doses. And the measurement tools developed by the program, including plantar-pressure metrics, EMG and device-derived signals, are sensitive enough to detect within-child change.

The evidence does not yet show that any of the devices improves gait or balance more than conventional therapy. That is the question for the registered gait trial and the perturbation-training trial, each of which has enrolled 25 children. Because both are feasibility-scale, their results will provide effect estimates and their uncertainty, not definitive answers; confirmatory trials of the size indicated in Section 10.4.3 will be needed before robot-assisted gait or balance training can be recommended over conventional care. The GRI and BRI remain methods under development until they have been validated against the clinical outcomes collected in these trials.

10.8 Summary

The program's completed gait and balance studies are small and exploratory, with one peer-reviewed feasibility paper and one manuscript in preparation. They show that the BWS and RPT systems can be used with children with CP, that the best level of support differs from child to child, and that change can be measured with the program's instrumentation. Efficacy remains untested. The registered gait trial (ACTRN12626001203347) has enrolled 25 adolescents, completed pre-assessment and began robot-assisted sessions on 19 October 2026; the perturbation-training trial has been conducted in 25 children with the BBS as primary outcome. Their results will be reported when the trials are complete.

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Chapter 11. Clinical Evidence for Social-Robot-Assisted Therapy

Abstract. This chapter appraises and synthesises the clinical evidence generated by the program on socially assistive robot (SAR) therapy for children with cerebral palsy (CP) in Kazakhstan. The QTrobot platform and its Kazakh- and Russian-language content are described in Chapter 7; here the concern is what was observed when the platform was used with children. In all, 170 different children took part in the program's social-robot studies. Six empirical studies are reviewed: a seven-session pilot feasibility trial (published), a ten-session longitudinal study with a standard-care comparison group (under review), a qualitative microgenetic study of cognitive behaviour (under review), an exploratory comparison of engagement in robot-assisted and tablet-based sessions (in preparation), a feasibility study of acoustic and listener-based speech outcomes (in preparation) and a pre–post study of narrative language after bilingual robot storytelling (in preparation). The program's published scoping review frames the international context. For each study the chapter sets out aims, participants, design, procedures, measures and results, followed by an appraisal of interpretation and limitations, with explicit attention to publication status and shared participants. The 2025 pilot randomised trial (10 vs 10 children, WISC-V outcome) and the sample size it implies for a confirmatory trial are also reported. The synthesis identifies converging findings (feasible bilingual delivery in routine rehabilitation, resolution of initial novelty within a few sessions, increased participation and verbal output, and the robot's role as a social focal point) and findings that do not converge (modest video-coded engagement, no gain in speech intelligibility despite more speech, and an unexpected engagement advantage for a tablet-only format). A section on the implementation barriers documented across the studies and a summary of what the evidence can and cannot yet support conclude the chapter.

Keywords: socially assistive robots; QTrobot; cerebral palsy; paediatric rehabilitation; feasibility; behavioural observation; engagement; narrative language; speech intelligibility; Kazakhstan

11.1 Introduction and Scope

11.1.1 Purpose and reporting conventions

A device description cannot tell a clinician whether children will accept a robot, whether sessions fit the rhythm of a busy rehabilitation centre, which outcomes move, and how confidently any movement can be attributed to the robot. This chapter brings together the answers that the program's social-robot studies currently provide. Because the studies are at different stages of publication, each is labelled with the status recorded in the program's paper register: *published* (with journal and digital object identifier), *under review* or *in preparation*. Numbers from manuscripts that are under review or in preparation may change. No simulated or synthetic data are reported; all results come from observations of children, recordings of their speech, or video of their sessions.

All studies operated under the approval of the Institutional Research Ethics Committee (IREC) of Nazarbayev University (approval 1081, 21 May 2025), with site approval from the host centre and written informed consent from parents or guardians. The program's randomised controlled trial of QTrobot-assisted therapy is registered with the Australian New Zealand Clinical Trials Registry as ACTRN12625001214426. The registration was retrospective: the first child was enrolled before the trial was registered. Results are reported with the statistics used by the original authors, and limitations are stated next to the results they qualify.

The program worked with 170 different children in its social-robot studies, all recruited through NCCR, which receives roughly 300 children each month. The manuscripts reviewed here account for fewer than 170 children (Table 11.1); the remaining children took part in work that has not yet been written up, such as the 2025 usability testing of the scripts (Chapter 7, Section 7.6).

11.1.2 Overview of the studies

Table 11.1 summarises the six empirical studies and the scoping review. They are ordered by the logic of the program: the pilot established feasibility; the longitudinal study asked whether change accumulated over a longer protocol and differed from standard care; the microgenetic and engagement studies examined, at a finer grain, how children behaved during sessions; and the speech and narrative studies turned to communicative outcomes that the scoping review had identified as poorly measured.

Table 11.1. Overview of the social-robot studies reviewed in this chapter.

Study (section)	Design	n (analysed)	Population and setting	Principal outcomes	Status
Scoping review (11.9) [1]	PRISMA-ScR review, six databases, 2015–2025	20 studies	Children ≤18 years with CP; SARs for cognitive, speech, communication rehabilitation	Robot types, outcomes, settings, gaps	Published, *J NeuroEng Rehabil* 2026;23:34, doi:10.1186/s12984-025-01852-0
Pilot feasibility trial (11.2) [2]	Single-group pre–post, 7 scripted sessions	9 enrolled; 8 analysed	CP, 5–12 years; paediatric rehabilitation centre, Astana	Feasibility; six behavioural outcomes; checklist items; behaviour mapping	Published (early access), *IEEE Trans Med Robot Bionics*, doi:10.1109/TMRB.2026.3733187
Longitudinal controlled study (11.3) [3]	Two parallel groups; 10-session protocol vs standard care	32 per group; 28 in trajectory models; 23 vs 32 in functional comparison	CP and other neurological conditions, 5–12 years; NCCR, Sept–Nov 2025	Session-level trajectories in 11 domains; functional task pre–post	Under review, *Int J Soc Robot* (SORO-D-26-00192)
Microgenetic study (11.4) [4]	Qualitative microgenetic multiple-case design	8 children; 65 sessions	Spastic CP, 7–10 years; Astana, Sept–Oct 2025	Interval-coded engagement; WISC-V-informed domain profiles and trajectories	Under review, *IEEE Trans Cogn Dev Syst*
Robot vs tablet engagement (11.5) [5]	Comparison of two non-equivalent groups	8 robot (65 sessions); 7 tablet (69 sessions)	CP, 6–10 years; same room and content	Segment-level engagement (1–5)	In preparation
Speech intelligibility	Single-group pre–	8 received the intervention; 7 analysed	CP, 4;10–10;6 years; Kazakh and Russian; 2026	Five acoustic measures;	In preparation

Study (section)	Design	n (analysed)	Population and setting	Principal outcomes	Status
(11.6) [6]	post feasibility			blinded listener identification	
Narrative language (11.7) [7]	Single-group pre–post	10 enrolled; 8 matched	CP, 4;10–10;6 years; Kazakh and Russian; 2026	Microstructure, story grammar, cohesion, elicitation dependency	In preparation
Pilot randomised trial, 2025 (11.8.5) [34]	Two-arm parallel pilot; 10 sessions over three weeks vs conventional therapy	10 intervention, 10 control	Children with musculoskeletal and neurological disorders; NCCR	WISC-V Full-Scale IQ; therapist observations	Results report in preparation

11.1.3 Cohorts and shared participants

The six empirical reports are not independent samples. They draw on four groups of children, called cohorts here for convenience; the labels are an editorial device not used in the papers.

Cohort A is the pilot: nine children enrolled and eight analysed [2]. It was conducted under IREC approval No. 1081 of 21 May 2025. None of the pilot children took part in any later cohort, and the later studies in any case excluded children with previous structured experience of a social robot [3,4].

Cohort B comprises the 32 intervention and 32 control children of the longitudinal study at NCCR, September–November 2025 [3]. The microgenetic study [4] analysed eight children who received the same ten modules in the same order, with a familiarisation session on 24 September and data collection from 25 September to 9 October 2025, and describes itself as embedded in the program's larger SAR-assisted communication and cognition intervention. The robot arm of the engagement study [5] (here *Cohort B′*) has ages, diagnoses and per-child session counts (9, 8, 8, 9, 8, 9, 8 and 6, totalling 65) identical to the microgenetic sample, and both papers report re-coding 34 of the 65 sessions; they are therefore two analyses of one video data set, not independent replications.

Cohort C is the seven children who received the same content on a tablet application after the robot sessions had ended [5].

Cohort D underlies the speech [6] and narrative [7] studies. Ten children were enrolled; one never attended and one withdrew after the baseline assessment, so eight received all ten sessions [7]. The speech manuscript counts these eight as its enrolled sample and analysed seven, one child having no usable recording [6]; the seven match children P1–P7 of the narrative study in age, sex, CP type and language. The assessment picture used in both studies was created in May 2026, which places this cohort in or after May 2026, after Cohort B. The narrative manuscript states an age criterion of 5–12 years, whereas the speech manuscript states 4–12 years for the same cohort [6,7]; the youngest child (4 years 10 months) shows that the 4–12-year criterion was the one applied.

The registered trial, ACTRN12625001214426, was registered retrospectively. The speech and narrative manuscripts state that their studies were conducted within the larger project covered by the registration

but were not themselves randomised, and that their outcomes were exploratory additions to the registered protocol [6,7]. The allocation procedures also differed between studies: in the longitudinal study the supervising therapist assigned children to the intervention or control group by a draw from a written list of eligible children [3], whereas in the engagement study the clinic's list of eligible children was split into two groups before any child was seen, which its authors explicitly describe as non-random [5].

11.2 Pilot Feasibility Trial of Script-Based QTrobot Sessions

Status: published in early access, IEEE Transactions on Medical Robotics and Bionics, doi:10.1109/TMRB.2026.3733187 [2].

11.2.1 Aims

The pilot was the program's first clinical use of the QTrobot. Its premise was that the SAR literature came almost entirely from high-income Western and East Asian settings, and that nothing was known about robot-assisted therapy in a Central Asian centre characterised by Kazakh–Russian bilingualism and limited specialist availability; the authors note, citing UNICEF, that only 28.6% of children with a registered disability in Kazakhstan are covered by specialised social services [2,8]. The study asked whether a QTrobot intervention could be delivered feasibly within the centre, what effects it had on observable communication, cognition and social behaviour, and whether engagement differed statistically between baseline and a later session.

11.2.2 Participants

Nine children with CP aged 5–12 years were recruited from the centre's rehabilitation program; inclusion required adequate vision and hearing, the ability to respond to verbal prompts and to follow simple instructions, and exclusion applied to severe uncorrected sensory impairment or acute medical complications. Mean age was 86.1 months (SD 21.5; range 60–120); six were boys; eight had spastic CP and one an unrecorded type; seven spoke Kazakh and two Russian; five lived in Astana. Three children completed all seven sessions, two completed six, three completed four and one completed one. That child withdrew for health reasons, leaving eight analysable children. The per-participant table of the same paper lists one analysed child as having ataxic CP (G80.4), which does not agree with the demographic count of eight spastic cases. Functional classifications (GMFCS, CFCS) were not collected.

11.2.3 Design and procedures

The design was a one-group pretest–post-test study without a control group. Seven scripts were written by the research team at the Center of Excellence in Medical Robotics and Research (CEMRR) with the centre's rehabilitation specialists, reviewed by experts for content validity, and delivered identically to every child on seven consecutive days in sessions of about 10–15 minutes. They drew on stories and situations familiar to children in Kazakhstan (the Wise Donkey of Bukhara, Aldar Köse, a market, a hospital, a kitchen, a yurt) and combined storytelling, emotion recognition, turn-taking, sorting and role play, in Kazakh or Russian. The therapist operated the robot from one tablet while a second tablet in front of the child showed pictures and response options (Chapter 7).

Session 1 was the baseline and Session 4, not Session 7, the post-intervention point, because only three children completed all seven sessions whereas all eight completed four. The two sessions were designed to be comparable in task structure and cognitive load. The consequence is that the statistically evaluated exposure was three sessions.

11.2.4 Measures

Engagement was defined through eye contact, motor and vocal responses, emotional expression, attention and initiative. Two instruments were used: an observational checklist adapted from items of the Social Responsiveness Scale, Second Edition (SRS-2) [9], rated by frequency (not observed, rare, sometimes, often) in social, communication and cognitive domains; and behaviour mapping, a narrative observational record of each child's reactions, imitation, attention and task completion across all sessions. A research observer rated sessions live and a centre psychologist rated them independently from video. Percentage agreement on binary checklist items was 97.9% at Session 1 and 95.8% at Session 4; Kuder–Richardson 20 was 0.32 and 0.79, the low baseline value being attributed to most children scoring zero on most items at entry.

11.2.5 Results

Six behavioural outcomes were compared between Sessions 1 and 4 with Wilcoxon signed-rank tests (n = 8). None reached significance (all $p > 0.05$). Effect sizes ($r = Z/\sqrt{N}$) were large for initiative/engagement ($r = 0.786$) and moderate-to-large for motor response ($r = 0.556$). Median eye contact rose from 3.5 (interquartile range [IQR] 1–4) to 4.0 (IQR 3–4), attention from 3.5 (IQR 0–4) to 4.0 (IQR 2–4) and initiative by one point; motor response (2.0) and emotional expression (2.5) were unchanged; vocal response fell from 1.0 to 0.0 (IQR 0–4 at both points), which the authors relate to greater task complexity at Session 4.

Table 11.2. Checklist item medians (IQR) at Session 1 and Session 4 in the pilot trial (n = 8; 0 = not observed, 1 = rare, 2 = sometimes, 3 = often) [2].

Domain	Item	Session 1	Session 4	Change
Social skills	Eye contact with robot or instructor	3.00 (0.50)	3.00 (0.25)	0.00
Social skills	Social smile / positive affect	1.50 (1.50)	2.00 (1.25)	+0.50
Social skills	Initiates or responds to greetings	0.50 (3.00)	1.50 (3.00)	+1.00
Social skills	Imitates robot gestures or emotions	0.00 (0.00)	2.00 (3.00)	+2.00
Communication	Non-verbal communication	2.00 (2.00)	2.50 (1.00)	+0.50
Communication	Verbal communication	0.50 (1.50)	1.00 (2.00)	+0.50
Communication	Turn-taking / response to prompts	2.00 (2.00)	3.00 (1.00)	+1.00
Cognition	Sustained attention	3.00 (0.50)	3.00 (0.25)	0.00
Cognition	Task accuracy / correct responses	1.00 (2.00)	2.00 (1.25)	+1.00
Cognition	Follows instructions / completes tasks	2.00 (2.00)	3.00 (1.00)	+1.00

As tabulated, eight items increased and two (eye contact, sustained attention) were unchanged near the scale ceiling; imitation of the robot changed most. The paper's text summarises the same table as improvement in "9 of 10 items" with a change of +1.50 for imitation; the values above are those of the table. The six behavioural outcomes analysed with the Wilcoxon test are not single checklist items: each was operationalised from several checklist items (for example, eye contact from initiating joint attention and initiating social interaction items) [2], which is why their medians (up to 4.0) exceed the 0–3 range of an individual item. The paper does not report the maximum of each outcome, so their medians should be compared only within an outcome, not across outcomes.

Cross-participant analysis of the behaviour-mapping narratives identified ten recurring patterns. Acute entry distress in three children had resolved by Session 4, and none of them regressed. Novelty (surprise,

staring, admiration) turned into task-directed engagement within two to three sessions. The tablet had its own learning curve, from random touching or parent-assisted pressing to independent selection. Correct responding improved in every child (for example, from 50% to 80% in one child and from 50% to 100% in another). Parental assistance faded fully in one child and partially in others. Unprompted verbal initiation, such as greeting the robot, appeared in three children by Session 4 and never in four, and the authors propose it as a milestone worth tracking. Overall trajectories were classified as strong improvement in two children, notable or moderate improvement in four, maintained and deepened in one, and partial improvement in the child with ataxic CP; beyond Session 4, engagement was maintained or deepened in most children who continued.

11.2.6 Interpretation and limitations

The pilot's clearest contribution is feasibility: sessions ran within the centre's routine without serious technical difficulty, therapists operated the interface after minimal training, bilingual scripts worked as planned, and children tolerated repeated sessions. The behavioural findings are directionally encouraging, most clearly for imitation, task accuracy, instruction following and turn-taking, but not statistically established. There was no control group; the analysed exposure was three sessions; raters knew the session number; the checklist was adapted rather than validated; and the sample was small and lacked functional classifications. The authors' conclusion, that the study supports feasibility and justifies longer controlled designs, is the appropriate reading.

11.3 Longitudinal Controlled Study of Behavioural Trajectories

Status: under review, International Journal of Social Robotics, manuscript SORO-D-26-00192 [3]. Figures may change in revision.

11.3.1 Aims

The pilot left open whether gains continue over a longer protocol and whether children receiving robot sessions change differently from comparable children in standard care. The longitudinal study asked whether social, communicative, cognitive and functional behaviours changed across ten QTrobot sessions; which domains changed most; how heterogeneous responses were and whether baseline predicted them; and whether a standard-care group improved comparably on a structured functional task. Its distinctive feature is analytic: rather than comparing two time points, the authors observed every session and modelled the whole trajectory, following the growth-curve literature [10] and multi-session child–robot studies showing marked day-to-day variation in children's states [11,12].

11.3.2 Participants

Thirty-two children receiving rehabilitation at NCCR formed the intervention group and 32 children from the same caseload and period the control group. Eligible children were 5–12 years old, had a documented diagnosis of CP or another neurological condition, could sit for about 20 minutes and had a consenting parent; children needing urgent medical management or with previous structured therapeutic experience of a social robot were excluded.

Table 11.3. Participant characteristics in the longitudinal controlled study [3].

Characteristic	Intervention (n = 32)	Control (n = 29 with records)
Age, years, mean (SD); range	8.3 (2.1); 5–12	8.9 (2.2); 5–12
Male / female, n (%)	18 (56.3) / 14 (43.8)	16 (55.2) / 13 (44.8)
Cerebral palsy, n (%)	28 (87.5)	27 (93.1)

Characteristic	Intervention (n = 32)	Control (n = 29 with records)
Spastic diplegia / hemiplegia, n	15 / 7	17 / 6
Dyskinetic / spastic tetraplegia, n	5 / 1	3 / 1
Other neurological conditions, n (%)	4 (12.5)	2 (6.9)
Kazakh / Russian sessions, n (%)	24 (75.0) / 8 (25.0)	—
Sessions attended, mean (SD); range	8.62 (2.28); 2–10	—
Attended ≥7 / all 10 sessions, n (%)	28 (87.5) / 19 (59.4)	—

The non-CP conditions were sequelae of intracranial injury (two children), non-CP spastic hemiplegia and hydrocephalus in the intervention group, and Arnold–Chiari syndrome and craniosynostosis in the control group. Records for three controls could not be retrieved, although all 32 contributed functional task data. The findings therefore concern children with CP and related neurological conditions.

11.3.3 Design, intervention and measures

Two parallel groups were followed over about ten weeks; the manuscript describes allocation by the supervising therapist drawing from a written list and acknowledges that this simple procedure cannot exclude residual confounding. Controls continued NCCR's conventional therapist-delivered rehabilitation. The intervention consisted of ten fixed-script modules delivered in the same order to every child, so that session number and module coincided. Five modules were built on Kazakh and Central Asian folklore (the Wise Donkey of Bukhara, the Greedy Fox and the Magic Well, Aldar Köse, the Swan Mother, the Brave Batyr) and the others on everyday settings (market, doctor, kitchen, yurt, the Nauryz festival); module content and the robot's configuration are described in Chapter 7. Each session had a 2–3 minute opening in which the robot greeted the child by name and sang a thematic song, a main activity phase in which the therapist prompted as needed without replacing the robot's instructional role, and a 1–2 minute closing with praise and a farewell. Sessions lasted from about 6 to 15 minutes or more. Each child was addressed in his or her own language (24 children in Kazakh, 8 in Russian); Kazakh speech used the ISSAI KazakhTTS synthesiser running on the robot and Russian the robot's built-in voice (Chapter 7, Section 7.4.2).

Immediately after each session, the facilitating therapist completed an observational checklist built from SRS-2 items [9], converted from caregiver report to observed frequency (0–3) and supplemented by in-house items on cognition, functional participation and activities of daily living (ADL). Items were summed into four categories (Social Skills, Communication, Cognition, ADL) and seven Social Skills sub-domains: initiating and responding to joint attention (IJA, RJA), initiating and responding to behavioural requests (IBR, RBR), initiating and responding to social interaction (ISI, RSI) and social imitation. The adapted checklist has no construct, criterion or convergent validity evidence. An independent rater, blind to the primary scores, coded a random 31 of 277 sessions (11.2%) from video: the overall intraclass correlation ICC(A,1), interpreted according to Koo and Li [13], was 0.520, good for ADL (0.891), Cognition (0.881) and Communication (0.751), moderate for IJA (0.657) and RJA (0.594), and poor-to-moderate for the other social sub-domains (0.101–0.487). Cronbach's α was 0.761 across domains but 0.572 within Social Skills, largely because IBR correlated negatively with the other sub-domains.

Both groups also completed three sorting tasks (shapes, vegetables and coloured balls by card instruction) before and after the intervention period, each scored 0–2 for comprehension, accuracy, verbal communication and prompt dependency (maximum 24).

11.3.4 Analysis

The 264 sessions of the 28 children who attended at least seven sessions (87.5%) formed the analytic sample, following the recommendation that growth models include at least 60–70% of planned occasions [10]. The four excluded children had attended two to five sessions and did not differ systematically in age or diagnosis; reasons for non-attendance were not recorded. For each domain a linear mixed-effects model with a child-specific random intercept was fitted,

$$y_{ij} = \beta_0 + \beta_1 \,\mathrm{Session}_{ij} + u_{0i} + \varepsilon_{ij}$$

where β_1 is the mean change per session (session treated as continuous, 1–10), u_{0i} the child's random intercept and ε_{ij} the residual. A quadratic term $\beta_2 \cdot \mathrm{Session}^2_{ij}$ tested for curvature, and piecewise models compared Sessions 1–5 with 6–10. Sensitivity analyses used the 23 children with nine or more sessions (226 observations), and an exploratory analysis stratified children by baseline Social Skills tertile.

11.3.5 Results

Trajectories. All eleven linear models yielded significant slopes ($p \le 0.002$), nine positive and two negative (Table 11.4). Cognition had the largest category slope ($\beta = 0.577$ per session) and social imitation the steepest rise relative to its range. RJA and IBR declined. For RJA, RBR and RSI the random-intercept variance was near zero, with convergence warnings suggesting boundary solutions. Between-child spread widened over time (Social Skills SD 6.8 at Session 1, 11.4 at Session 10).

Table 11.4. Domain means at Sessions 1 and 10 and linear mixed-effects slopes per session (N = 28; 264 sessions) [3].

Domain (range)	Session 1, mean (SD)	Session 10, mean (SD)	β (SE)	95% CI	p
IJA (0–24)	11.6 (2.7)	13.5 (3.7)	0.192 (0.047)	0.10 to 0.28	<0.001
RJA (0–6)	4.4 (1.6)	2.4 (2.3)	−0.155 (0.045)	−0.24 to −0.07	<0.001
IBR (0–15)	1.8 (1.7)	0.1 (0.3)	−0.194 (0.026)	−0.24 to −0.14	<0.001
RBR (0–6)	2.8 (1.3)	3.1 (1.4)	0.105 (0.031)	0.05 to 0.17	<0.001
ISI (0–9)	6.1 (1.7)	7.8 (2.0)	0.175 (0.025)	0.13 to 0.22	<0.001
RSI (0–18)	7.0 (2.0)	10.3 (4.4)	0.304 (0.068)	0.17 to 0.44	<0.001
Social imitation (0–6)	2.3 (1.0)	4.3 (1.4)	0.191 (0.022)	0.15 to 0.23	<0.001
Social Skills (0–84)	36.0 (6.8)	41.5 (11.4)	0.642 (0.154)	0.34 to 0.94	<0.001
ADL (0–36)	24.0 (5.3)	28.0 (6.9)	0.399 (0.087)	0.23 to 0.57	<0.001
Communication (0–51)	29.2 (4.5)	33.1 (9.0)	0.323 (0.105)	0.12 to 0.53	0.002

Domain (range)	Session 1, mean (SD)	Session 10, mean (SD)	β (SE)	95% CI	p
Cognition (0–30)	20.1 (6.4)	25.8 (7.1)	0.577 (0.085)	0.41 to 0.74	<0.001

Shape of change. Quadratic coefficients were negative in every domain (−0.383 to −0.023) and are reported as significant in ten of eleven (stated as $p \leq 0.051$; a value of 0.051 would not meet the 0.05 threshold, so the count needs checking). The authors therefore regard an inverted U, with steep gains over Sessions 1–5 and stabilisation or modest decline afterward, as the better description, and present linear slopes only as summaries of direction. The Social Skills aggregate, for example, rose to 46.3 (SD 4.5) at Session 5 before falling back; Cognition rose steeply over Sessions 1–4 and then stabilised.

Robustness and heterogeneity. Restricting to children with nine or more sessions preserved the sign and significance of every slope ($p \leq 0.005$), with attenuation for ADL ($\beta = 0.259$) and Social Skills (0.540). In the exploratory tertile analysis, the lowest Social Skills tertile (Session 1 mean about 30) gained about 21 points by Session 7, roughly 70%, whereas the highest tertile (about 44) peaked around Sessions 4–5 and declined, consistent with a ceiling; all tertiles converged downward at Sessions 9–10. The reported tertile sizes (10, 9 and 10) sum to 29, not 28. Because the stratification was not prespecified and the lowest group had most room to rise, regression to the mean cannot be excluded.

Functional tasks. Pre and post data were available for 23 intervention children and 32 controls (Table 11.5). Baseline medians were identical (19.0; $U = 368.5$, $p = 1.000$). The intervention group improved (median change +2.0; Wilcoxon $W = 10.5$, $p < 0.001$; Cohen's d on paired differences 1.066) and the control group did not (median change 0.0; $U = 490.0$, $p = 0.772$), but the groups did not differ at post-test ($U = 423.5$, $p = 0.346$). The effect sizes that accompany the Mann–Whitney tests in the manuscript (0.501 at baseline, 0.575 at post-test and 0.479 for the control group's pre–post comparison) are labelled rank-biserial correlations, but they equal U divided by the product of the two sample sizes (for example, $423.5/(23 \times 32) = 0.575$). They are therefore probabilities of superiority, for which 0.5 indicates no difference; expressed as rank-biserial correlations they would be close to zero (0.00, 0.15 and −0.04). Intervention-group gains lay mainly in the verbal communication and prompt-dependency domains; comprehension and accuracy were near ceiling in both groups from the start.

Table 11.5. Functional task totals (maximum 24) [3].

Group	n	Pre, mean (SD)	Post, mean (SD)	Median pre → post	Within-group test
QTrobot intervention	23	17.22 (5.52)	18.65 (5.93)	19.0 → 21.0	$W = 10.5$, $p < 0.001$
Standard care	32	16.84 (6.37)	17.06 (6.63)	19.0 → 19.0	$p = 0.772$

11.3.6 Interpretation and limitations

This is the program's largest social-robot study and the first to report session-level trajectories of QTrobot-assisted therapy for children with CP in Central Asia. Its strengths are a protocol long enough to show the shape of change, high retention, robustness to a stricter attendance threshold, culturally grounded bilingual content and transparent reporting of reliability. Read cautiously, it shows that therapist-rated social, communicative, cognitive and daily-living behaviours rose over the first half of the protocol and then plateaued, most clearly for imitation and social responding, and that children starting lowest gained most. The authors interpret the RJA and IBR declines as "adaptive autonomy": children who had learned the robot's predictable routine needed fewer redirections and no longer had to solicit its attention. They acknowledge this reading is post hoc and that regression through fatigue, floor

effects or reduced cueing by the therapist remain possible. The structure of the checklist offers a further, measurement-based explanation: some items in these sub-domains depend on the session routine (for example, eye contact with the robot "when the SAR is inactive"), and the form also contains negatively worded items whose scoring direction is not reported (Chapter 7, Section 7.7.1).

The limitations are substantial. The instrument is unvalidated, and Cognition, the domain with the largest slope, consists of in-house items. Ratings were made by the facilitating therapist, unblinded to session number, and the sub-domains with the strongest positive trajectories had the weakest inter-rater agreement, whereas ADL, Cognition and Communication merit more confidence. The fixed module order confounds session with content; session length varied and dose was not modelled; the sample mixed CP and non-CP diagnoses without GMFCS data. Above all, the only comparison with standard care showed no between-group difference at post-test, and a significant change in one arm alongside a non-significant change in the other is not a test of the intervention effect. The control group's pre–post change was tested with the unpaired Mann–Whitney U test, which the manuscript justifies by unequal pre- and post-test samples [3]; its functional-task table, however, reports 32 control children at both time points. If the same 32 children were assessed twice, a paired test (Wilcoxon signed-rank, as used for the intervention group) would be the appropriate analysis, and the unpaired test, which ignores the correlation between a child's two scores, is less sensitive to change. The conclusion that the control group showed no detectable change should therefore be held provisionally until the paired analysis is reported. The study provides strong evidence of feasibility and retention and suggestive, unblinded evidence of in-session improvement, but not evidence of efficacy over standard care.

11.4 Qualitative Microgenetic Study of Cognitive Behaviour

Status: under review, IEEE Transactions on Cognitive and Developmental Systems [4]. Figures may change in revision.

11.4.1 Aims

Children with CP often perform below their capacity on standardised cognitive tests because the tests demand fine motor responses, physical effort or rapid speech, and may not suit every language and culture. The microgenetic study therefore asked not whether robot sessions improve cognition but whether repeated sessions provide a context in which cognitive behaviour becomes *observable*, and how that behaviour fluctuates and stabilises. Its questions concerned how children orient to a robot confined to the social layer of the session, how engagement evolves, and which behaviours, organised by the five index domains of the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V) [14], become visible and how consistently they can be summarised as within-child profiles and trajectories.

11.4.2 Participants, design and procedures

Eight children aged 7–10 years with spastic CP (five diplegia, three hemiplegia; four boys and four girls) were selected purposively with the clinical team. Inclusion required a neurologist-confirmed diagnosis, adequate vision and hearing and a consistent response modality (speech, gesture, gaze or assistive technology); uncontrolled seizures and robot-assisted rehabilitation in the preceding six months were exclusions. Communication ranged from fluent speech (several children) to partially verbal interaction with gesture and gaze (one child, P8). All children continued their multidisciplinary rehabilitation, which for some included robotic gait training.

The design was a qualitative microgenetic multiple-case study, an approach from developmental psychology that observes the same participants intensively and at close intervals so that the process of change, not only its occurrence, can be described [15]. After a familiarisation session on 24 September

2025 (Session 1, not coded), sessions ran from 25 September to 9 October 2025, usually once daily per child, using the ten Cohort B modules in fixed order; because of absences, a session number did not always denote the same module for every child. Analysed sessions per child ranged from six to nine (65 in total), mean duration per child from 6.1 to 7.2 minutes. Two therapists led the sessions (38 and 27), the second taking over most sessions from 2 October; neither took part in coding.

The session separated a *social layer* from a *task layer*. The robot greeted the child, narrated, asked every question aloud in Kazakh or Russian and delivered contingent feedback with gestures and facial expressions; the child-facing tablet only displayed stimuli and registered touches. Tablet answers were scored automatically and spoken or gestural answers were adjudicated by the therapist on a control tablet, since speech recognition was not used. This separation made it possible to ask whether children attended to the robot even though nothing needed for the task was on it.

11.4.3 Measures and analysis

A behaviour-mapping protocol grounded in Fredricks and colleagues' model of behavioural, emotional and cognitive engagement [16] and in Vygotsky's distinction between independent and scaffolded performance was applied retrospectively from video in 10-second intervals. For each interval one researcher recorded the robot's action, a free-text description of the child's verbal, non-verbal, facial, gaze and emotional behaviour, a behavioural category and an engagement rating from 1 (disengaged) to 5 (peak). Gaze and robot-action frequencies were later derived by dictionary search of the descriptors, not by automated video analysis.

Coded records were interpreted narratively through the five WISC-V domains: verbal comprehension (VCI), visual–spatial processing (VSI), fluid reasoning (FRI), working memory (WMI) and processing speed (PSI). Two researchers converted the narratives into ordinal 1–5 domain ratings per child (1 = critical weakness, 5 = dominant strength) from accumulated pairwise comparisons between domains, and each domain's course across early, middle and late sessions was classified as increase, plateau or decrease. The WISC-V was not administered; its structure served only as an interpretive vocabulary.

Reliability was assessed at three steps by researchers not otherwise involved. Re-coding of 34 of 65 sessions (52%) gave Cohen's $\kappa = 0.71$ and 81.8% agreement over 1,158 paired observations, substantial by Landis and Koch's benchmarks [17]. Blind re-derivation of all 40 domain ratings gave 27.5% exact agreement, 75.0% within half a point, quadratic-weighted $\kappa = 0.64$ and a mean absolute difference of 0.51, interpreted by the authors as moderate because exact agreement was low; the 29 disagreements were adjudicated, mostly toward the middle of the scale, and 49 of 56 recorded pairwise directions were satisfied by the final ratings. Trajectory classifications, prepared by one researcher and reviewed by a second, were audited for transfer into the summary table, agreeing in 38 of 40 cases ($\kappa = 0.90$); the two transcription errors were corrected.

11.4.4 Results

Orientation to the robot. Of 2,341 coded intervals, 1,390 had a documented gaze target; of these, 57.4% included gaze to the tablet, 52.2% gaze to the robot and 29.9% alternation between them, while gaze to the therapist (14.5%) or away (5.8%) was less common. Robot-directed gaze occurred in 63 of 65 sessions and in every child (32.0–80.6% of gaze-described intervals). Spontaneous social behaviour toward the robot, such as returning its greeting, imitating its gestures or anticipating its air-kiss routine from an earlier session, appeared in 43 intervals across 26 sessions and seven children. Positive feedback was recorded in 211 intervals across 63 sessions, a positive-to-corrective ratio of about 26:1.

Engagement. Group mean engagement was highest in the first analysed session (M = 2.74, SD 0.51), fell at the next (2.46), and from the fourth session onward held between about 2.48 and 2.65, between the low and moderate anchors. Entry values ranged from 1.87 (P5) to 3.45 (P6); P4 fluctuated most, reaching 1.97; P2 peaked late at 3.14. Final-session means spanned 2.12–2.64, and no child declined persistently. Only three children contributed to the last session.

Domain profiles and trajectories. Cohort medians were highest for VSI (4.00) and FRI (3.75), intermediate for VCI (3.25) and PSI (3.00) and lowest for WMI (2.75); no child received 5.0 in any domain, and PSI had the narrowest range (2.0–3.0). P8 had uniformly low ratings, including in domains requiring no speech. Qualitatively, visual–spatial processing and reasoning were most visible when children could answer by touch or gesture, comprehension often exceeded what expressive speech suggested, working memory was sensitive to cumulative load, and slow responding often reflected motor execution, confirmation-seeking or fatigue. Table 11.6 gives the trajectory classifications.

Table 11.6. Course of observed domain-relevant behaviour across the session sequence (↑ increase, → plateau, ↓ decrease) [4].

Domain	P1	P2	P3	P4	P5	P6	P7	P8	↑	→	↓
Verbal comprehension	↑	↑	↑	↑	↑	↑	↑	→	7	1	0
Fluid reasoning	↑	↑	↑	↑	↑	↑	↑	↓	7	0	1
Visual–spatial	→	↑	→	↑	→	→	→	→	2	6	0
Working memory	↑	↑	↑	↑	→	↑	→	→	5	3	0
Processing speed	↑	→	↑	→	↑	↑	↓	→	4	3	1

P8, the least verbal child with the fewest sessions, was the only exception in VCI and FRI; the only other decrease (PSI in P7) coincided with her final sessions and lowest engagement (2.14) and was attributed to fatigue.

11.4.5 Interpretation and limitations

The most robust finding is behavioural: although every task element was on the tablet, children looked at the robot in about half of the gaze-documented intervals and seven of eight responded socially to it, so the robot functioned as a social focal point layered over the task interface. Engagement followed the novelty pattern known from long-term child–robot studies [18,19]: a high first session, a dip and a modest plateau. The cognitive findings are best read as a proof of method, suggesting that repeated sessions let comprehension and reasoning be seen in children whose speech or movement would mask them in testing, and that cognitive expression is strongly modality-dependent. They do not show that cognition improved. There was no comparison condition; the window was eleven working days; the WISC-V frame was not validated against formal assessment; absolute ratings were partly anchored on engagement ratings; module order was fixed; the lead therapist changed midway; the tablet did not log item-level accuracy or latency, so processing speed was judged only at 10-second resolution; attendance varied; and GMFCS levels were not recorded. The authors propose a three-arm comparison delivering the same modules by robot, by tablet alone and by a therapist alone.

11.5 Engagement in Robot-Assisted and Tablet-Based Sessions

Status: manuscript in preparation; reliability statistics not yet reported [5].

11.5.1 Aims, participants and design

Direct robot–tablet comparisons have mostly involved autistic children, and comparison conditions in CP studies have usually been non-digital, such as switch-adapted toys [20]. This exploratory study compared engagement in QTrobot sessions with engagement in tablet-application sessions that delivered the same scripted stories, categorisation and emotion-recognition tasks without the robot, and set out to publish a transparent engagement codebook suited to children with motor and speech impairment. The robot group was Cohort B′ (eight children, 65 sessions, ages 7–10, five spastic diplegia and three spastic hemiplegia); the tablet group was seven different children (69 sessions, ages 6–10; two spastic diplegia, three spastic hemiplegia, two dyskinetic CP). The clinic's eligibility list was split into two groups before any child was seen; this was not randomisation, and the robot sessions preceded the tablet sessions. Both formats used the same room and session structure, with sessions intended to last no more than about 10 minutes. In the robot sessions one therapist supported the child while a second operated the robot from the control tablet, an arrangement the manuscript calls Wizard-of-Oz and this book calls semi-autonomous (Chapter 7, Section 7.3.3); in the tablet sessions the therapist's attention was fully available to the child.

11.5.2 Measures and analysis

Each recording was divided into 10-second segments, each scored once on a five-level codebook written by a psychologist and an inclusive-education specialist. The codebook rests on two axes, source of initiative and substantiveness of contribution, and ignores correctness, loudness, intelligibility and affect intensity. A fixed decision order is applied: no observable action defaults to level 3; a disengagement marker gives level 2 (partial) or 1 (complete); any answer to a question is level 4; an unprompted or substantively expanded contribution is level 5; navigational presses, echoes and isolated nods are level 3; a motor failure with visible intent is at least level 4. Because the disengagement check comes first, a segment containing both a valid answer and a brief disengagement marker scores 2. Scores were averaged by segment, session and participant, and inference used the child as the unit ($n = 15$): an exact permutation (Mann–Whitney) test with Cliff's δ, repeated for Sessions 1–6, in which every child contributed. Re-coding of 34 robot and 30 tablet sessions by two different independent raters, one per format, has been completed, but the weighted κ values are not yet reported

11.5.3 Results

Every tablet-group child had a higher mean engagement score than every robot-group child. Participant means ranged from 2.40 to 2.73 in the robot group (mean 2.56, SD 0.12) and from 3.20 to 3.55 in the tablet group (mean 3.37, SD 0.12): $U = 56$ (the maximum possible), exact two-sided $p \approx 0.0003$, Cliff's $\delta = 1.00$. The separation persisted for Sessions 1–6 (2.36–2.84 versus 3.19–3.69). Time at levels 4–5 was 7.8–18.3% per child with the robot and 20.1–49.0% with the tablet. A disengagement marker was present in 55.9% of robot segments (level 2 alone, 49.9%) but 0.8% of tablet segments, where 67.0% of segments were level 3 and 27.9% level 4; spontaneous level 5 contributions were also rarer with the robot (1.6% versus 4.3%). Within each format engagement usually declined from first to last session, more steeply with the robot (for example, 3.31 to 2.14 and 3.45 to 2.55) than with the tablet (largest decline 3.85 to 3.21), and only three robot-group children reached the ninth session, whereas six of seven tablet-group children completed ten.

11.5.4 Interpretation and limitations

The manuscript is candid about its limits, and the chapter adopts its reading. The separation is statistically clear but cannot be attributed to the robot. The groups were different children, non-randomly

allocated, with somewhat different diagnoses; format was confounded with time period, therapist familiarity with the scripts and therapist role; and the coding rule favours the tablet, because robot sessions require the child's gaze to move among robot, tablet and adult, and any brief glance away turns an otherwise engaged segment into level 2. The authors judge it likely that this rule substantially inflates the gap and may even reverse its true direction. Reliability is not yet reported, each format had its own rater, and the coder could not be blinded. Because the robot-group videos are those of the microgenetic study, the low values here do not independently confirm the modest engagement plateau reported there.

The result runs against earlier CP studies in which the robot was compared with non-digital materials [20,21]. It sits closer to stakeholder data from autism research in which a tablet version of a robot-assisted training scenario was often preferred for its familiarity and ease of use [22], although preference and moment-to-moment engagement are different constructs. The practical lesson is that an active digital control delivering identical content is a far more demanding comparator than a toy, and that the robot's added value over a well-designed tablet application cannot be assumed.

11.6 Objective Speech Outcomes: Acoustic and Listener Measures

Status: manuscript in preparation; target journal not decided [6].

11.6.1 Aims and participants

The program's scoping review found that none of the 20 included SAR studies in CP measured speech instrumentally or through blinded listener judgements, and that multilingual children were underrepresented [1,6]. The field could say that children speak more readily around robots, but not whether their speech changes. This study tested whether a two-layer protocol, Praat-based acoustic analysis plus blinded listener word identification, linked word by word, could be applied in a robot storytelling intervention for Kazakh- and Russian-speaking children with CP, and reported the protocol's performance alongside preliminary pre–post results.

The study belongs to Cohort D. Of the eight children who received the intervention, seven were analysed (one had no usable recording): four girls and three boys aged 4 years 10 months to 10 years 6 months (mean 8 years 1 month), three Kazakh- and four Russian-speaking, three with dyskinetic CP, three with spastic hemiplegia and one with spastic diplegia. Inclusion required an age of 4–12 years and at least single-word speech. Clinical notes described expressive speech from sounds and single words to phrasal speech, with dysarthria noted in three children; GMFCS, MACS, CFCS and dysarthria severity ratings were unavailable.

11.6.2 Intervention, measures and analysis

Each child received ten individual sessions over two weeks with the QTrobot (RD-V3 AI@Edge), 6–12 minutes each, in the dominant language; Russian used the robot's built-in Acapela voice and Kazakh the ISSAI KazakhTTS model. Each session combined a robot-told story with an interactive activity and comprehension questions, and one asked the child to retell the story. Speech was elicited immediately before the first and directly after the last session by asking the child to describe a single, culturally appropriate picture (a grandmother, two children and a dog under a tree with a kite caught in it, with a yurt and mountains), recorded with a lavalier microphone at 48 kHz without noise cancellation.

A native-speaking researcher marked word boundaries by hand with a custom Parselmouth-based tool, and five measures were computed per token: duration, mean fundamental frequency (F0), first and second formants (F1, F2) and intensity, with pitch and formants recomputed under child-appropriate settings (pitch 120–650 Hz, formant ceiling 8000 Hz). Five adult female listeners, native in both

languages and blind to child, timepoint and aims, identified each clip from a closed list of 58 glosses (chance about 1.7%). Before analysis, clips flagged by a blinded listener as incompletely recorded were excluded and an automatic timestamp check identified overlapping clips, whose content was verified against listener responses by predefined rules. The primary analysis compared matched pairs (the same word from the same child at both timepoints) with Wilcoxon tests and rank-biserial effect sizes; a mixed-effects logistic model with random intercepts for child, word and listener used all retained ratings.

11.6.3 Results

All children completed both recordings and all listeners the task. Of 151 tokens (39 pre-test, 112 post-test; 7–43 per child), 19 were excluded on the truncation flag and 8 after the overlap audit, and one was relabelled, leaving 124 clips (82.1%) and 620 ratings; 21 of the 27 exclusions were post-test clips. Listener accuracy ranged from 49.2% to 67.7%, pairwise agreement was 76.9% and Fleiss' κ 0.518 (moderate), essentially unchanged with excluded clips retained (0.513). Applying retrospectively the criteria it recommends for a controlled study (≥80% of children with both recordings, ≥75% usable clips, at least moderate listener agreement), the manuscript reports all three met. Children produced about three times as many codable words after the intervention.

Table 11.7. Acoustic change in the twelve matched word pairs (six children) [6].

Measure	Pairs changing in stated direction	Median change	Default settings: p (r)	Child settings: p (r)
Duration	10 of 12 shorter	−0.28 s	0.077 (0.59)	not recomputed
F0	9 of 12 higher (10 of 12 with child settings)	+25.5 Hz	0.077 (0.59)	0.027 (0.72)
Intensity	8 of 12 louder	+5.1 dB	0.110 (0.54)	0.110 (0.54)
F2	9 of 12 lower	−190 Hz	0.064 (0.62)	0.569 (0.21)
F1	6 up, 6 down	—	0.910 (0.05)	0.910

No acoustic comparison survived Holm correction, and the F2 effect, which disappeared under child settings, was treated as a measurement artefact. One word ("grandmother") contributed five of the twelve pairs, and one child had no word in common between recordings.

Identification did not change systematically. Across matched pairs the median rose from 80% to 100% ($W = 20.0$, $p = 0.480$, $r = 0.27$), with six pairs better, four worse and two unchanged. Over all 620 ratings the odds ratio for correct identification after the intervention was 1.22 (95% credible interval 0.98–1.53). The word was the largest source of variance (SD 1.33), ahead of child (0.96) and listener (0.48). Four children were identified better after the intervention, all of whom started low (30–57%), and three worse, all of whom started high (80–88%); the largest decline (80% to 20%) came from a heavily truncated, noisy post-test recording that the authors regard as uninterpretable.

11.6.4 Interpretation and limitations

The protocol worked, at a cost: almost one clip in five was lost, and the losses were not neutral. A damaged clip is almost never identified, so damaged pre-test clips depress the baseline and manufacture apparent improvement. For one child, the unaudited data showed identification unchanged at 67%; after four unusable pre-test clips were removed her baseline was 88% and the change became a decline to 71%. Audio quality control is therefore a safeguard against false-positive treatment effects. Two cheap

safeguards proved their value, a listener-completed "not recorded in full" column, which yielded an exclusion criterion independent of results, and an automatic overlap check; converging listener responses also allowed clip content to be verified by auditors who did not speak the target languages. Automatic energy-based segmentation could not replace manual word boundaries in dysarthric child speech.

Shorter, louder words with higher pitch fit a shift from slow, word-by-word production toward more fluent connected speech, consistent with the tripling of codable words. The pattern resembles the variables targeted by intensive voice treatment (LSVT LOUD) in children with spastic CP [23], and the dissociation between acoustic and intelligibility change matches a systematic review of motor speech interventions in CP [24]. Intelligibility is hard to move: gains of about 11–15% in the Speech Systems Approach trial required intensive, speech-focused therapy over several weeks [25], so a two-week storytelling program would not be expected to shift it. Alternative explanations include the lack of a control condition, reuse of the same picture, uncalibrated recording conditions, arousal from the immediately preceding session, a single non-blinded annotator, single-listener truncation flags and non-independent word pairs. The authors recommend for the controlled study a fixed list of five to ten picture words repeated at both timepoints, calibrated recordings, a post-test separated from the last session and a follow-up assessment.

11.7 Bilingual Robot Storytelling and Narrative Language

Status: manuscript in preparation; target journal not decided [7].

11.7.1 Aims, participants and intervention

Narrative ability supports literacy, school participation and peer relationships, and children with CP often score lower on narrative tasks; yet narrative assessment resources for Kazakh, an agglutinative language, are scarce, and no SAR study had delivered scripted stories in Kazakh. This single-group pre–post study in Cohort D asked whether robot storytelling in Kazakh and Russian was feasible and what changes in narrative microstructure, macrostructure and cohesion followed. Ten children were enrolled; one never attended, one withdrew after the baseline assessment, and eight completed all ten sessions with matched data (ages 4 years 10 months to 10 years 6 months; three dyskinetic, three spastic hemiplegic, two spastic diplegic; three assessed in Kazakh and five in Russian). The age criterion applied was 4–12 years, as stated in the speech manuscript for the same cohort; the narrative manuscript's 5–12 years does not match its youngest participant (4 years 10 months) (Section 11.1.3).

The ten modules used the stories and activities of Cohort B, listed in the narrative manuscript in a different order (Chapter 7, Section 7.5.3), each written independently in Kazakh and Russian rather than translated. Children were invited to retell the robot's stories and answer key questions; one module was a full retelling. Sessions lasted about 6–12 minutes (roughly 60–120 minutes in total over two weeks), in one language per child, with the robot semi-autonomous under therapist control.

11.7.2 Measures and analysis

The outcome was the single-scene picture-narration task of Section 11.6. Transcripts were checked against audio by a second researcher, and only the child's utterances were analysed. Microstructure comprised utterances, mean length of utterance in words (MLU), longest utterance, number of different words (NDW) and type–token ratio (TTR); NDW and TTR were treated as raw counts because both depend on sample length and their clinical validity has been questioned [26]. Macrostructure was scored on seven story-grammar elements in the Stein and Glenn tradition [27] (setting, character, initiating event, internal response, attempt, consequence, resolution; each 0, 0.5 or 1, composite 0–7). Cohesive

ties and the spontaneous versus prompted origin of content were also coded. A blinded second rater coded story grammar for three children (weighted $\kappa = 0.80$), and a second analyst reproduced all measures for all children (macrostructure $\kappa = 0.79$; microstructure ICC 0.91–0.99 for children with short utterances and 0.63–0.96 for children with longer connected speech). Wilcoxon and sign tests were used, with Benjamini–Hochberg correction.

11.7.3 Results

Table 11.8. Narrative microstructure before and after robot storytelling (pre / post; Long. = longest utterance in words) [7].

Child	Language	Utterances	MLU	Long.	NDW	TTR
P1	Kazakh	2 / 5	1.00 / 1.00	1 / 1	2 / 4	1.00 / 0.80
P2	Russian	9 / 25	1.33 / 1.20	3 / 3	11 / 25	0.92 / 0.83
P3	Kazakh	8 / 22	1.12 / 1.23	2 / 2	8 / 17	0.89 / 0.63
P4	Kazakh	7 / 16	1.00 / 1.12	1 / 2	5 / 17	0.71 / 0.94
P5	Russian	9 / 12	2.44 / 2.58	6 / 6	21 / 25	0.95 / 0.81
P6	Russian	5 / 22	4.00 / 2.91	7 / 8	19 / 48	0.95 / 0.75
P7	Russian	8 / 26	4.62 / 3.54	10 / 14	31 / 57	0.84 / 0.62
P8	Russian	10 / 6	3.20 / 4.33	6 / 12	22 / 25	0.69 / 0.96

Utterances increased in seven of eight children (median 8 to 19; uncorrected $p = 0.042$, not significant after correction); the one decrease was attributed to fewer follow-up prompts. NDW increased in every child (median 15 to 25; corrected $p = 0.043$, $r = 0.89$), but this reflects more output rather than demonstrated lexical diversity. MLU did not change (median 1.89 to 1.91; $p = 1.00$); its fall in the two most productive children reflected many short answers to follow-up questions, while their longest utterances held or grew. Longest utterance ($p = 0.098$) and TTR ($p = 0.624$) did not change significantly.

The story-grammar composite rose from a median of 2.0 to 3.5 (sign test 8/0; corrected $p = 0.043$, $r = 0.89$), but gains were concentrated in children who already produced connected speech. P6 moved from an object list to an initiating event, character action and causal reasoning, and P7 added an explicit internal response, a third character and causal, temporal and adversative connectives to an already episodic account. P5 and P8 showed emerging change, producing for the first time a spontaneous causal action statement or an initiating event and attempt. The remaining four children stayed at a labelling level, and their gains of one point or less consisted entirely of prompted or partially credited elements; they produced no spontaneous content at either timepoint. In P6 and P7 the spontaneous share of content fell (from 100% to 38% and 31%), meaning that much of their additional output was elicited by questions, whereas P8's spontaneous count rose from one to five.

11.7.4 Interpretation and limitations

Bilingual robot storytelling was feasible, and the most consistent change was in verbal productivity, which the authors interpret primarily as an engagement and participation effect rather than restructured linguistic competence, in line with a literature in which SAR effects on engagement are better supported than direct language effects [1,20,21]. Macrostructural growth appeared where development would predict it, in children who already combined words, and distinguishing prompted from spontaneous content proved essential to avoid overstating competence, particularly as some forced-choice answers were inconsistent. Without a control condition, maturation, practice with the identical picture and familiarity with robot and examiner remain alternative explanations. A single scene structurally limits

consequences and resolutions, threatening the validity of the macrostructure score, and a multi-scene wordless picture book is recommended. Automated and human segmentation diverged for the children with the largest gains; Kazakh and Russian samples were pooled although word-based MLU is not equivalent across agglutinative and fusional languages, and the children with the largest gains were mostly Russian-speaking; functional classifications were unavailable; the age range was wide; and the two language versions were not formally matched for length or complexity.

11.8 Synthesis Across Studies

The six studies differ in cohort, outcome, analytic tradition and maturity, so synthesis must be qualitative. This section identifies findings that recur across cohorts or methods, findings that do not fit together, and lessons for the program's registered trial.

11.8.1 What is converging

Feasibility of culturally adapted bilingual delivery. Every study that addressed feasibility found that QTrobot sessions could be integrated into routine paediatric rehabilitation in Astana. Retention was high where measured systematically (87.5% of the longitudinal intervention group attended at least seven of ten sessions) [3], sessions ran without serious technical disruption [2], and Kazakh content was delivered through a locally developed synthesiser alongside Russian [3,6,7]. Folklore-based and everyday-life modules were reused across all four cohorts. No study tested whether culturally adapted content outperforms non-adapted content, which the pilot authors list as a question for future work [2]. Feasibility was not unconditional: sessions were lost to illness, scheduling, recording failures and robot connectivity problems [4], and reasons for attrition were not recorded in the largest study [3].

An early novelty or anxiety phase that resolves within a few sessions. Three sources describe the same temporal shape. In the pilot, entry anxiety had resolved by the fourth session and novelty had turned into task-directed engagement within two to three sessions [2]; in the longitudinal cohort most domains rose steeply over five sessions and then plateaued, with uniformly negative quadratic terms [3]; and video-coded engagement in the microgenetic cohort peaked in the first analysed session and stabilised from the fourth [4]. This mirrors long-term child–robot research [18,19] and implies, as the longitudinal authors suggest, that new content or greater difficulty may be needed around Sessions 8–9 to sustain progress [3].

More participation and more talk. With different instruments in different cohorts, children's participation rose: turn-taking, instruction following and imitation in the pilot [2]; imitation and social responding and initiation in the longitudinal cohort [3]; codable words roughly tripled in the speech study [6]; and utterances rose in seven of eight children in the narrative study [7]. The program's authors read this as primarily an engagement and participation effect rather than a change in underlying linguistic or cognitive capacity [7], which is also how the international literature reads the evidence (Section 11.9).

The robot as a social focal point. Where the session design allowed a test, children oriented to and interacted with the robot although it carried no task content [4], and imitation of the robot was the most visible change in the pilot [2].

Larger relative change in children who start lower, and marked heterogeneity. The lowest baseline tertile gained most in the longitudinal study [3], and the four children whose speech identification improved were those who started lowest [6]; regression to the mean and ceiling effects are alternative explanations. Every study stresses heterogeneous individual trajectories [2–4], and the narrative study

adds a developmental gradient, with higher-order gains only in children who already produced connected speech [7].

11.8.2 What is not converging

Level of engagement versus direction of change. Therapist-rated checklists show rising behaviour over sessions [2,3], whereas independent video coding places mean engagement between the low and moderate anchors and flat after the first session [4], and the stricter engagement codebook applied to the same videos finds disengagement markers in more than half of robot segments [5]. These are different cohorts, instruments and constructs (frequency of target behaviours versus moment-to-moment engagement), so they are not strictly contradictory, but they caution against describing robot sessions as uniformly highly engaging. The two analyses of the Cohort B′ videos also use differently anchored engagement scales and describe the same sessions in different terms (semi-autonomous operation [4] versus Wizard-of-Oz [5]). The sessions themselves were the same: several adults from the research team were present, the robot followed a fixed script paced from a control tablet, and each child was addressed in Kazakh or Russian according to preference (Chapter 7, Sections 7.3.3–7.4.3). The difference between the two sets of results therefore lies in the coding rules, not in the sessions coded.

Robot versus tablet. The only direct comparison favoured the tablet completely [5], contrary to earlier CP studies [20,21]. For the reasons in Section 11.5.4 it cannot be read as a format effect, but it removes any basis for assuming that the robot adds engagement over a tablet delivering the same content, precisely the question the microgenetic authors' proposed three-arm design would answer [4].

Quantity versus quality of speech. Children talked more after robot storytelling, but listeners did not identify their words better [6], MLU did not change, and in the children with the clearest narrative gains much of the extra output was prompted [7].

Statistical significance. The pilot found no significant change [2] whereas the longitudinal study found significant slopes in every domain [3], reflecting sample size, observations per child and the move from two time points to full trajectories, but also different raters and instruments. In the longitudinal study's only comparison with standard care, the groups did not differ at post-test [3].

Declines that may or may not indicate progress. RJA and IBR declined in the longitudinal cohort [3], vocal response fell between Sessions 1 and 4 in the pilot [2], and processing-speed behaviour declined in one microgenetic case [4]. Each has a plausible benign explanation (less need for prompting, harder tasks, fatigue), none of which has been tested.

11.8.3 Measurement and reliability

Table 11.9 summarises the instruments and reliability evidence. Every behavioural instrument was developed or adapted within the program and none has been validated; the checklist derives from a parent and teacher questionnaire normed on autistic children [9]. Agreement was strongest where the coded unit was concrete (interval coding $\kappa = 0.71$; ADL and Cognition ICCs near 0.89) and weakest where coders inferred social intent or summarised across sessions (social sub-domain ICCs 0.101–0.487; exact profile agreement 27.5%). The studies in which the person delivering the session rated behaviour report the most consistently positive change; those coding video retrospectively report more modest and mixed findings.

Table 11.9. Principal outcome instruments and reliability evidence.

Study	Instrument	Rater and timing	Reliability evidence
Pilot [2]	SRS-2-derived checklist; behaviour mapping	Live observer; centre psychologist from video	97.9% and 95.8% agreement; KR-20 0.32 and 0.79
Longitudinal [3]	SRS-2-derived checklist with in-house items; sorting tasks	Facilitating therapist after each session	ICC(A,1) 0.520 overall (31 sessions), 0.101–0.891 by domain; α 0.761
Microgenetic [4]	10-second interval coding; 1–5 engagement; WISC-V-informed ratings	Researcher from video	κ 0.71 (interval); weighted κ 0.64 (profiles); κ 0.90 (trajectory transfer)
Engagement [5]	10-second segment codebook, 1–5	Main coder from video	34 robot and 30 tablet sessions re-coded; results pending
Speech [6]	Praat acoustics; closed-set identification	Single annotator; five blinded listeners	Fleiss' κ 0.518
Narrative [7]	Microstructure; story grammar; cohesion; elicitation	Transcriber; blinded second rater; full replication	Weighted κ 0.80 and 0.79; ICC 0.63–0.99

11.8.4 Common threats to validity and implications for the registered trial

The studies share five threats to validity that the registered trial (ACTRN12625001214426) is positioned to address: absent or weak comparison groups; raters aware of session and condition; confounding of session number with module content through fixed module order; incomplete clinical characterisation, since no study reported GMFCS levels and none can therefore say for whom the robot works; and measurement problems, including unvalidated instruments, functional tasks near ceiling and a tablet application that did not log item-level accuracy or response time. The manuscripts already propose remedies: validated outcomes such as the SRS-2 itself, blinded independent coding, counterbalanced module order, stratification by CP subtype and functional level, tablet logging of stimulus onset, touch time and correctness, a fixed word list and calibrated recordings for speech, and a multi-scene picture book for narrative [3,4,6,7].

The registered trial addresses the first and last of these threats most directly. It is planned as an explanatory parallel randomised controlled trial comparing QTrobot-assisted sessions with conventional standard care, with children randomised to the two arms and a three-week intervention period, and with the WISC-V, a normed and formally administered test, as the outcome, assessed at baseline and after the intervention in both arms together with social-skill assessments; analysis is by non-parametric tests and analysis of variance [34]. The program calendar placed baseline assessment in April–June 2026, the three-week intervention and the conventional-therapy control program in July–August 2026, post-intervention assessment in September–October 2026 and analysis in October–December 2026 [34]. Chapter 3 (Section 3.5.7) describes the trial within the program's clinical framework.

11.8.5 The 2025 pilot randomised trial and the sample size for a confirmatory trial

Before the registered trial, the program ran a pilot randomised trial at NCCR in 2025 to estimate the effect size and variability needed to plan it [34]. Ten children were allocated to QTrobot-assisted therapy and ten to conventional therapy. Each child in the intervention group had ten sessions with the robot over three weeks, each built on a different one of ten bilingual Kazakh–Russian scripts aimed at communication, attention and social reciprocity. Outcomes were assessed with the WISC-V Full-Scale IQ (FSIQ), together with qualitative behavioural observations by clinical therapists [34]. The full results

of this pilot have not yet been reported. The program has released only the inputs to the sample-size calculation: a between-group difference of 4 FSIQ points, with standard deviations of 7.1 points in the intervention group and 4.7 points in the control group.

The pooled standard deviation is $\sqrt{[(7.1^2 + 4.7^2)/2]} = 6.02$ points, so the difference corresponds to a standardised effect of about 0.66. With a two-sided α of 0.05 and 80% power, the number of children needed per group is $n = 15.68 \times 6.02^2 / 4^2 = 35.5$, that is, 36 per group (72 in total); allowing for 15% attrition ($36 \times 1.15 = 41.4$) gives 42 per group (84 in total). These figures, and the corresponding ones for the gait-robot pilots, are set out in Chapter 3 (Section 3.5.4, Table 3.7). They exceed the application's planning target of 30 children for the social-robot intervention [34] and the 10 children per arm of the current phase's reduced pilot sampling strategy. An estimate from ten children per arm is imprecise: from the same summary values, the approximate 95% confidence interval for the 4-point difference runs from about −1.7 to 9.7 points, so the true effect could be considerably smaller or larger. A trial powered on these inputs should therefore be regarded as a confirmatory study for a future phase, and the current phase as explanatory and feasibility-scale.

11.9 Relation to the International Literature

Status: published, Journal of NeuroEngineering and Rehabilitation 2026;23:34, doi:10.1186/s12984-025-01852-0 [1].

The program's scoping review, conducted under PRISMA-ScR, searched six databases for English-language peer-reviewed studies from 2015 to 2025 of social robots used in cognitive, speech or communication rehabilitation of children aged 18 or younger with CP. Twenty studies were included (Table 11.10).

Table 11.10. The international evidence base identified by the scoping review [1].

Feature	Finding
Geography	Mostly Western and European, with Latin American and Asian studies; none from Central Asia
Designs	Mainly feasibility, pilot, design/validation and case studies; one randomised controlled trial
Sample size	Most studies had fewer than 20 participants
Robots	Humanoids dominant, especially NAO; some animaloid and non-anthropomorphic platforms
Setting and delivery	Mostly clinics (n = 9); therapist-led (n = 10) or mixed-mode (n = 9); fully autonomous delivery rare
Typical dose	20–40 minutes, 1–3 sessions per week
Outcome domains	Speech production, language comprehension, attention/memory, social communication, symbolic play, motor function with social interaction
Child acceptance	High in 75% of studies, moderate in 17%, mixed in 8%
Gaps	Small samples, short interventions, heterogeneous outcomes, few follow-ups, underrepresentation of severe CP (GMFCS/MACS IV–V) and multilingual children

Several reviewed studies provide benchmarks. Five of eight young children with complex CP engaged more with an animaloid robot than with switch-adapted toys [20]; a robot-assisted speech therapy study reported gains in phonology, morphosyntax and semantics in 29 children over 73 sessions [28]; robot-mediated free play improved playfulness, with gains persisting at follow-up [29]; children preferred an

embodied robot to a screen agent for enjoyment ($p = 0.018$) and companionship ($p = 0.026$) [30]; and caregivers and clinicians rated a robotic platform at about 4.3–4.5 out of 5 over a two-month deployment [31]. An earlier meta-analysis reported effective engagement across communication, motor and social domains [21].

Against this background the program makes four contributions: the first Central Asian evidence and the first delivery in Kazakh and Russian, addressing the review's finding that multilingual and non-Western populations are underrepresented; a ten-session protocol with 32 children per group and session-by-session modelling, larger and longer than most reviewed studies; instrumental acoustic and blinded perceptual speech outcomes, which no reviewed study used [6]; and an active digital comparator. It also reproduces limitations the review identified: small samples outside the longitudinal study, two-week interventions, no follow-up, unvalidated and heterogeneous measures, no functional classifications and a single platform. In one respect it complicates the consensus: the review concluded that SARs are engaging and acceptable, and the pilot and longitudinal data agree, but the video-coded analyses show modest engagement and no advantage over a tablet. The autism literature offers a related caution, a moderate pooled effect on social functioning (Hedges' $g = 0.35$, 95% CI 0.09–0.61) from mostly short interventions averaging about nine sessions in randomised trials [32], a figure the longitudinal authors cite only for context and do not compare with their own unstandardised estimates [3].

11.10 Implementation Barriers

The outcome studies were not designed to study implementation, but together they document the practical conditions under which robot-assisted therapy was delivered at NCCR. Five groups of barriers recur.

Scheduling. Robot sessions had to fit around each child's individually prescribed rehabilitation program, usually in a morning window of 08:00–12:00 [4]. Children missed sessions through illness and timetable conflicts, so that attendance in the longitudinal study ranged from 2 to 10 sessions and only 19 of 32 children completed all ten [3]; in the microgenetic cohort a session number did not always correspond to the same module for every child [4]. During the program's own refinement cycle, the intervention schedule was adjusted to align better with the therapists' existing routines [34].

Staffing. A session of about ten minutes typically involved four to five adults from the research team, with one or two NCCR clinicians present (Chapter 7, Section 7.3.4). The therapist launched and paced the robot, adjudicated spoken and gestured answers and, in the longitudinal study, also completed the outcome ratings [3,4]. The lead therapist changed partway through the microgenetic cohort [4], and manual coding of video was labour-intensive in every study.

Technical issues. Sessions or recordings were lost to recording-equipment failures, camera malfunctions and connectivity problems with the robot [4,5]; the tablet did not log item-level responses [4]; nearly one speech clip in five failed the audio audit [6]; and a Kazakh voice had to be integrated because the manufacturer did not supply one [3,6].

Approvals and documentation. All studies operated under IREC approval No. 1081 with site approval from the centre and written parental consent [2–4]. The trial registration was retrospective, functional classifications (GMFCS, MACS, CFCS) were not available in clinical records [6,7], demographic records could not be retrieved for three control children, and reasons for attrition were not recorded in the largest study [3].

Caregiver involvement. Parents gave consent, contributed to the needs assessment (35 families) and to usability feedback through questionnaires (Chapter 7, Section 7.6), and could remain in the room. In the

pilot, parents gave substantial physical help in early sessions, which faded in some children but not others, and the authors recommend an explicit protocol for withdrawing that help gradually [2].

The scoping review identifies cost, technical infrastructure and professional training as general barriers to the clinical use of SARs [1]. Members of the research team are also preparing a collaborative autoethnography of the organisational barriers they encountered in implementing QTrobot-assisted therapy for children with CP [33]. That manuscript is in preparation, and its findings are not summarised here.

11.11 Summary

This chapter reviewed six empirical studies of QTrobot-assisted therapy for children with CP in Kazakhstan, the 2025 pilot randomised trial and the program's scoping review; in all, 170 different children took part in the program's social-robot studies. One study is published (the pilot, IEEE Transactions on Medical Robotics and Bionics, early access), two are under review (the longitudinal study, International Journal of Social Robotics; the microgenetic study, IEEE Transactions on Cognitive and Developmental Systems), and three are in preparation (engagement, speech and narrative). The studies draw on four cohorts and partly share participants and video data. The trial that frames them, ACTRN12625001214426, was registered retrospectively. The 2025 pilot randomised trial implies that a confirmatory trial on WISC-V FSIQ would need 36 children per group, or 42 allowing for attrition (Chapter 3).

Four conclusions are reasonably well supported. Culturally adapted, bilingual robot-assisted sessions can be delivered in routine paediatric rehabilitation in Astana with high retention. Initial novelty or anxiety typically resolves within two to four sessions, after which therapist-rated behaviours rise for about five sessions and then plateau. Children participate and talk more in and after robot-assisted sessions and treat the robot as a social partner even when all task content is on a tablet. Responses are heterogeneous, larger in some respects for children who start lower, and in narrative language limited to children who already combine words.

The evidence does not yet support claims of efficacy. The only comparison with standard care showed no between-group difference at post-test; most outcome instruments are unvalidated and were rated by unblinded therapists; video-coded engagement was modest and lower than with a tablet delivering the same content, although that comparison is confounded; and more speech was not clearer speech. A randomised trial with a formally administered outcome (the WISC-V), blinded assessment, counterbalanced content, recorded functional classifications and an adequate sample is needed to answer these questions; the registered trial is a step in that direction, and its results are pending. Chapter 12 discusses these findings alongside the gait and balance evidence of Chapter 10.

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Chapter 12. Discussion: Toward Personalised Paediatric Rehabilitation

Abstract. This chapter reads the program's results across devices rather than device by device. Three themes recur: children with cerebral palsy (CP) respond very differently to the same intervention, the program's instruments can record that variation within each child, and the evidence remains at the feasibility and exploratory stage while the program's controlled trials are under way. The chapter discusses what these themes imply for individualised therapy, for measurement, for study design and for the place of social robots alongside motor devices, and it compares the program's position with the international evidence summarised in Chapter 2.

Keywords: personalised rehabilitation; heterogeneity; cerebral palsy; outcome measurement; feasibility; evidence hierarchy; socially assistive robots

12.1 An Integrated Reading of the Program

The program set out to test a portfolio of technologies, not a single device. That breadth is visible in its results. The Gait Rehabilitation Robot, the body-weight support (BWS) system and the Robotic Perturbation Trainer (RPT) address walking and balance at different points: the robot guides the stepping pattern, the BWS system changes the load the child carries, and the RPT challenges the child's reactive control. The socially assistive robot addresses communication, cognition and participation, which the motor devices do not touch. Software connects them by turning device and sensor signals into indices that a clinician can follow over a course of therapy.

The scale of clinical work was made possible by the setting. The National Center for Children's Rehabilitation (NCCR) in Astana receives roughly 300 children a month, and within the program 170 children took part in the social-robot (QTrobot) studies, 25 in the perturbation-training trial and 25 in the gait-robot trial, with all children different within each strand. In the gait trial (ACTRN12626001203347), enrolment began on 10 September 2026; pre-assessments were carried out first, and robot-assisted sessions began on 19 October 2026, after the conditions of the ethics committee's approval for use of the device had been met. Its results, and those of the perturbation-training trial, are pending (Chapter 10).

Across these very different devices, the completed studies converge on a small number of points. Each device could be used with children and adolescents with CP within the routine program of a national rehabilitation centre. Retention in the social-robot studies was high, and the published RPT study recorded no protocol deviations (Chapters 6 and 11). The children's responses were heterogeneous: the BWS level selected for each child varied across the tested range of 0–30% of body weight (Chapter 5), the two adolescents in the published RPT study followed different trajectories (Chapter 6), and in the social-robot studies children who started lowest gained most on therapist-rated measures (Chapter 11). None of the completed studies was designed to show efficacy.

12.2 Heterogeneity and the Case for Individualisation

CP is a single diagnostic label for a wide range of motor types, distributions and severities, often combined with impairments of communication, cognition and behaviour (Chapter 1). The program's results suggest that this clinical heterogeneity carries through to how children respond to devices: children at the same GMFCS level could rank the tested BWS conditions differently, and responses to the social robot varied with the child's starting level and language ability.

This has a practical consequence. Fixed protocols, such as one BWS level, one perturbation magnitude or one script set for all children, are convenient for trials but are unlikely to be optimal for individuals. The program's response has been to build individualisation into the devices themselves: the multidomain selection of a BWS level (Chapter 5), progression rules for perturbation magnitude (Chapter 6), language assignment and adaptive pacing for the social robot (Chapter 7), and session-by-session indices and rule-based recommendations in the gait analysis software (Chapter 8). The next step is to test whether individualised settings produce better outcomes than standard settings. That requires a randomised comparison, not only within-child optimisation.

12.3 Certainty of Individual Recommendations

Individualisation raises a methodological question that group trials rarely face: how certain is a recommendation for one child? The BWS pilot addressed this with robustness analyses, which showed that the selection was stable for most children but not for all (Chapter 5). The same question applies to any device-derived index. A Gait Recovery Index value is useful to a therapist only if its measurement error is known, so that a real change can be distinguished from session-to-session noise. Its joint-strength component illustrates the point: it rests on the load-cell measurement of the patient's joint torque contribution, whose accuracy depends on calibration and on the moment-arm estimate (Chapter 8). Establishing the reliability and minimal detectable change of the program's indices in patients is therefore a priority, ahead of any use of them, or of the recommendations derived from them, for clinical decisions.

12.4 Measurement Lessons

Three lessons on measurement emerge from the program. First, standard clinical tests in paediatric CP often lack established thresholds for meaningful change, which complicates the interpretation of small studies of both gait and balance (Chapters 5, 6 and 10). Second, many of the instruments used in the social-robot studies were adapted or developed for the program and rated by therapists who knew the allocation; validated, blinded outcomes are needed for confirmatory trials (Chapter 11). Third, clinical records did not always contain standardised functional classifications, which limits subgroup analysis; the program's data platform and its pipeline for de-identification and structured extraction of Russian-language records were developed partly to address this (Chapter 9).

12.5 Social and Motor Rehabilitation Together

Most rehabilitation robotics research treats motor and social-cognitive therapy as separate fields. The program combined them in one clinical setting, which allowed the same families and therapists to experience both. The social-robot studies showed that children engaged with a robot that addressed them in their own language, Kazakh or Russian, and that therapist-rated behaviour rose over the first part of a course of sessions before reaching a plateau (Chapter 11). Whether a social robot could also improve engagement in motor therapy, for example by encouraging a child during gait-robot or perturbation sessions, was not tested by the program and is a natural question for future work, alongside the VR scenarios already developed for the gait robot (Chapter 9).

12.6 Comparison with International Evidence

International reviews of robot-assisted gait training in CP report mixed effects on walking outcomes, with considerable heterogeneity between studies, devices and dosing [1–4]. A meta-analysis comparing robot-assisted gait therapy with conventional therapy or treadmill training found advantages for robotic therapy in some outcomes, including walking speed and walking distance, but not consistently across

outcomes or comparators [1]; a systematic review of robotic exoskeletons for CP, co-authored by members of the program team, surveys the device classes and protocols that underlie this heterogeneity [3]. Broader appraisals of CP interventions continue to place task-specific, intensive practice at the centre of motor therapy [5], a principle that robotic devices can support by increasing the dose and repeatability of practice but do not replace. The program's completed feasibility studies are consistent with this picture: changes in some measures for some children, without the controlled evidence needed to claim superiority over conventional therapy. Reviews of socially assistive robots for children with CP likewise report feasibility and engagement but few controlled outcomes [6–8], and the program's own scoping review noted the scarcity of studies in languages other than English [8]. The program's bilingual Kazakh and Russian work contributes directly to that gap.

12.7 Limitations of the Program's Evidence

The limitations of the individual studies are discussed in each chapter. At the program level, five stand out. First, the studies were conducted at a single centre. Second, sample sizes are modest: the gait and perturbation trials each enrol 25 children, which makes them explanatory, feasibility-scale studies consistent with the program's reduced pilot sampling strategy, whereas sample-size calculations based on the 2025 pilots indicate that a confirmatory gait trial would need substantially more participants per group (Chapter 3). Third, the QTrobot randomised trial (ACTRN12625001214426) was registered retrospectively, after the first child had been enrolled, and several social-robot outcomes were rated by unblinded therapists. Fourth, most results remain unpublished or under review at the time of writing, and the results of the 2025 pilots and of the current gait and perturbation trials are pending. Fifth, establishing whether children move between GMFCS levels, the outcome that families and health systems care most about, will require longer follow-up than the program period allows.

12.8 Summary

Read together, the program's studies show that a portfolio of rehabilitation robots can be introduced into routine paediatric care at a national centre in Kazakhstan, that children's responses differ enough to justify testing individualised settings, and that the program's measurement tools can track within-child change. They do not yet show that robotic therapy outperforms conventional therapy. The priorities that follow are completion and reporting of the controlled trials, randomised comparisons of individualised versus standard settings, reliability studies of the device-derived indices, validated and blinded outcomes, adequately powered multicentre trials, and longer follow-up.

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Chapter 13. Translation, Commercialisation and Future Directions

Abstract. A rehabilitation robot helps children only when it is available in clinics, affordable to health systems and trusted by therapists. This chapter describes how the program's outputs are to be carried toward that point. It summarises the intellectual property generated and its ownership, outlines the regulatory pathway for medical devices in Kazakhstan within the framework of the Eurasian Economic Union, describes the route from registration to public procurement through the single distributor, and sets out the next scientific steps, including confirmatory trials, longer follow-up, a next-generation paediatric perturbation platform and extension of the technologies to elderly stroke survivors and adults with neurological disabilities. It closes with four recommendations for health and science policy in Kazakhstan.

Keywords: technology transfer; medical device regulation; Kazakhstan; Eurasian Economic Union; intellectual property; public procurement; commercialisation; stroke rehabilitation; health policy

13.1 Intellectual Property Generated by the Program

All copyrights and patents arising from program BR27199433 are owned by Nazarbayev University Research Administration (NURA). The program's registered intellectual property to date consists of five Republic of Kazakhstan software copyright certificates obtained in June 2026 (Table 9.1): the GARAS gait analysis and rehabilitation recommendation system (No. 74083), the VR-based exoskeleton training program (No. 74149), the NCCR Rehabilitation Platform (No. 74396), the Kazakh speech-synthesis routing system for QTrobot (No. 74308), and the Kazakh and Russian scripts for robot-assisted therapy for children with CP (No. 74309).

Patent applications will be filed for the program's three rehabilitation devices: the Gait Rehabilitation Robot, the adaptive body-weight support (BWS) system and the Robotic Perturbation Trainer (RPT). The program's application foresaw first filing in Kazakhstan followed by an international application under the Patent Cooperation Treaty. Filing before the devices' designs are disclosed in further detail in publications is the main practical constraint on the timing of these applications.

The social-robot work is treated differently. QTrobot is a commercial platform, and the program's contribution is localised software and therapy content: the Kazakh speech routing, the bilingual scripts and the session method. This content will not be commercialised.

13.2 Regulatory Pathway in Kazakhstan

A rehabilitation device used in clinical care in Kazakhstan must be registered as a medical device. The legal framework is set by the Code of the Republic of Kazakhstan "On Public Health and Healthcare System" of 7 July 2020 [1], together with the rules of the Eurasian Economic Union (EAEU), of which Kazakhstan is a member. The EAEU Agreement on common principles and rules for the circulation of medical devices of 23 December 2014 [2] provides for a common market in medical devices, with registration and expert evaluation of safety, quality and effectiveness under rules approved by Decision No. 46 of the Council of the Eurasian Economic Commission of 12 February 2016 [3] and risk classification under Decision No. 173 of the Board of the Commission of 22 December 2015 [4]. In Kazakhstan, expert evaluation for registration is carried out by the National Center for Expertise of Medicines and Medical Devices.

Registration rests on technical and clinical evidence that the program's devices are only partly placed to supply. The dossier for a powered rehabilitation device typically includes verification against the IEC 60601 family of standards for medical electrical equipment [5], a risk-management file prepared to ISO 14971 [6], software life-cycle documentation to IEC 62304 where software controls the device [7], manufacture under a quality management system conforming to ISO 13485 [8], and clinical evidence appropriate to the device's risk class. The Gait Rehabilitation Robot illustrates the path: it is already registered in Kazakhstan as a Class 2a medical device (Chapter 4). The BWS system and the RPT are at the stage of research prototypes with bench validation and early clinical studies (Chapters 5 and 6). Both will go through medical-device registration with the National Center for Expertise of Medicines and Medical Devices. The BWS report's recommendation of an independent hardware vent on overpressure or power loss (Chapter 5) and the documentation of stopping behaviour for the RPT (Chapter 6) are examples of design work that registration will require.

Software that makes or informs clinical decisions may itself be a medical device. If GARAS is to recommend rehabilitation settings in routine care, its intended use and risk class will need to be defined and its clinical validity demonstrated (Chapters 8 and 9). The same applies to any future version of the VR program that adjusts robotic assistance automatically.

13.3 From Research Prototypes to Public Procurement

Registration makes a device lawful to use; it does not by itself make it available. In Kazakhstan, medicines and medical devices provided within the guaranteed volume of free medical care and the system of compulsory social health insurance are procured centrally through the single distributor, SK-Pharmacy, under the framework of the Code [1]. For a domestically developed rehabilitation device, the practical route to children in public care therefore runs from state registration to inclusion in the single distributor's procurement, and then to supply to public rehabilitation centres. The BWS system and the RPT will go through the SK-Pharmacy registration process after state registration.

The program's commercialisation plan follows from this route. Public rehabilitation centres for children and adults, beginning with national centres such as NCCR and extending to regional rehabilitation centres, are the primary customers, reached through national procurement. Private rehabilitation clinics and export to neighbouring EAEU markets, where a registration under the Union's rules can support access, are secondary opportunities. The program's application argued that domestically developed devices could be offered at lower cost than imported systems of comparable function, which is relevant to procurement budgets in Kazakhstan and in other middle-income countries; that argument will need to be substantiated with cost and outcome data. Licensing of NURA's intellectual property to a manufacturer holding the necessary quality system and manufacturing licence is one route to production that NURA's ownership of the intellectual property makes possible.

The author's interests in the technology are declared in the front matter.

13.4 Next Scientific Steps

Several lines of work follow directly from the results in this book:

1. Completing and reporting the gait trial (ACTRN12626001203347) and the perturbation-training trial, and reporting the 2025 pilot studies and the QTrobot randomised trial (ACTRN12625001214426), with blinded assessment wherever it can be arranged.

2. Designing adequately powered confirmatory trials. The sample-size calculations based on the 2025 pilots (Chapter 3) indicate that a confirmatory gait trial would require about 24–32 children per group before allowance for attrition (28–37 per group with 15% attrition),

depending on the comparison, and a confirmatory social-robot trial 36 per group (42 with attrition). Trials of this size are likely to require more than one centre.

3. Testing individualised versus standard device settings in randomised comparisons, starting with the level of body-weight support.

4. Establishing the reliability, minimal detectable change and validity of the Gait Recovery Index, the Balance Recovery Index and other device-derived indices on patient data, and evaluating the recommendations generated by GARAS against clinical judgement.

5. Following children long enough to determine whether gains are retained and whether functional classification levels, including GMFCS level, change over time; the program period is too short to answer this question.

6. Developing the planned next-generation paediatric perturbation system (Chapter 6) and testing multi-plane perturbations in children.

7. Extending the technologies to elderly stroke survivors and to adults with neurological disabilities. The Gait Rehabilitation Robot, the BWS system and the RPT are adjustable devices whose principles are not specific to children, and the bilingual social-robot approach may also transfer to adult rehabilitation. Each extension will require its own ethics approval, device-fit assessment and outcome measures.

8. Releasing the program's de-identified dataset, once the repository and licence are settled under the conditionally approved ethics amendment (Chapter 9), to support independent analysis.

13.5 Policy Recommendations

The following four recommendations are drawn from the program's experience. They are framed conditionally, because the program's evidence is at the feasibility and exploratory stage and does not by itself justify changes to clinical standards.

Recommendation 1: Incorporate robot-assisted gait and balance training into national paediatric rehabilitation standards once efficacy is confirmed. International reviews show that robot-assisted gait training can improve some walking outcomes in children with CP but that results are inconsistent across studies, devices and comparators (Chapters 2 and 12). The program has shown that such devices can be introduced into routine care at a national centre, but its controlled trials are small and their results are pending. Robot-assisted gait and balance training should therefore enter the clinical protocols and standards of the Ministry of Health only when adequately powered randomised trials have shown benefit over an equivalent dose of conventional therapy for defined groups of children. When that threshold is met, standards should specify the patient groups (for example by age and GMFCS level), the dose, the competencies of staff and the outcome measures to be recorded, so that robotic therapy is added where it helps rather than used as a substitute for therapist time.

Recommendation 2: Fund multicentre trials of paediatric rehabilitation technology and a national CP registry with standardised instrumented outcomes. The program's sample-size calculations show that confirmatory trials will need more children than a single centre can recruit within a typical grant period, even one as large as NCCR. Program-targeted funding should therefore support multicentre trials that link national and regional rehabilitation centres under shared protocols, blinded assessment and prospective registration. In parallel, a national CP registry would provide the denominator data that Kazakhstan currently lacks (Chapter 1), allow long-term follow-up of outcomes such as change in GMFCS level, and support the identification of children who might benefit from particular therapies. Such a registry should record standardised classifications (GMFCS, MACS, CFCS) and a minimum set

of clinical outcomes, and, where centres are equipped, instrumented gait and balance measures, so that device-derived indices can be validated on a national scale.

Recommendation 3: Create a regulatory and procurement pathway for domestically developed rehabilitation devices. Domestically developed devices face a long sequence of steps between a working prototype and a child in a public rehabilitation centre: design verification, quality-management certification, state registration within the EAEU framework, and inclusion in public procurement through the single distributor. Each step is reasonable, but together they are difficult for university-originated technologies to navigate. A defined pathway, with regulatory advice available at the design stage, recognition of clinical data generated under ethics-approved trials in national centres, and clear criteria for inclusion of registered rehabilitation devices in national procurement, would shorten this route without lowering safety standards. Procurement decisions should be linked to evidence of clinical benefit and to whole-life costs, including service and training, so that domestic devices compete on value rather than on initial price alone.

Recommendation 4: Support bilingual digital and social-robot therapy content as a public good, with data-protection-compliant data-sharing infrastructure. Therapy software and content in Kazakh and Russian are scarce, and the program had to develop its own Kazakh speech routing, therapy scripts, VR scenes and record-processing methods (Chapters 7 and 9). Such content benefits every centre that serves Kazakh- and Russian-speaking children, and the program has chosen not to commercialise its social-robot content. Public funding should support the development, validation and open distribution of bilingual therapy content, so that each centre does not have to build its own. Equally, the value of clinical data grows when they can be pooled and reanalysed. National infrastructure for sharing de-identified rehabilitation data, compliant with the Law "On Personal Data and Their Protection" [9], with agreed standards for de-identification and controlled access, would allow results from individual programs to be combined and checked independently.

13.6 Summary

The program has produced registered software owned by NURA, field-tested research prototypes of a body-weight support system and a robotic perturbation trainer, and clinical experience with a registered gait rehabilitation robot and a social robot in routine paediatric care. Patent applications for the three devices will be filed, and the BWS system and the RPT will go through state registration and the SK-Pharmacy process that leads to public procurement, with public rehabilitation centres as the primary customers. Moving the devices from prototype to product will require regulatory work and, above all, controlled evidence of benefit. The scientific agenda that follows is to complete and report the trials, design confirmatory multicentre studies, test individualisation directly, validate the program's indices, follow children for longer, build the next-generation perturbation platform, and extend the work to elderly stroke survivors and adults with neurological disabilities. Four policy recommendations — evidence-based inclusion in national standards, multicentre trials and a national CP registry, a pathway from registration to procurement for domestic devices, and public support for bilingual therapy content and data-sharing infrastructure — would help ensure that the technologies that prove effective reach the children and adults who need them.

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Conclusion

This book has described a national program that set out to bring rehabilitation robotics to children with cerebral palsy in Kazakhstan and to test it honestly.

The program built or adapted four devices and used them with children at the National Center for Children's Rehabilitation. The Gait Rehabilitation Robot, a registered medical device, was adapted for paediatric use, given load-cell sensing at every joint and a controller whose assistance is composed of independently bounded terms. An adaptive body-weight support system with compliant pneumatic actuation was designed and built by our team. The Robotic Perturbation Trainer progressed from a four-cable transverse-plane mechanism to a reconfigurable cable-driven robot that can perturb walking in all three planes. QTrobot was given a Kazakh voice and a set of bilingual therapy scripts. Around these devices the program built GARAS, the NCCR Rehabilitation Platform, a virtual-reality training program and a family of data-collection protocols. Five software copyright certificates were obtained, and patent applications for the devices will be filed. All of this intellectual property belongs to Nazarbayev University Research Administration.

The evidence gathered so far is of uneven maturity, and I have tried to report it as such. Three program papers are published: the scoping review of social robots for children with cerebral palsy, the methods paper on the first Robotic Perturbation Trainer, and the feasibility study of QTrobot-assisted sessions. Others are under review or in preparation. Taken together, these studies show that the devices can be delivered within a routine rehabilitation setting, that children with very different levels of function can take part, that children respond differently to the same settings, which supports individualised parameter selection, and that the program's instruments can record change within each child in considerable detail. The social-robot studies, which involved 170 children, describe engagement, communication and cognitive behaviour during sessions, but most were uncontrolled or used non-randomised comparison groups.

What the evidence does not yet show is equally important. No result in this book establishes that robot-assisted gait training, perturbation-based balance training or social-robot therapy is more effective than conventional rehabilitation for children with cerebral palsy. The 2025 pilot randomised trials were designed to estimate effect sizes, and their full results are still to be reported. The sample-size calculations based on those pilots show that a confirmatory trial would need about 37 children per group for the gait robot and 42 per group for the social robot. The device-derived indices, the Gait Recovery Index and the Balance Recovery Index, are promising but have not yet been validated against clinical outcomes in children.

The pending trials will begin to fill these gaps. The randomised trial of the Gait Rehabilitation Robot, registered as ACTRN12626001203347, enrolled 25 children from September 2026, and robot-assisted sessions began in October 2026. The perturbation-training trial has enrolled 25 children. These trials will provide the first controlled estimates of change in walking endurance, gait and balance, and the first opportunity to test whether the robots' own measurements track the clinical tests that therapists trust.

The program's most durable contribution may therefore lie less in any single device than in what it has put in place together: domestically developed devices on a path to registration, therapy content adapted to the languages in which Kazakhstani children live, a data infrastructure for multimodal measurement, and registered trials in a national rehabilitation centre. With these in place, the questions that matter to children and families, whether they walk, balance, communicate and take part better and for longer, can now be answered with controlled evidence. Answering them, in larger and multicentre trials, is the work that lies ahead.

Appendices

Appendix A. Outcome Measures and Assessment Forms

This appendix lists the data-collection forms used in the program's clinical studies and reproduces, in English, the two instruments from the social-robot studies that are not described in full elsewhere in the book. All participant information has been removed; the forms are shown as blank instruments.

Table A.1. Data-collection forms used in the program.

Form	Used in	Content	Chapter
NCCR pre-assessment form: gait rehabilitation (cerebral palsy)	Gait-robot trial	Patient details (age, sex, CP type, affected side, GMFCS level); body measurements (weight, bilateral leg length from greater trochanter to lateral malleolus, height) needed for robot set-up; footprint-method spatial gait parameters (step and stride length, step width, foot angle); cadence; 10MWT (three comfortable and one fast trial); TUG (one practice and two timed trials); 6MWT where a 20 m course is available; observational gait checklist (e.g. toe-walking, hip hiking, circumduction, crouch, scissoring); summary sheet; instruction to run a passive calibration on the robot before the first session so that baseline load-cell values can be recorded	4, 8, 10
Adaptive BWS baseline (0% BW) pre-assessment booklet (two versions, the later one for the Cometa WaveX system)	BWS study	Collection protocol (one comfortable self-selected belt speed per child, reused in all sessions; discard the first 10–20 strides; record at least 30–40 clean strides); cohort roster; participant and clinical details; sensor montage (16 WaveX channels and two 16-cell insoles); set-up checklist; EMG probe placement and signal quality; walking-trial log; baseline spatial, temporal and plantar-loading parameters; baseline EMG reference amplitudes (the 0% denominators); baseline dynamic stability; tolerance, observations and adverse events	5
Adaptive BWS unweighing-sweep session booklet (10–30% BW, Cometa WaveX)	BWS study	Session protocol (fresh 0% re-reference walk after electrode re-placement; levels presented at constant belt speed; familiarisation, stride discard and clean-stride recording at each level; predefined stop rules; archiving of raw traces); per-level trial log; loading and symmetry across levels; extensor-drive floor (soleus and gastrocnemius activation relative to 0%); spatial and temporal parameters; co-contraction; dynamic stability; per-child determination of the recommended training level	5
QTrobot structured observational checklist	SAR feasibility and longitudinal studies	Reproduced below (Tables A.2 and A.3)	7, 11
Engagement-level codebook (1–5 scale,	Robot vs tablet	Reproduced below (Tables A.4–A.6)	7,

Form	Used in	Content	Chapter
robot–tablet sessions)	engagement study		11

The data-collection forms were prepared in English and used by bilingual staff; Kazakh and Russian versions of the consent and assent documents were used with families (Chapter 3).

A.1 QTrobot structured observational checklist

The checklist was completed by an observer for each session. Each item is marked as observed (Yes/No) and, if observed, rated for frequency (Rare, Sometimes, Often), with space for comments. The social-skills items are grouped under joint attention, behavioural requests, social interaction, imitation, and interaction and activities of daily living (ADL). The communication and cognition items additionally carry a score field. Item wording is reproduced from the form with minor corrections of spelling; where the source form leaves part of an item blank, this is shown in square brackets.

Table A.2. Observational checklist, Part 1: social skills.

Category	Observation item
1. Initiating joint attention (IJA)	Makes eye contact with the robot (SAR) and instructor
	Presence of social smile
	Initiates and responds to greetings
	Tries to manipulate or touch the robot
	Alternates gaze between the robot and the instructor's eyes
	Points with extended index finger to the robot, picture or poster before the tester points
	Gets the tester's attention to point to the tablet
	Initiates interaction
2. Responding to joint attention (RJA)	Follows the instructor's pointing gesture to the robot or to pictures on the tablet
	Follows the instructor's line of regard to look left, right or behind
3. Initiating behavioural requests (IBR)	Makes eye contact when the robot is inactive (not touching)
	Extends arm toward the out-of-reach robot
	Combines eye contact with a reaching gesture (appeal)
	Hands or pushes the object to the instructor (possibly with eye contact)
	Points to request a toy or object
4. Responding to behavioural requests (RBR)	Gives the requested object when the tester says "Give it to me" (with or without gesture)

Category	Observation item
	Follows the instructor's or therapist's request when asked to do something
5. Initiating social interaction (ISI)	Initiates turn-taking (acts after instruction)
	Engages in eye contact or smiling while interacting with the robot
	Initiates (claps, taps on the table, or changes body posture)
6. Responding to social interaction (RSI)	Looks at the tester after being called
	Vocalises, claps or taps the table
	Combines the act and eye contact
	Returns the tablet consecutively during turn-taking
	Returns objects at the instructor's request by placing toys or other objects on the table or in the instructor's hand
	Looks at the instructor or therapist instead of the robot during robot interaction
7. Social imitation	Points or claps in imitation of the tester's gestures
	Imitates or repeats gestures, emotions, actions or behaviours demonstrated by the robot during the session
8. Interaction and ADL	Engages in joint or group activities and interest groups appropriate for age
	Displays self-control during robot activities and structured play
	Interacts appropriately with instructors and others present in the room
	Participates in social and everyday self-care skill development (e.g. dressing, feeding)
	Shows growing confidence in completing tasks independently
	Tries to maintain an appropriate posture for interaction
	Responds calmly and adequately during interaction
	Self-help routines, such as sitting or standing without support
	Uses appropriate assistive devices
	Age-appropriate emotional responses
	Requests help
	Well-behaved; displays appropriate social manners

Response format for each item: Yes / No; frequency Rare / Sometimes / Often; comments.

Table A.3. Observational checklist, Part 2: communication and cognition.

Domain	Checklist item
Communication	Communicates non-verbally
	Understands and follows verbal instructions appropriately
	Uses speech for communication
	Speech is clear
	Speech is unclear

Domain	Checklist item
	Responds to questions and provides detailed answers
	Shows evidence of thinking before conversational turns
	Participates in reading simple texts with retelling
	Speaks with confidence and clarity when communicating
	Shows delayed speech or response when speaking
	Attempts to speak but with unclear articulation (e.g. words not fully formed)
	Does not attempt to speak or engage verbally during the session
	Engages in verbal interaction with others (e.g. responds to questions or comments)
	Uses gestures or non-verbal cues to communicate when unable to speak clearly
	Attempts to clarify or correct own speech when not understood
	Follows conversational turn-taking (waits for others to finish before responding)
	Uses a variety of words or expressions during conversation
Cognition	Pays sustained attention
	Shows development of logical thinking and memory (remembers the previous task)
	Understands cause and effect of activities
	Shows improved voluntary memory and retention of information
	Participates actively in robot sessions targeting [skill not specified on form]
	Is familiar with basic [concepts not specified on form] and their meanings
	Sustains engagement with the tasks or activities
	Retells a story or responds to questions (auditory comprehension)
	Creates a story
	Encouraged to continue development in social communication and self-help routines

Response format for each item: Yes / No; frequency Rare / Sometimes / Often; score; comments.

A.2 Engagement-level codebook (scale 1–5) for robot–tablet sessions

The codebook is a universal coding instrument for sessions in which a child with CP interacts with a robot–tablet system or a tablet application. A score from 1 to 5 is assigned to each time segment (for example, every 10 seconds) on two axes: the *source of initiative* (was the action triggered by a question or prompt from the robot or therapist, or initiated by the child?) and the *substantiveness* of the action (is there a confirmed content contribution, as opposed to mere presence or a mechanical button press?). The level does not depend directly on the correctness of the answer, the loudness or intelligibility of speech, facial expressiveness on its own, the length of the utterance, or the emotional valence of the reaction.

Table A.4. Engagement levels and sub-codes.

Level	Definition	Sub-codes and rules
1 – D	No visual, auditory or behavioural	Differs from Level 2 in that there is no orientation to the task at all, not merely distraction.

Level	Definition	Sub-codes and rules
disengaged	orientation to the robot or tablet; attention fully occupied by an unrelated, substantive stimulus; no response to a direct prompt to return to the task.	
2 – Low engagement	Brief, unstable, formal attention with a clearly observable marker of disengagement.	Markers: gaze averted while physically present; standing up or switching to another activity; seeking contact with the therapist instead of the task; evident loss of focus after an external distraction. A mechanical button press at the therapist's request without gaze aversion is Level 3, not 2.
3 – Moderate engagement	Sustained presence without a confirmed content contribution (the baseline level).	3.1 Navigational action ("next" without a content choice), even if fully independent. 3.2 Incomplete attempt (reaching and withdrawing; "thinking") with no observable outcome in the segment; a child who stops and waits for the adult to act stays at 3. 3.3 Silence or general refusal ("I don't know" with no further attempt, head shake) while contact is maintained. 3.4 Isolated agreement ("yes" or nod) with no confirming action; if the child agrees with almost any question, code all isolated "yes" responses in that session conservatively (no higher than 3–4). 3.5 Questioning echo of a word or number the adult has just said. 3.6 Unconfirmed vocalisation whose relevance cannot be established. 3.7 Affect without action (smile, laugh); note its nature separately. 3.8 Fleeting, undirected imitation of what is on screen.

Level	Definition	Sub-codes and rules
4 – Highengagement	An active, confirmed content contribution triggered by a question from the robot or the therapist.	4.1 Content-based button press (any answer option, correct or not). 4.2 Verbal or non-verbal content response to a direct question, of any length or quality, including a continuation of a question asked earlier. 4.3 Active attempt that fails because of motor limitation, when directed intent is visible (intent is coded, not motor success). 4.4 Content action performed on instruction (emotion, gesture, movement), however weakly expressed. 4.5 Honest verbalisation of uncertainty ("I don't know", "I can't") given as a substantive answer. 4.6 Humorous or creative response showing active processing. 4.7 Emotionally charged but on-topic response. 4.8 Continuation of an uninterrupted prompted stream across segments (remains 4). 4.9 Reaction to feedback that does not break contact with the task (a temporary drop to 3 is allowed after technically erroneous feedback, with the reason noted). 4.10 Content action under substantial scaffolding: lower bound of 4 or 3, depending on independence; note the degree of scaffolding.
5 – Peakengagement	A content contribution initiated by the child without a prompt, or one that substantively exceeds what was asked. The criterion is the source of initiative, not quality or length.	5.1 Response before the question is completed (anticipation). 5.2 Spontaneous content contribution during a narrative (non-question) line. 5.3 Fully unprompted initiative (comment, story or observation). 5.4 Expansion well beyond the scope of the question (a complete answer to an open question remains 4). 5.5 Spontaneous metacommentary about the session. 5.6 Independent correct judgement against an adult's misleading prompt. 5.7 Content press followed by an unprompted substantive addition. 5.8 Spontaneous linguistic creativity (own synonym or rephrasing). 5.9 Directed spontaneous demonstration addressed to the adult. 5.10 Spontaneous humour or creative interpretation connecting the content to oneself.

Table A.5. Decision algorithm applied to each segment.

Step	Question	Coding
1	Is there an observable action or utterance from the child in this segment?	No (only "thinking" or "getting ready") → 3
2	Is there a clear marker of disengagement from the task?	Partial disengagement with presence maintained → 2; complete withdrawal with no orientation to the task → 1
3	If there is an action, what was its source?	Echo of a word or number the adult just said → 3; response to a question from robot or therapist, of any length or correctness →

Step	Question	Coding
		4; without a question, before the question is completed, or substantively beyond it → 5
4	Is the action a navigational "next" with no content choice?	→ 3
5	Is there a motor failure with visible, directed intent to complete a content action?	→ at least 4
6	Is there an isolated "yes" or nod with no confirming action?	→ no higher than 4, more often 3

Table A.6. Common coding error points.

Situation	Level	Rationale
Response to a question from the robot (not the therapist)	4, not 5	The source of the question does not matter; a question was asked
Elaborate but prompted response	4, not 5	Length or quality do not substitute for spontaneity
Complete answer to an open-ended question, within its scope	4	Remains within the scope requested
Response that exceeds the scope of the question	5	Clear expansion beyond the request
Echo of a word the adult just said	3	Confirmation-seeking, not generation
The same word or number, proposed first by the child	4–5	The source is the child
"Thinking" or "getting ready" with no outcome in the segment	3	Process is not result
Content-based button press	4	Regardless of verbalisation and correctness
Isolated "yes" with no action	3–4	Risk of acquiescence bias
Uninterrupted prompted stream	4 throughout	Do not raise because of length
Uninterrupted spontaneous stream	5 throughout	Determined by the source at onset
Smile or laugh with no substantive action	Does not raise the level	Affect is not a substitute for content
Failed attempt due to motor limitations	4, not lower	Intent is coded, not motor success
Correct response by gesture, no press attempt	4	Gesture is equivalent to a verbal content response
Child stops on their own, waiting for help	3	Distinguishes passive waiting from a genuine attempt
Humorous or emotional but on-topic response	4	Active processing of content
Content-based press under substantial scaffolding	3–4	Depends on the degree of independence

Qualitative comment categories (recorded separately; they do not change the numeric score): nature of affect (joy at content, defensive reaction, reaction to praise or to an error); degree of scaffolding; ambiguous cultural or social gestures, which require contextual annotation; signs of fatigue (head down, yawning, wanting to skip or end early); the child's stable communicative profile; perseverative patterns (always selecting the same option, which should not be counted as a content press under rule 4.1 if it is an automatised motor pattern); and therapist behaviour effects (scripted praise, excessive repetition, pre-empting the child's answer, acting without checking in with the child).

Appendix B. Trial Protocol Summaries

The two summaries below follow the structure of the SPIRIT checklist in condensed form. They contain only information available to the author at the time of writing.

Table B.1. Summary of the randomised controlled trial of robot-assisted gait training (ACTRN12626001203347).

Item	Description
Registration	ANZCTR, ACTRN12626001203347
Funding	Program BR27199433, Science Committee, MSHE of the Republic of Kazakhstan; co-financing from Zein Invest LLP
Setting	National Center for Children's Rehabilitation (NCCR), Astana, Kazakhstan
Design	Explanatory, parallel, two-arm randomised controlled trial
Participants	Children and adolescents with CP, 13–18 years, GMFCS I–III; able to report pain; upper-limb manual muscle test ≥ 3+; Modified Ashworth Scale ≤ 2; no unconsolidated fractures or fixed contractures; good general health. Device-fit criteria in the 2025 pilot: height 160–195 cm, shoe size ≥ 38
Intervention	Ten sessions of 20 minutes of robot-assisted gait training with the Gait Rehabilitation Robot (model A-GEAR-V1), in addition to the child's NCCR programme
Comparator	Conventional (manual) gait rehabilitation
Primary outcome	Six-minute walk test (6MWT), baseline and post-intervention
Secondary outcomes	10MWT; TUG; GMFM-88; Paediatric Berg Balance Scale; sEMG, IMU and insole gait parameters; Gait Recovery Index
Sample size	Application target 23 (6MWT, 80% power); 25 enrolled. Confirmatory-trial estimate from the 2025 pilot: 32 per group, 37 with 15% attrition (Chapter 3)
Randomisation	Computer-generated allocation sequence
Follow-up	Seven children from Astana recruited for follow-up assessments
Ethics	NU-IREC conditional approval for device use, 14 October 2026; conditions met
Status (October 2026)	Enrolment began 10 September 2026; 25 children enrolled; pre-assessment only before 14 October 2026; robot sessions began 19 October 2026 and are continuing; results pending

Table B.2. Summary of the randomised controlled trial of QTrobot-assisted therapy (ACTRN12625001214426).

Item	Description
Registration	ANZCTR, ACTRN12625001214426; retrospectively registered (first enrolment preceded registration)
Funding	Program BR27199433, Science Committee, MSHE of the Republic of Kazakhstan; co-financing from Zein Invest LLP
Setting	National Center for Children's Rehabilitation (NCCR), Astana, Kazakhstan
Design	Randomised controlled trial, QTrobot-assisted therapy vs conventional therapy
Participants	Children with CP, 5–12 years, GMFCS I–III, in good general health (criteria of the 2025 QTrobot cohort in the program application)
Intervention	QTrobot (LuxAI, AI@Edge) sessions delivered in the child's language (Kazakh or Russian) using the program's bilingual scripts; in the 2025 pilot, ten sessions over three weeks with ten scripts
Comparator	Conventional therapy
Primary outcome	WISC-V Full-Scale IQ (planning basis of the sample-size calculation)
Measures in associated studies	Structured observational checklist (Appendix A.1); functional tasks; behavioural mapping
Sample size	Application target 30 (80% power); 2025 pilot 10 vs 10. Confirmatory-trial estimate from the pilot: 36 per group, 42 with 15% attrition (Chapter 3)
Ethics	NU-IREC Approval No. 1081, 21 May 2025
Associated studies	Longitudinal controlled study, speech-intelligibility study and narrative-language study conducted within the same project (Chapter 11)
Status	Results of the pilot pending report; associated studies under review or in preparation

Appendix C. Technical Specifications of the Devices

Table C.1. Gait Rehabilitation Robot (model A-GEAR-V1).

Parameter	Specification
Type	Bilateral hip–knee lower-limb exoskeleton mounted on a suspension system, used with a rehabilitation treadmill
Regulatory status	Registered medical device in Kazakhstan, Class 2a
Hip range	−35° to +35° (flexion/extension)
Knee range	0–50° (flexion)
Segment speed	Up to 60°/s
Step frequency; step length	0.2–1.0 Hz (12–60 steps/min); 0.2–0.8 m on the treadmill
Treadmill speed (compatible models)	0.2–3.0 km/h, step ≤ 0.1 km/h
Patient limits	Adolescents 12–17 years and adults; body mass up to 100 kg; height 120–190 cm in the technical specifications (100–190 cm in the patient-limits section of the manual)
Cuffs	Thigh and shank cuffs with liner inserts; all sizes available at NCCR
Actuation	Motor drives at hip and knee, 64:1 reduction; ODrive v3.6 motor controllers (firmware 0.5.6, torque mode) on a 250 kbit/s CAN bus; drive firmware V3.6

Parameter	Specification
Sensing	Joint encoders; four Futek load cells (one per joint), standard on the device
Controller (current form)	Commanded torque composed of independently bounded terms; clinical modes are masks over those terms; three safety terms always active; torque caps 20 N·m (hip) and 16 N·m (knee); slew limit 27 N·m/s; range-of-motion walls; speed brake; per-excursion work bound; physically admissible friction identification
Safety	Emergency stop on cord; dry-contact stop input for the treadmill; software and mechanical limits on angles and speeds; mechanical locks and safety slings
Power	~220 V, 50 Hz, Class I (protective earth); standby ≤ 40 W, typical ≤ 300 W, peak ≤ 600 W
Classification (IEC 60601-1 / 60601-1-2 / 60529 / 62304)	Class I, type B applied parts; EMC Group 1 Class A; IP20; software safety class B
Operating mode	Intermittent: ≤ 30 min on, ≥ 10 min off
Mass and dimensions	Base module 50 kg, 880 × 650 × 1100 mm; with suspension system 150 kg, 880 × 1200 × 2200 mm
Associated software	GARAS (certificate №74083); VR exoskeleton training program (certificate №74149)

Sources: operating manual of the Gait Rehabilitation Robot; controller manuscript (Keikibayev, Sagidoldin and Jamwal, submitted); Chapter 4.

Table C.2. Adaptive body-weight support system.

Parameter	Specification
Frame	100 × 100 × 4 mm profile tube; 12 mm base plates; 6 mm bracket for pulley and cylinder
Actuator	Pneumatic cylinder SC63×400 (63 mm bore, 400 mm stroke)
Transmission	2:1 cable–pulley mechanism; ≈ 800 mm suspension travel (requirement ≥ 600 mm)
Force	Theoretical rod force 2182 N at 7 bar; ≈ 1855 N with efficiency η ≈ 0.85; ≈ 95 kgf at the suspension point
Pneumatics	Air preparation unit Optimus AC4010-04; manual pressure regulator (0–10 bar); Maxnic 4H210-8 five-port valve; throttle fitting and muffler on the exhaust line
Sensors	Load cell YZC-516C in the load path (part of the control loop); linear cable-displacement sensor BRT38-L; pressure sensor
Controller	Arduino Mega; two-position (hysteresis) control of pressure or force with timing constraints, anti-chatter logic and mutual valve interlocking
Modes	Manual (pressure regulator) and automatic (set-point control with data logging)
Harness	Designed by the program team together with the BWS system
Safety	Hardware E-STOP input; design recommendation: independent hardware emergency vent on overpressure or loss of power
Rationale for pneumatics	Compliance during changes in unweighing force
Status	Used in a seven-child pilot (NU-IREC No. 1081); phase-synchronised mode under development; registration planned

Sources: BWS technical report and manuscript in preparation; Chapter 5.

Table C.3. Robotic Perturbation Trainer: published four-cable version and final multi-plane version.

Parameter	Four-cable transverse-plane RPT (published, *MethodsX* 2026)	Multi-plane RPT (final version; manuscript)
Mechanism	Cable-driven planar parallel mechanism around a treadmill	Reconfigurable cable-driven parallel robot around a treadmill
Actuators	4 × CubeMars AK80-64 brushless DC motors with 64:1 planetary gearbox (rated 48 N·m, peak 120 N·m); 14-bit encoders	4 × CubeMars AK80-64 motors, each with a concentric 0.20 m diameter pulley
Drive electronics	ODrive 24 V, v3.6 (DRV8301 pre-driver; STM32F4 microcontroller)	Not reported in the manuscript
Geometry	Actuators at the treadmill corners (±45°, ±135°) with 0.25 m arms	Motor–pulley units on vertically adjustable carriages at the corners of a 2.5 m × 1.5 m rigid frame
End-effector	Waist belt with four attachment points at 90°	Cable attachment points on a ring of radius 0.15 m around the pelvis (body-weight-support safety jacket)
Maximum cable force	Up to 480 N (from peak torque and arm length)	Cable tensions up to 1400 N (as reported)
Perturbation planes	Transverse (four diagonal directions)	Planar (transverse) mode with carriages at pelvic height (1.0 m); spatial (sagittal and frontal, with vertical component) mode with carriages lowered (e.g. 0.6 m)
Pretension	10 N per cable	10% of the maximum perturbation force
Clinical/validation range	65–85 N, 400 ms pulses, 15–18 s random intervals	Validation: once per gait cycle at 10% of body weight; magnitudes scalable from 10% to 50% of body weight
Validation	Bench (FUTEK LCM300 load cells); two adolescents with CP, ten sessions	Three healthy adults at 0.5 km/h; sEMG of seven muscles bilaterally (Noraxon Ultium, 2 kHz)
Fall protection	BWS harness	BWS safety jacket

Sources: Khawaja et al., MethodsX 17 (2026) 104051 (Chapter 6); Kabysheva et al., manuscript.

Table C.4. QTrobot configuration used in the program.

Parameter	Configuration
Robot	QTrobot AI@Edge (LuxAI S.A., Luxembourg), child-sized humanoid (approximately 63 cm)
Expressive capabilities	LCD face with animated expressions; two arms and a movable head (12 degrees of freedom in the upper body)
Sensing	3D depth camera; four-microphone array
Computing	Raspberry Pi board for motors, display, sensors and audio; onboard NVIDIA Jetson AGX Orin
Kazakh speech	ISSAI KazakhTTS (ESPnet), developed at Nazarbayev University, running in a Docker container on the Jetson AGX Orin; audio played through the Raspberry Pi's speakers

Parameter	Configuration
Russian and other speech	Built-in Acapela voice
Language routing	Router takes over the robot's speech service and sends Kazakh text to the ISSAI voice and all other text to the Acapela voice (certificate №74308)
Therapy content	Kazakh and Russian scripts for robot-assisted therapy for children with CP (certificate №74309), authored in LuxAI's visual programming tool
Session configuration	Learner's tablet in front of the child; educator's tablet for the therapist to launch and pace modules; video recording of the session
Staffing	Normally four to five members of the research team (educators and therapists), with one or two NCCR clinicians present; parents involved
Commercialisation	The program's QTrobot content will not be commercialised

Sources: program manuscripts and author information; Chapter 7.

Appendix D. Program Outputs

Table D.1. Publications and manuscripts arising from program BR27199433.

Output	Authors	Venue	Status (October 2026)
Social robots in cognitive and speech rehabilitation for children with cerebral palsy: a scoping review	Zhaisanbek A, Karibzhanova S, Hayat I, Abdikalyk A, Khawaja AR, Mussina D, Mukhopadhyay S, Jamwal PK	*J NeuroEng Rehabil* 2026;23:34; doi:10.1186/s12984-025-01852-0	Published
USE of SARs in the rehabilitation of children with cerebral palsy	Karibzhanova S, Mukhopadhyay S, Hayat I, Zhaisanbek A, Abdikalyk A, Khawaja AR, Shakenov M, Musadilova G, Jamwal PK	*IEEE Trans Med Robot Bionics*; doi:10.1109/TMRB.2026.3733187	Published (early access)
A robotic perturbation trainer for transverse-plane gait perturbations in pediatric cerebral palsy	Khawaja AR, Sagidoldin D, Karibzhanova D, Jin Y, Niyetkaliyev A, Dauletbayev S, Khan NA, Jamwal PK	*MethodsX* 2026;17:104051; doi:10.1016/j.mex.2026.104051	Published
QTRobot-assisted intervention for children with cerebral palsy and neurological conditions: a longitudinal controlled study of behavioural outcomes	Hayat I, Mukhopadhyay S, Urumbassarova Z, Karibzhanova S, Soltanova A, Jamwal PK	*Int J Soc Robot* (SORO-D-26-00192)	Under review

Output	Authors	Venue	Status (October 2026)
Socially assistive robot-based interventions for observing cognitive behaviour in children with cerebral palsy: a qualitative microgenetic study	Soltanova A, Hayat I, Mukhopadhyay S, Smagulova K, Jamwal PK	*IEEE Trans Cogn Dev Syst*	Submitted; under review
Bounded compositional torque control for a lower-limb gait exoskeleton	Keikibayev D, Sagidoldin D, Jamwal PK	—	Submitted manuscript
Neuromuscular adaptations to multi-plane gait perturbations through dominance-specific muscle activation analysis	Kabysheva A, Kogai T, Zholdas T, Khan NA, Goyal T, Khawaja AR, Karibzhanova D, Dauletbayev S, Jamwal PK	—	Manuscript
A multidomain gait analysis framework for individualized selection of body-weight support during treadmill training in children with cerebral palsy: exploratory study	Program research team	—	In preparation
Engagement in robot-assisted and tablet-based sessions for children with cerebral palsy: a preliminary quantitative analysis	Program research team	—	In preparation
Can speech intelligibility be measured objectively in robot assisted rehabilitation? A feasibility study of acoustic and blinded listener outcomes in Kazakh and Russian speaking children with cerebral palsy	Program research team	—	In preparation
A socially assistive robot delivering bilingual stories to support narrative language in children with cerebral palsy: a preliminary pre–post study	Program research team	—	In preparation
Collaborative autoethnography of organisational barriers to implementing QTrobot-assisted therapy	Program research team	—	In preparation

Output	Authors	Venue	Status (October 2026)
Rule-based de-identification and structured extraction from Russian-language clinical documents	Program research team	—	

Table D.2. Software copyright certificates of the Republic of Kazakhstan obtained by the program. All are owned by Nazarbayev University Research Administration (NURA).

Certificate №	Software	Chapter
74083	GARAS: gait analysis and rehabilitation recommendation system	8
74149	Virtual-reality-based exoskeleton training program for patients with cerebral palsy	4, 9
74396	NCCR_Rehabilitation_Platform_2025	9
74308	Kazakh speech-synthesis routing system for QTrobot	7
74309	Therapy for children with cerebral palsy using social robots (Kazakh and Russian scripts)	7, 11

Patent applications for the Gait Rehabilitation Robot, the BWS system and the RPT will be filed; all patents arising from the program will be owned by NURA.

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