Pathways to self-initiated mobility: Adoption and use of mobility aids by young children with developmental disabilities

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ABSTRACT

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Self-initiated mobility is a critical driver of early childhood development, supporting autonomy, exploration, social engagement, and participation. As children acquire new mobility skills, they experience cascading developmental effects across motor, cognitive, linguistic, and social domains. For young children with developmental disabilities, however, opportunities for self-initiated mobility are often limited by physical impairments, inaccessible environments, and limited access to age-appropriate mobility technologies. While increasing attention has been given to supporting mobility for children with disabilities at the same time as typically developing peers, important questions remain regarding how mobility aids function within children's everyday environments and how they impact physical development.

This dissertation examines how mobility technologies, device configurations, and environments of use shape self-initiated mobility experiences for young children with developmental disabilities. Drawing from engineering, rehabilitation science, biomechanics, and disability studies, mobility is

conceptualized as an interaction among the child, technology, and the physical and social environment. Across four observational, experimental, and mixed-methods studies conducted in laboratory and community settings, this work evaluates three mobility aids designed for young children: modified ride-on car (mROCs), the Permobil Explorer Mini powered mobility device, and an open-area partial bodyweight support (PBWS) system.

Although qualitative research has identified inaccessible surfaces and inadequate space as barriers to mobility aid use, quantitative evidence describing how environmental accessibility shapes mobility behavior has been limited. By integrating embedded sensors, geospatial tracking, and open-source accessibility data, we quantified community-based modified ride-on car use over a one-year period. Findings demonstrated that environmental accessibility influenced mobility intervention success, with children living in more pedestrian-friendly neighborhoods using their devices more frequently and traveling greater distances than children living in less accessible environments. These findings indicate that access to self-initiated mobility for young children is shaped not only by device availability, but also by the accessibility of the surrounding built environment.

Community-based mobility is frequently evaluated using caregiver reports and clinical assessments, yet objective sensing technologies offer opportunities to quantify mobility behavior in real-world settings. To advance measurement of community-based powered mobility, this study compared device-integrated data loggers, GPS trackers, and caregiver-reported activity logs using data from a randomized crossover trial involving two pediatric mobility devices. Sensor-based measures provided objective information regarding frequency, duration, and distance of use, while caregiver reports captured contextual information regarding participation, engagement, and non-locomotor interactions with devices. These findings demonstrate that no single measurement approach fully characterizes self-initiated mobility and support combining engineering-based sensing methods with caregiver perspectives to evaluate mobility interventions in real-world settings.

Concerns regarding the physical implications of supporting self-initiated mobility, particularly related to posture, physical activity, and musculoskeletal development, remain a barrier to ON-Time mobility. To address these concerns, children's physical activity, posture, and biomechanical responses during play were examined using wearable sensors across multiple mobility conditions. In one study comparing play with and without partial bodyweight support, children demonstrated high levels of physical activity in both conditions, while PBWS supported increased time spent in

upright postures across sessions. In a second study comparing unassisted mobility, PBWS, and powered mobility with static and dynamic seating configurations, children explored the largest areas when using powered mobility. Muscle activity was higher during PBWS and unassisted mobility than during powered mobility, and upright posture was highly variable across conditions but occurred most frequently for the greatest number of children when using powered mobility with a dynamic seat configuration. Together, these findings show that technologies supporting self-initiated mobility redistribute physical effort and postural demands rather than reduce activity, and that different devices afford distinct movement opportunities aligned with different developmental and therapeutic goals.

Caregiver perspectives provided critical context for understanding how mobility aid use is experienced and integrated in daily life. Across interviews conducted before and after children's exposure to multiple mobility aids, caregivers described enthusiasm for mobility technologies and perceived benefits for children's autonomy, exploration, and development. At the same time, families navigated societal and clinical norms that prioritize independent walking, along with practical challenges related to device fit within the home, feasibility of use, and access. Systemic factors, including insurance coverage, cost, and provider support, were described as key enablers or barriers to supporting self-initiated mobility. Caregivers emphasized that mobility aids were most successful when they aligned with family routines and supported participation across multiple settings.

Taken together, this dissertation situates mobility for young children with developmental disabilities at the intersection of engineering, rehabilitation medicine, and disability studies. Across studies, children's self-initiated mobility experiences were shaped not only by device capabilities, but also by neighborhood accessibility, measurement practices, physical demands, and caregiver priorities. Considering these factors together underscores that supporting mobility requires attention to children's lived experiences across environments rather than focusing solely on movement metrics or device performance. Across laboratory and community settings, these findings emphasize the importance of accessible environments, mixed-method assessment approaches, and family-centered practices to support self-initiated mobility for young children with developmental disabilities.

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Chapter 1

INTRODUCTION

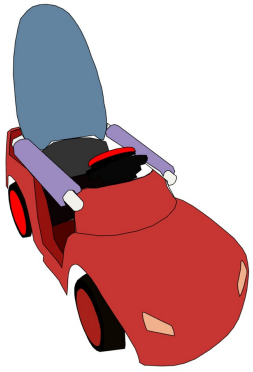
Self-initiated mobility is critical for an individual's autonomy, community participation, social engagement, and dignity [1]. From developmental research, it is well established that as children learn to move independently they experience cascading developmental benefits across domains, including language, cognition, and social interaction [2, 3]. Yet the trajectories through which young children acquire independent mobility are highly variable. Children may crawl, scoot, bunny hop, crab walk, wheel, or step as they discover how to navigate their environments [4, 5]. Across all these pathways, mobility emerges through extensive exploration, trial, and error; a child learning to walk falls hundreds of times per day [6] and a young child learning to use a joystick with a powered mobility device begins with basic cause-effect activations before refining directional control [7, 8].

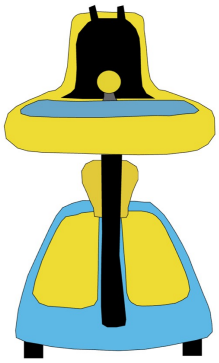
For young children with developmental disabilities, early opportunities for exploration can be shaped, or constrained, by the environments they encounter and the availability of mobility aids. Providing the supports necessary to enable play and participation therefore requires a reimagining of what assistive technology looks like, how it is accessed, and how it is incorporated into daily routines and home environments. Open-source approaches, such as 3D printed manual wheelchairs or adaptations of commercially-available toys and ride-on vehicles, represent one way for families to access assistive technology for their child [9, 10]. In parallel, small organizations initiated by families of children with disabilities, such as the Frog Foundation and Bella's Bumbas, work to source mobility aids for other families with similar needs. The emergence of new commercial technologies, such as the Permobil Explorer Mini powered mobility device, may reflect calls to redesign pediatric mobility technology [11]. In this emerging era of creating access for the youngest children, it is critical that we identify favorable aspects of current technologies, necessary improvements, and understand how young children learn to use them.

1.1 Focus of the dissertation

This dissertation in mechanical engineering uses a mixed-method approach to understand how the environment of use, type and design of a mobility aid impacts self-initiated mobility for young children with developmental disabilities. By integrating quantitative measures of device use with qualitative insights from caregivers, this work aims to identify design and contextual factors that support mobility, participation, and age-appropriate exploration. The majority of young children interact with assistive technology routinely, most commonly through infant positioning equipment such as highchairs and bouncers. This dissertation, however, focuses specifically on mobility aids for young children with disabilities. Three mobility aids are examined in depth throughout: two powered mobility devices and an open-area partial bodyweight support system (Table 1.1). Across studies, device use will be measured in both home and experimental settings, compared across devices, and examined within the broader systems that shape how these technologies are used.

Table 1.1: Three mobility aids are used throughout this thesis: the modified ride-on car (MROC), the Permobil Explorer Mini (EM), and the Portable Mobility Aid for Children (PUMA).





Modified ride-on car (MROC)	**Explorer Mini (EM)**	**PUMA**
Chapter 3	Chapter 4	Chapter 5
Chapter 4	Chapter 6	Chapter 6
	Chapter 7	Chapter 7

1.2 Significance

This dissertation brings together knowledge from mechanical engineering, rehabilitation medicine, disability studies, and biomechanics, to understand how young children adapt to mobility aids and

how families incorporate them into their lives. With this interdisciplinary analysis, the primary contributions of this research are:

1.2.1 Environmental accessibility impacts young children's mobility

Chapter 3 provides empirical evidence that environmental accessibility shapes mobility opportunities for young children using powered mobility devices. Using integrated data loggers and GPS tracking embedded within fourteen children's modified ride-on cars over a one-year period, this work demonstrated that children primarily used their devices at or near home, and that outdoor use was associated with longer play sessions, greater distances traveled, and increased active engagement. Children living in more pedestrian-friendly neighborhoods exhibited higher usage and traveled farther distances when using their devices, highlighting the role of the built environment in shaping mobility opportunities. By integrating neighborhood accessibility data from Project Sidewalk, this work further illustrated how sidewalk accessibility may influence families' usage patterns, with contrasting cases demonstrating consistent outdoor driving routines in highly accessible areas versus limited use in areas with poor sidewalk infrastructure. While prior qualitative research has identified environmental inaccessibility as a perceived barrier to mobility device use for young children [12, 13, 14, 15], this study is the first to quantitatively document the effects of environmental accessibility on community-based mobility in early childhood. These findings underscore that the effectiveness of early mobility technologies is contingent upon accessible environments, with implications extending across the lifespan.

1.2.2 Advancing measurement of community-based powered mobility

A central contribution of this dissertation is the advancement of methods for measuring mobility aid use in community-based contexts. As a secondary analysis of data from a multi-site clinical trial, Chapter 4 compares integrated data loggers, GPS trackers, and caregiver-reported activity logs across two pediatric mobility devices. This work demonstrated that no single measurement approach fully captures children's mobility experiences. Integrated data loggers and GPS trackers showed the strongest agreement for several usage metrics, while caregiver reports provided com-

plementary information regarding context, engagement, and non-locomotor use of devices. These findings highlight the complexity of "mobility usage" that encompasses presence, activity, and engagement, and that different measurement tools capture distinct aspects. By empirically comparing tracking modalities and documenting their strengths and limitations, this work provides practical guidance for future researchers designing community-based studies of pediatric mobility. More broadly, it supports a mixed-methods approach to measurement that combines quantitative sensing technologies with contextual and experiential data to better reflect real-world mobility.

1.2.3 Quantifying physical wellbeing and function with mobility aids

A persistent concern in pediatric rehabilitation is the impact of mobility on children's physical development [16]. For long-term health, children need opportunities to move through a variety of postures throughout the day, particularly upright positions that support bone health and musculoskeletal development [17, 18]. However, there is limited quantitative evidence regarding how mobility aids contribute to children's physical activity, posture, and muscular engagement during everyday use. This dissertation aims to quantify how different mobility aids shape children's physical activity and biomechanical function during play. Chapter 5 measured children's physical activity and upright postures while playing both with and without partial bodyweight-support assistance. Findings from this study show that children maintained high physical activity levels across conditions, while partial bodyweight support increased time spent upright. Building on this approach, Chapter 6 extends biomechanical measurement to compare multiple mobility aids and configurations using wearable sensors to capture muscle activation and upright posture. Results show that mobility aids can support upright positioning for children who are not yet independently standing, while also revealing that device type and configuration influence muscular demands. Clinically, this work supports more intentional device selection based on therapeutic goals, such as promoting upright posture, and suggests that access to multiple mobility aids may better support children's functional development. This research provides quantitative evidence for integrating biomechanical considerations into early mobility interventions, reinforcing the role of mobility aids as tools that can support both participation and physical health.

1.2.4 Caregiver perception of different types of mobility aids

Prior literature has broadly covered caregivers' perspectives related to one type of mobility aid, but not the use of multiple mobility aids. Chapter 7 captures caregivers' perspectives on both ambulatory and wheeled mobility aids for their young child with developmental disabilities. Qualitative thematic analysis reveals that families view mobility aids as tools that support autonomy, exploration, and social participation, while simultaneously navigating societal norms and structural barriers that prioritize independent walking, rather than interdependence and mobility aid use. As has been documented in prior work, caregivers describe challenges related to fitting mobility aids within home environments, feasibility, and finding devices that fit their child specifically. This work highlights the importance of aligning device design, clinical recommendations, and measurement approaches with family priorities and daily realities. These findings align with those from Chapter 4 that "success" of early mobility interventions cannot be evaluated solely through motor outcomes, but must also account for usability and sustainability within family life.

1.3 Dissertation Overview

This dissertation includes analyses from four experimental studies using three different mobility aids for young children with developmental disabilities and delays: a modified ride-on car, the Permobil Explorer Mini powered mobility device, and the Portable Mobility Aid for Children (PUMA, Enliten, LLC), an open-area partial-bodyweight support system (Table 1.1). Chapter 2 provides additional information on each mobility device and elaborates on the importance of self-initiated mobility for supporting children's development, as well as the ways in which developmental disabilities can affect this process.

Chapter 3 quantifies modified ride-on car use in the community environment over the course of one year and examines how usage relates to environmental attributes, such as sidewalk accessibility [19]. Chapter 4 compares methods for tracking powered mobility device use in the community environment, while simultaneously comparing children's use of two different powered mobility devices as part of a multi-site clinical trial [20]. Chapter 5 quantifies the effects of PUMA use on physical activity and posture for children with Down syndrome as part of a multi-site clinical trial

(Hoffman et al. *In review at Developmental Neurorehabilitation*). Chapter 6 compares children's movement and biomechanics with two mobility aids and without (Hoffman et al. *In preparation for Developmental Medicine & Child Neurology*). Chapter 7 illuminates caregivers' perceptions of using two different types of mobility aids with their children who have developmental disabilities and delays (*In preparation for Pediatric Physical Therapy*). The final chapter summarizes the key findings and impact of this body of work and outlines directions for future research.

Positionality

Throughout this dissertation, the term *"we"* is utilized as research is inherently collaborative, and each study had its own distinct team that made it feasible. At the start of each chapter, the contributing team members are identified, and additional team members are included in the Acknowledgments. Additionally, each project involved participating families who are not named individually; their contributions were essential, and this research would not have been possible without them. I approach this work as a disabled scholar, a rehabilitation engineer, and a play expert. Throughout this dissertation, I developed expertise in signal processing, biomechanics, and qualitative methods; all of which are applied throughout.

Chapter 2

BACKGROUND

This chapter provides the theoretical and clinical context for examining access to self-initiated mobility for young children with developmental disabilities. We begin with an overview of motor development in infancy, highlighting variability in developmental trajectories and the contextual factors that shape emerging mobility skills. The chapter then discusses self-initiated mobility as a driver of developmental cascades, describing how changes in movement influence children's opportunities for learning, social interaction, and participation. Building on this perspective, the ON Time Mobility framework is introduced as a guiding theory that emphasizes timely, frequent, multimodal, and socially embedded access to mobility during early development. We then shift to explaining the clinical context of early intervention services in the United States, with focused discussion of two populations represented throughout this dissertation, children with cerebral palsy and children with Down syndrome. Finally, the chapter reviews the range of mobility aids used in early intervention, highlighting both their developmental potential and gaps in their current capabilities. This section includes detailed descriptions of the three mobility aids examined throughout this dissertation: two powered mobility devices and an open-area partial bodyweight support system.

2.1 Motor development in young children

Mobility refers to the changing of one's location in space with agency and purpose [4]. In contrast to gait, which is often studied in controlled contexts, such as treadmill walking or straight-line overground walking, mobility rarely includes consistent cyclic movements. Instead, mobility is nonlinear, especially in its developing stages. For example, beginning walkers typically move in short bouts consisting of a few steps with frequent falls and turns [4, 6]. This chapter discusses the emergence of *self-initiated mobility*, which we define as a child directing their movement through

space under their own agency.

2.1.1 Gross motor developmental trajectories

Standardized measures of gross motor developmental milestones, such as those defined by the World Health Organization through the observation of developing infants in six countries [21], provide normative estimates for when children typically achieve select motor behaviors (Figure 2.1). However, children's motor development follows a nonlinear trajectory, such that the initial emergence of a motor skill does not indicate immediate or consistent use. Infants may demonstrate a newly acquired motor behavior sporadically and may not reliably incorporate it into their daily routines for some time after first onset [22]. In the United States, the Centers for Disease Control and Prevention revised developmental surveillance milestone checklists in 2022, a change that included the "controversial" removal of crawling as a milestone [23]. This decision aligns with developmental literature demonstrating that many pre-walkers do not crawl and instead adopt individualized strategies for mobility [4]. Findings from the WHO motor milestones study, which established normative developmental estimates, similarly indicated that 4.3% of children did not crawl on hands and knees, yet otherwise demonstrated the other measured developmental skills [21]. This evidence raises the question of the benefits of utilizing normative estimates and charting developmental trajectories [24].

The emergence and timing of motor behaviors are influenced by caregiving practices, cultural norms, and the use of infant positioning equipment [4, 24, 28, 29]. For example, in central Asia, gahvora cradling, an infant care practice in which children are tightly swaddled and bound in a cradle bed with limited opportunities for movement, has been shown to delay the emergence of motor milestones [28, 30]. Despite these delays, children reared in gahvora environments demonstrate motor performance comparable to children in the United States by four to five years of age [31]. In Western culture, infants also spend substantial time in infant positioning equipment, with one U.S. survey study finding that children spend on average 5.14 hours per day in containers [32], and another finding that both typically developing children and those with or at risk for cerebral palsy spend approximately 25% of their waking hours in devices [33]. The high use of commercialized infant positioning equipment in the United States has raised concerns about "container baby syn-

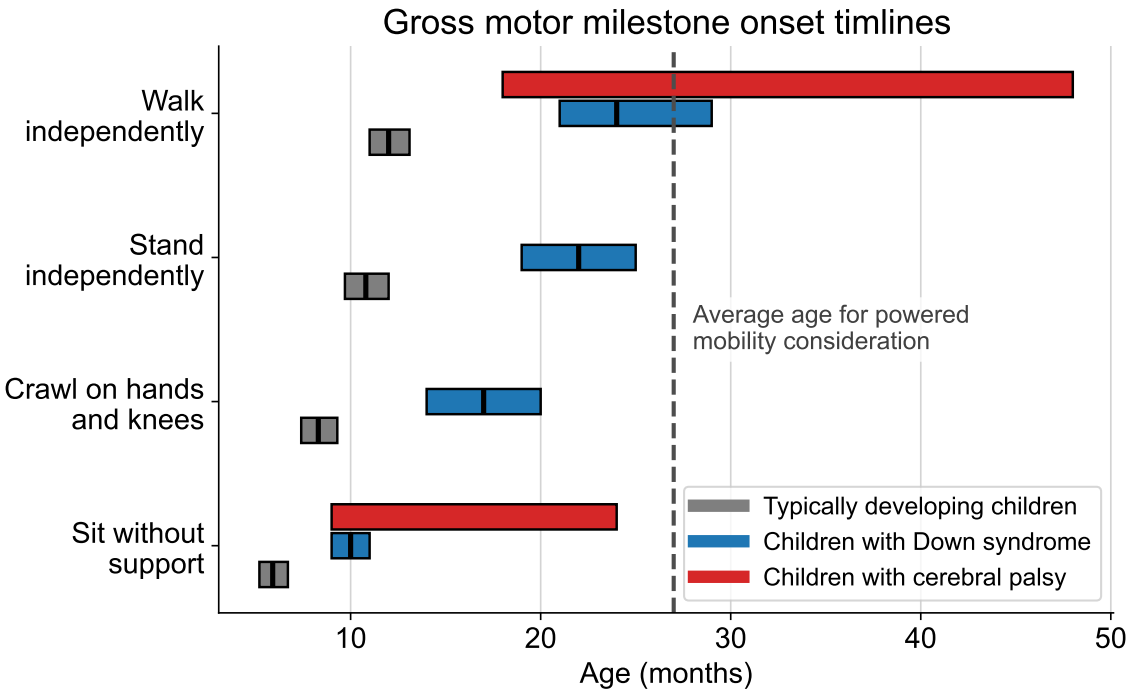


Figure 2.1: Estimates of gross motor milestone onset for typically developing children [21], children with Down syndrome [25], and children with cerebral palsy [26, 27]. Bars for typically developing children and children with Down syndrome show the 25th, 50th, and 75th percentiles. The average age of powered mobility device consideration is also demarcated [16].

drome" [34], and the potential adverse effects that prolonged or excessive use of these devices may have on infant development [32]. Even the structural design of this equipment can shape observable motor behaviors. For example, infants who have not yet independently developed rolling may roll from supine to prone when placed on inclined surfaces, raising safety concerns related to the use of infant positioning equipment like bouncers [35]. This shows that motor trajectories are influenced by the context and environment in which a child develops.

2.1.2 Importance of self-initiated mobility and developmental cascades

Infants and toddlers spend much of their earliest lives being carried by caregivers or transported in strollers, both forms of passive locomotion that limit autonomous exploration of the environment. Along typical developmental timelines, children gradually transition toward self-initiated mobility, beginning around six months of age, through a range of movement forms including crawling,

bottom shuffling, cruising, and eventually independent stepping [5, 36]. Although these forms of mobility differ in biomechanics and timing, they share a common functional characteristic: they allow children to move through space under their own control.

From a developmental psychology perspective, motor development is a driver of change across multiple domains. The evidence shows that gains in motor skills alter how infants access the environment, creating new contexts and opportunities for learning [2, 36, 37, 38]. The emergence of independent sitting frees infants' hands for object exploration and manipulation, enabling richer play experiences [39, 40]. Simultaneously, the upright trunk posture facilitates the emergence of syllabic vocalizations and early language growth [2]. Similarly, the onset of independent walking shifts how children can engage with their surroundings. Walking frees a toddler's hands for carrying objects across space [41], increases visual access to people and distal objects [42], and even changes interactions with caregivers [43, 44]. For example, mothers of newly walking infants use language that is more action-oriented and directive, indicating perceptual changes in their child's abilities to initiate and sustain goal-directed activity [43, 44]. The interconnected nature of these changes across domains is described as the *developmental cascades*, which refers to processes by which change or disruption in one domain spreads over time to influence development in other domains [2, 36, 37].

2.1.3 ON Time Mobility

Developmental cascades form the basis of the ON Time mobility framework, in which the emergence of self-initiated mobility can have positive downstream consequences on development by altering children's ability to interact independently with their physical and social environment [3]. Self-initiated mobility allows children to select destinations, initiate social interactions, access new objects and people, and generates new learning opportunities. Hence, if access to self-initiated mobility supports growth in other domains, delays or restrictions in opportunities for self-initiated mobility may have consequences that extend beyond motor development. The ON Time Mobility framework advocates for access to self-initiated mobility at developmentally appropriate ages through five connected principles: timing, urgency, multimodal access, frequency, and sociability [3]. The principles of *timing* and *urgency* emphasize access to mobility during critical developmental

time periods, when neuroplasticity is highest, and delays in mobility access may have downstream developmental consequences. The *multimodal* principle recognizes that there is not a single correct form of mobility; use of any and all forms of self-initiated mobility with and without assistive technology should be encouraged [5]. Building on this, the *frequency* principle establishes the guidelines that mobility opportunities must be available often and embedded in daily routines, rather than be isolated to a clinical environment [45]. Finally, the *sociability* principle states that mobility is most relevant when it also supports social engagement, communication, and participation with others [2, 36]. These principles explicitly link mobility access to broader learning trajectories, and as such, the ON Time Mobility framework serves as the guiding theoretical foundation for this dissertation, motivating both the focus on self-initiated mobility during critical developmental periods and the investigation of how young children with disabilities learn to use mobility aids.

2.2 Early intervention services for children with developmental disabilities

Early intervention describes coordinated services aimed at improving developmental outcomes for infants and toddlers with or at risk for delays. In the United States, these services are administered through Part C of the Individuals With Disabilities Education Act (IDEA) [46]. Eligibility criteria vary by state and can include documented developmental delays, a diagnosed physical or mental condition with a high probability of resulting in delay, or risk factors related to biological or environmental conditions such as low birth weight or nutritional concerns [47, 48, 49]. Under federal guidelines, developmental delay must be present in at least one of five domains: cognitive, physical or sensory, communication, social-emotional, or adaptive development [48]. Identification of eligible children typically occurs through developmental monitoring and screening by healthcare providers. However, only a portion of children who qualify for services are ultimately identified and referred [49, 50]. In 2023, approximately 440,000 children, or 4% of the United States population under three, received early intervention services [51]. Throughout this dissertation, we will discuss mobility supports provided to young children receiving early intervention services. Early intervention describes coordinated services aimed at improving developmental outcomes for infants and toddlers with or at risk for delays. In the United States, these services are administered through Part C of the Individuals With Disabilities Education Act (IDEA) [46]. Eligibility criteria vary by

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2.2.1 Cerebral palsy

Cerebral palsy is the most prevalent pediatric neurodevelopmental disability, affecting approximately 3 out of every 1,000 children in the United States [52, 53]. Children with cerebral palsy present with a wide range of functional abilities, as the term encompasses a group of disorders resulting from non-progressive injury to the developing brain occurring shortly before, during, or after birth [54, 55]. Although the underlying brain injury is non-progressive, the clinical presentation may change across development as children grow and encounter increasing environmental demands [27, 56]. Motor impairments are a defining feature of cerebral palsy, and commonly include difficulties with movement coordination, postural control, and selective motor control, as well as irregular muscle tone [55]. The most common clinical presentation is spastic cerebral palsy, characterized by increased muscle tone and exaggerated stretch reflexes, while other presentations include dyskinetic cerebral palsy, marked by involuntary movements, and ataxic cerebral palsy, associated with balance and coordination difficulties [55]. Many children exhibit mixed motor presentations, reflecting the heterogeneous nature of cerebral palsy.

To support clinical decision-making and describe functional mobility, children with cerebral palsy are typically classified according to their gross motor abilities using the Gross Motor Function

Classification System (GMFCS), which consists of five levels defined by a child's self-initiated movement and use of assistive devices [57, 58]. Children who walk independently in all settings, albeit with challenges related to speed, balance, and coordination are classified as GMFCS I. Children who experience greater difficulty with long distances or uneven terrain are classified as GMFCS Level II, and may use mobility aids in community settings [27, 58]. Children who require a hand-held mobility device for walking and who commonly use wheeled mobility for longer distances are classified as GMFCS Level III [27, 58]. Children with higher support needs who typically require physical assistance or powered mobility for most functional mobility are classified as GMFCS Levels IV or V [27, 58]. Gross motor function level is closely associated with the timing and likelihood of independent walking [27]. Most children classified as GMFCS Level I walk independently in home and community settings by four years of age (Figure 2.1), whereas children classified as GMFCS Levels II and III may have a later walking onset and commonly utilize assistive devices for mobility [27]. Individuals with cerebral palsy with higher support needs typically use wheeled or supported mobility strategies to move through their environments [57, 58, 59].

2.2.2 Down syndrome

Down syndrome is one of the most common neurodevelopmental conditions and results from Trisomy 21, or three copies of the 21^{st} chromosome. The live birth prevalence in the United States is estimated between 1 in 707 and 1 in 824 births [60, 61], with approximately 250,000 people in the United States [62] and 419,000 people in Europe [63] living with Down syndrome. The incidence of Down syndrome has increased over time, largely because the likelihood of Down syndrome rises with increasing maternal age [64, 65]. Children with Down syndrome commonly experience challenges related to muscle strength, power, and endurance [66]. These functional differences are associated with a combination of neuromotor and musculoskeletal factors, including cerebellar hyperplasia, hypotonia, and joint laxity [66, 67, 68]. Cerebellar hyperplasia refers to a developmental difference in which the cerebellum, a brain region involved in balance, coordination, posture, and motor control is larger due to altered early growth. In addition, hypotonia, or low muscle tone, and ligamentous laxity contribute to reduced joint stability and alignment. Together, these factors contribute to delays in both gross and fine motor development (Figure 2.1). Reported ages of walk-

ing onset for children with Down syndrome show considerable variability across studies. Although walking most commonly emerges between 21 and 29 months [25, 69, 70], caregiver reports indicate that some children walk substantially later; in one sample, 5 of 15 children were not yet walking independently at 36–41 months [71]. In addition to motor and biomechanical differences, children with Down syndrome often experience intellectual disability as well as delays in other developmental domains, including language and feeding [71]. Thus, for children with Down syndrome, delayed access to independent mobility may be especially consequential, with the potential to contribute to developmental cascades affecting cognition, language, and participation.

Evidence-based interventions for young children with central hypotonia, including those with Down syndrome, remain limited [72, 73]. Prior research indicates that treadmill training can promote earlier walking onset and improve gait parameters in children with Down syndrome who are learning to walk or already ambulatory [72, 73, 74]. Treadmill training typically involves supporting a child over a moving treadmill to practice stepping and/or manually guiding the lower limbs during stepping movements. Despite its evidence base, treadmill training can be difficult to implement in practice; in one survey, 23 of 91 therapists reported being unable to use treadmill training due to limited resources [66]. Current clinical guidelines for young children with hypotonia also recommend the use of mobility aids and adaptive equipment to support activity and participation [72, 75, 76]. Consistent with these recommendations, a recent case study applying the ON Time Mobility framework, including the use of a supported stepping device beginning at 9 months old, reported that the child achieved independent walking of 10 steps without the device by 20 months of age [76].

2.3 Mobility devices in early intervention

Mobility devices for young children with disabilities have ranged from ad hoc solutions created by caregivers and clinicians to commercially manufactured products intended specifically for young children. Artifact analysis of powered mobility devices for young children highlights the variability in available positioning options, customization, and access methods, many of which appeared on the market only briefly before being discontinued [11]. This short product lifespan underscores the challenges of designing universally accessible devices for a highly heterogeneous infant and

toddler population served in early intervention contexts, as well as the limited commercial incentives for companies to invest in low-volume pediatric technology sectors. Across early intervention, mobility devices can be broadly grouped into wearable supports, supported stepping devices, and wheeled mobility, each reflecting different approaches to enabling movement, participation, and environmental interaction (Figure 2.2).

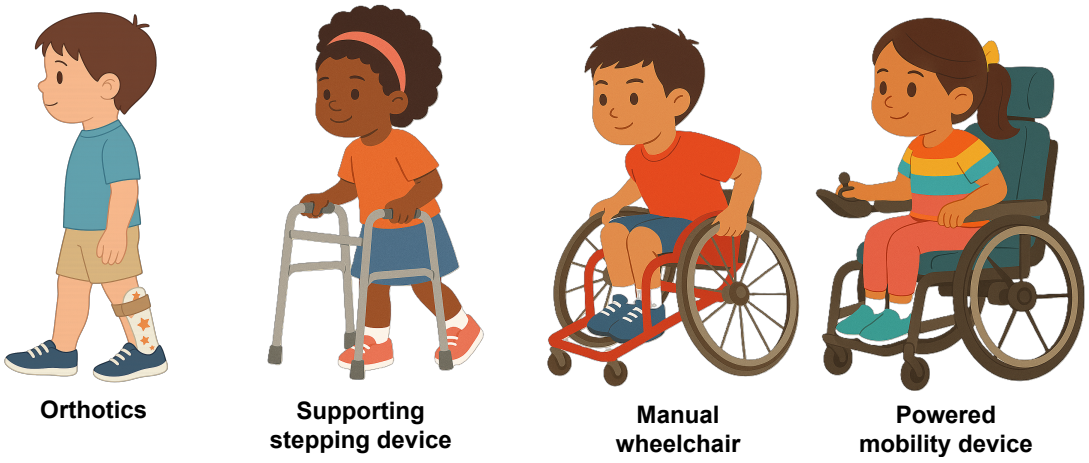

Figure 2.2: Types of mobility aids. *Images created with generative AI*

The form and function of mobility aids vary widely, reflecting the diversity of developmental needs across early childhood. Wearable supports such as ankle–foot orthoses (AFOs), supramalleolar orthoses (SMOs), and compressive garments provide postural stability and alignment. Orthotic use supports functional mobility in upright postures, and can also shape musculoskeletal development. Although AFO wearers describe them as uncomfortable, they also find that they benefit their mobility and independence [77]. A recent study showed that 75% of young children with cerebral palsy, across GMFCS levels, had lower-extremity orthotics [78]. Orthotics are also frequently prescribed for children with Down syndrome to provide support due to the low muscle tone and ligament laxity of the condition [66]. However, there is not strong evidence for orthotic use for pre-ambulant Down syndrome [76, 79], and early use of orthoses may even lead to decreased motor skill development after walking onset [80]. Despite their widespread use, orthotic interventions alone rarely provide independent mobility, and instead serve as part of a broader constellation of supports.

Supported stepping devices, such as hand-held walkers and gait trainers, offer opportunities to

practice stepping and participate in upright play with peers. Gait trainers can increase the ability of a child to take steps and increase walking distances, while also supporting upright postures that benefit bowel function and bone mineral density [81]. Equally important, supported stepping devices are associated with benefits to participation, engagement, autonomy, self-efficacy, self-esteem, and increased happiness for children [18]. A survey of 513 pediatric physical therapists found that gait trainers were most often recommended for children with cerebral palsy, spina bifida, spinal cord injury, or pediatric orthopedic disorders [82]. Surveys in Norway and the United States found that roughly one quarter to one third of children with cerebral palsy use walking aids, with reported rates of 26.2% in Norway and 28.8% in the U.S. [78, 83]. Despite their widespread clinical use and demonstrated benefits, there remains limited quantitative evidence characterizing real-world use patterns of supported stepping devices.

In contrast to wearable supports and supported stepping devices, wheeled mobility devices, including manual wheelchairs and a range of powered mobility devices, introduce opportunities for self-directed movement that are independent of a child's current ambulatory abilities. Wheeled mobility enables children to initiate, sustain, and direct movement across space, supporting access to environments and activities that may otherwise be inaccessible. In the United States, 45% of young children with cerebral palsy have a medical stroller or another form of wheeled mobility [78]. In Norway, 20.8% of children use a manual wheelchair and only 10% of children use powered mobility, despite evidence that 44 of 130 children in the sample would likely have been candidates for powered mobility [83]. Many children use wheeled mobility as part of a multimodal mobility repertoire, alternating between crawling or walking in familiar environments and using supported or wheeled mobility devices in community contexts where distances, fatigue, or environmental barriers limit ambulation [27, 56, 84]. Despite growing evidence that very young children can learn to operate powered mobility devices, referral and provision often occur relatively late in early childhood. The average age at which children are considered for powered mobility is approximately 2 years and 3 months [16] (Figure 2.1), even though research has demonstrated that children as young as 7 months can begin to learn powered mobility skills [85]. This gap between demonstrated capability and typical access reflects ongoing uncertainty about the role of wheeled mobility in infancy and toddlerhood.

Beyond differences in device type, access to and use of mobility equipment in early childhood

varies systematically by functional level, age, and service context. Children with cerebral palsy who have higher support needs typically require a greater number of mobility devices across development [78, 83, 86]. Despite this need, up to age three, children classified at GMFCS levels II–V remain largely dependent on others for mobility in community settings [27], rather than engaging in self-initiated mobility through mobility aids. Evidence further suggests that younger children with cerebral palsy have access to fewer mobility devices than older children [78, 83]. For example, one study found that 29% of children with cerebral palsy, primarily those under 48 months of age, relied on a stroller as their primary means of mobility [87]. Similarly, a survey in Norway reported that 24.6% of children with cerebral palsy under seven years of age used adapted strollers [83]. This pattern may reflect families' use of infant positioning equipment or passive mobility solutions, such as strollers, particularly in early childhood. While these devices support transportation and caregiving needs, they do not afford opportunities for self-initiated movement, highlighting a critical gap between mobility support and independent exploration during early development.

In response to this gap between mobility support and opportunities for independent exploration in early development, the remainder of this chapter describes the three mobility aids examined in this dissertation, two powered mobility devices and an open-area partial bodyweight support system, and reviews the relevant literature for each.

2.3.1 Modified ride-on cars

In response to limited access to commercial powered mobility devices in early childhood, community volunteers and researchers have adapted off-the-shelf toy ride-on cars for therapeutic use [9, 88]. These modified ride-on cars (mROCs) are typically customized to the child, with common adaptations including replacing foot pedal activation with an accessible switch and adding postural supports constructed from low-cost materials such as PVC pipe, pool noodles, and kickboards (Figure 2.3) [9, 88]. The evidence indicates that children as young as six months of age can use mROCs [89, 90]. Although mROCs may be appropriate for older children, published studies to date have primarily focused on children under 5 years of age, as prescribed powered wheelchairs are typically not provided until preschool age [91, 92].

A substantial body of research demonstrates that mROC use provides multiple benefits for

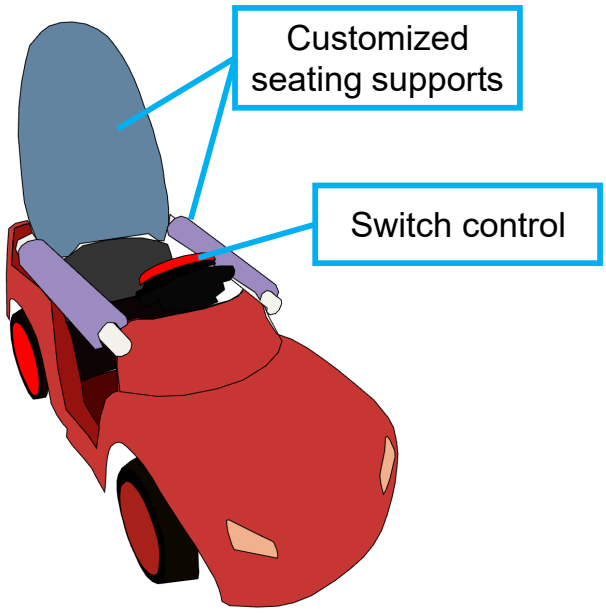

Figure 2.3: Modified ride-on car (mROC).

children and families [91]. Studies consistently report that mROCs are highly enjoyable for children [93, 94, 95, 96], while also reducing parental stress [97, 98]. mROC use has been associated with increased interaction with the environment [95, 99], as well as greater social interaction and participation during play and daily activities [94, 96, 99, 100]. Evidence further suggests potential functional advantages of mROCs relative to other mobility aids; for example, one case study found that a child using an mROC moved more quickly and experienced less fatigue than when using forearm crutches [101]. Although the literature remains limited, available studies also indicate that mROC use may be beneficial for children with Down syndrome [94]. Beyond mobility, mROCs can be adapted to support gross motor skill practice, such as promoting sit-to-stand transitions by requiring standing to activate movement [90, 102]. Despite these benefits, one of the most commonly reported barriers to mROC use is difficulty with control. While many children readily learn basic cause-and-effect relationships, steering the device often proves challenging, which can lead to reduced use once a child is ready to engage in purposeful, goal-directed exploration. As a result, mROCs may not developmentally progress with children beyond early exploratory use, highlighting an important gap in device design.

2.3.2 Permobil Explorer Mini

The Permobil Explorer Mini (EM) is a powered mobility device cleared by the Food and Drug Administration in 2020 for use by children aged 12 to 36 months (Figure 2.4). The device weighs 52 lbs, has a drive range of 3 miles, and is controlled via a proportional joystick with five speed options and a maximum speed of 1.5 mph (0.67 m/s). The EM was designed to support flexibility in use; the height of the seat and tray can be adjusted to accommodate growth and varied postures, and the seat can also be fully removed so that the device functions as a dynamic stander.

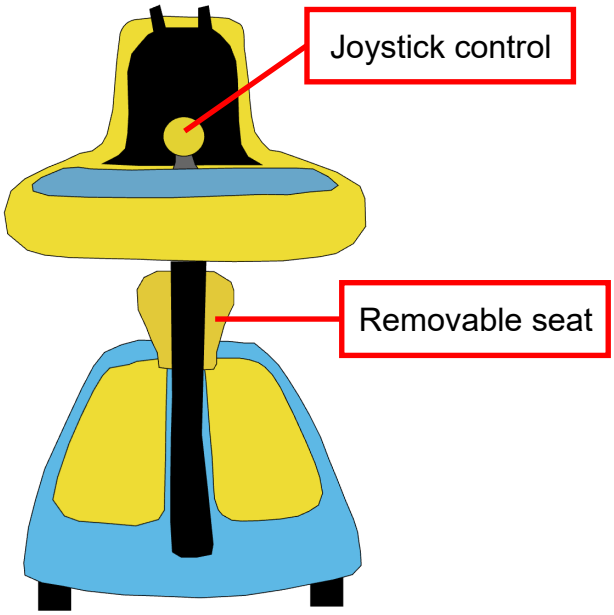

Figure 2.4: The Permobil Explorer Mini.

In an initial validation study of the EM, Plummer et al. [103] evaluated device use with 33 children aged 8-35 months with heterogeneous diagnoses, including cerebral palsy, Down syndrome, and spina bifida. Nearly all participants (94%) were able to move the device in at least one direction, and a similar proportion showed an observable emotional response while using the device, suggesting feasibility and engagement across clinical presentations [103]. Building on this work, subsequent studies have examined developmental and behavioral outcomes associated with repeated EM use in both home and structured play environments. Across these studies, children demonstrated significant improvements in cognitive, receptive and expressive language, fine motor, adaptive behavior, and socio-emotional development domains following EM use [104, 105]. Developmental gains may

also be related to the frequency of device use, as one study found that children who engaged with the EM for approximately 60 minutes per week showed larger improvements relative to peers with lower overall use [106]. Behavioral indicators further highlight changes following EM use. Language analyses measured increases in joyful vocalizations and reductions in expressions of distress following EM use [105], and caregiver reports suggest that children may experience improved sleep behaviors, such as fewer nighttime awakenings, after EM use [107].

To understand the mechanisms underlying these developmental changes, other studies have used sensor-based approaches to measure how children interact with and learn to control the EM. Quantitative analyses showed that children spent approximately 30% of each session in active motion and significantly increased their time moving across 12 sessions, indicating growing engagement [108]. On average, children traveled 54.8 meters per session, with some sessions reaching distances of up to 88.3 meters. Measures of device interaction showed increasing joystick complexity across sessions; however, only 48% of joystick activations resulted in device movement, highlighting a key design limitation of the EM that may constrain children's learning and control acquisition [108]. Additionally, children's joystick interactions vary widely; one study found that four children preferred a forward joystick direction while five used a backward direction [109]. This difference may be influenced by the relative ease of producing pulling motions, which rely on flexor muscle activation and require less postural control than pushing movements. This finding contrasts with research involving typically developing children using a joystick, who showed a preference for forward joystick movements [110]. Finally, the design of the EM supports a range of postural configurations, which have been shown to influence muscle activity, distance traveled, and the amount of bodyweight support [109].

2.3.3 Partial Bodyweight Support System

Using open-area partial bodyweight support (PBWS) systems may enhance children's motor development by enabling early, safe, and frequent opportunities for upright mobility. Powered systems, such as the ZeroG gait and balance system (Aretech, LLC, Sterling, VA), and passive systems, such as the Portable Mobility Aid for Children (PUMA; Enliten, LLC, Newark, DE), provide adjustable bodyweight support within a defined area, allowing children to transition between postures and

move freely without relying on hand-held devices (Figure 2.5). Across diverse populations, including children with spina bifida, Down syndrome, and spinal muscular atrophy, children showed gains in gross motor function [111, 112], increased walking distances [111, 113], and achievement of new motor milestones such as crawling, standing, and assisted walking [114]. Movement tracking through video coding and motion capture further demonstrated increases in independent locomotor activity, including more self-initiated steps and marked increases in total distance traveled, such as a 177% increase in path length during PBWS use [115] and 10–50 meters of movement per session [113]. Collectively, these findings indicate that PBWS systems help children move more frequently and independently, supporting exploratory behavior, functional endurance, and key components of motor learning.

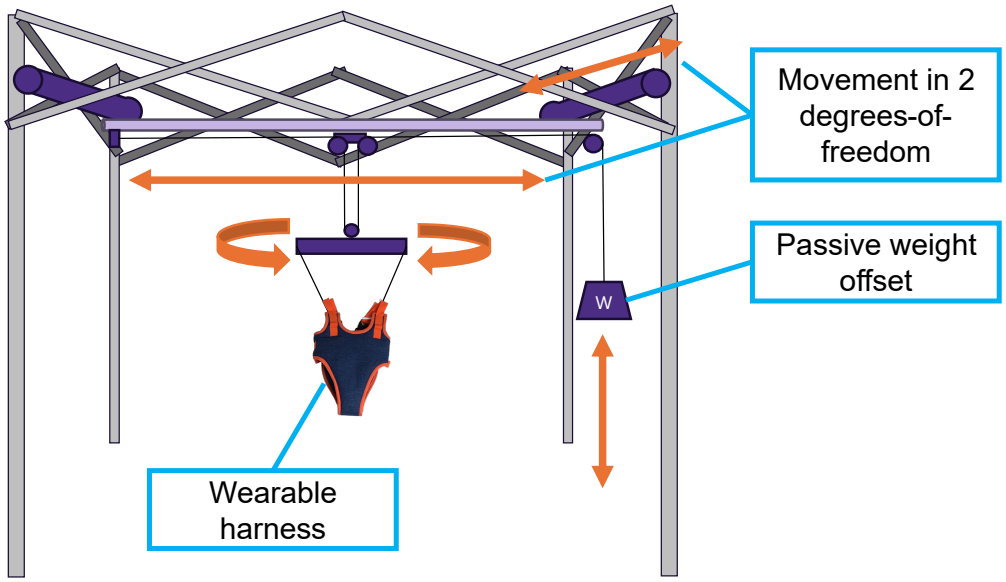

Figure 2.5: The Portable Mobility Aid for Children (PUMA)

Beyond motor gains, families consistently demonstrated strong acceptance, feasibility, and sustained engagement with PBWS systems during home use. Across studies, families used the devices between 2.7 and 6.1 days per week between 30 to 60 minutes each day [111, 115, 116], with one study reporting 117 days of use over 135 days [116]. Caregiver-reported perceptions were overwhelmingly positive, noting ease of use, safety, enjoyment, and favorable behavioral changes in infants and children [113, 114, 115, 117]. Although broader developmental measures such as the Bayley-III or mastery motivation showed minimal group-level change [112, 115], the overall evidence suggests that PBWS systems enhance opportunities for movement, exploration, and participation, which

are key developmental drivers.

2.4 Conclusion

This chapter has demonstrated that self-initiated mobility is a central driver of development, shaped by both children's abilities and the environments in which they move. The ways in which movement emerges are highly variable; however, access to movement with agency, rather than attainment of specific motor milestones, is the critical factor underlying emerging developmental cascades. Within this context, the ON Time Mobility framework provides a lens for understanding why age-appropriate, frequent, multimodal, and socially embedded mobility experiences are particularly important for young children with developmental disabilities. Despite this evidence, mobility for young children is often caregiver-directed, and delayed access to mobility aids further widens the mismatch between children's developmental needs and their opportunities for independent exploration. The mobility aids reviewed in this chapter show both the potential and the limitations of existing technologies to address this gap. In the following chapters, we will apply an engineering lens to examine how different forms of assisted mobility function in practice, and how they shape children's movement and interactions during early development.

Chapter 3

OFF TO THE PARK: A GEOSPATIAL INVESTIGATION OF ADAPTED RIDE-ON CAR USAGE

Disability and Rehabilitation: Assistive Technology

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Throughout the dissertation, the terminology modified ride-on car is used. However, the title of this chapter was not altered for consistency with the published manuscript.

Abstract

Modified ride-on cars (mROC) are an affordable, power mobility training tool for young children with disabilities. Previous qualitative research has identified environmental factors, such as weather and adequate drive space, as barriers to families' adoption of their mROC. However, we do not currently know the relationship between the built environment and mROC usage. In our current study, we quantified the driving patterns of 14 children (2.5 $\pm$ 1.45 years old, 8 male: 6 female) using ROCs outside and inside of their homes over the course of a year using a custom datalogger and geospatial data. To measure environmental accessibility, we used the *AccessScore* from Project Sidewalk, an open-source accessibility mapping initiative, and the Walk Score, a measure of neighborhood pedestrian-friendliness. The number of play sessions with the mROC ranged from 1 to 76; 4 participants used it less than 10 times and 4 participants used it more than 50 times. Our findings indicate that more play sessions took place indoors, within the participants' homes. However, when the mROC was used outside the home, children engaged in longer play sessions, actively drove for a larger portion of the session, and covered greater distances. Most children tended to drive their ROCs in close proximity to their homes, with an average maximum distance from home of 181 meters. Most notably, we found that children drove more in pedestrian-friendly neighborhoods and when in proximity to accessible paths. The accessibility of the built environment is paramount when providing any form of mobility device to a child. Providing an accessible place for a child to move, play, and explore is critical in helping a child and family adopt the mobility device into their daily life.

3.1 Introduction

A child engages with their surroundings by looking, touching, and exploring. The toddler years are typically known as a time of exploration, curiosity, and even troublemaking as children learn about themselves and their environments. Mobility is not only a key attribute of this exploration, it is also a fundamental aspect of identity development and a human right [11]. As such, On-Time mobility should be encouraged for every child in the manner that supports their exploration [3, 11, 118]. Powered mobility is a valuable option for children with disabilities, as it allows them to determine their own path, unlike a stroller or being carried by caregivers, which are typical forms of mobility for nonambulatory children. Research has shown that early power mobility device usage does not interfere with developmental skill acquisition and may actually benefit skill acquisition [11, 119, 120]. Modified ride-on cars (mROCs) are a popular power mobility device for children with disabilities, as they are affordable, aesthetically appealing, easy to transport, and can be modified for each child's needs [9, 88] (Figure 3.1).

The International Classification of Functioning, Disability, and Health (ICF) provides a useful framework to understand how children and families use powered mobility [121]. The ICF is comprised of five components: Body Functions and Structures, Activity, Participation, Environmental Factors, and Personal Factors. Previous research has focused on mROC usage within the Activity & Participation (e.g., stopping at a target) or Personal Factors domains (e.g., facial expressions and vocalizations). Few studies have examined Environmental Factors, such as the physical, social, and attitudinal environments in which the child lives and plays [12, 13].

A prior review of eleven mROC studies noted that the two largest barriers to device usage were limitations of the device (e.g., noisy and large size) and environmental barriers, such as the weather and inadequate drive space [13]. Qualitative studies have shown that families primarily use mROCs outdoors in their local neighborhood [94, 96]. Current mROC models have a large turn-radius, which can make driving in confined spaces difficult. As such, having access to a large space where the child can safely play and learn to use the device is paramount [12, 13, 93, 96, 122, 123]. Assessing the space where a child uses powered mobility is part of device provision, and can be a reason why a child may not receive a device [91, 124]. Quantifying how the environment interacts with, affords, and/or hinders mROC usage is critical to support future use and deployment. To date there has been no study that has examined how early powered mobility usage is impacted by the built environment [91]. Studies in adults using powered and manual wheelchairs have shown that community mobility is significantly impacted by access to transit, climate, and the physical environment [125, 126, 127].

The objective of this study was to quantify the driving patterns of children using mROCs in the community environment using geospatial data. The first aim of our research was to quantify how driving habits

differed when the child was driving outside versus inside of their home. Similar to prior research, we hypothesized that there would be more mROC usage outside of the home than inside. Our second aim was to evaluate where families used the mROC and investigate environmental factors that may affect usage. We hypothesized that families would use the mROC more if they lived in an area where there were places that they could drive to, such as a park. Understanding the relationship between the built environment and mROC usage is critical to guide families as they start their power mobility journey.

3.2 Methods

3.2.1 Participants

We recruited participants who met the following inclusion criteria: 1) were between 12 and 48 months old at study onset; 2) had a diagnosis of developmental delay or cerebral palsy with any level (I-V) of associated motor ability according to the Gross Motor Function Classification System (GMFCS) or communication ability according to the Communication Function Classification System (CFCS); 3) and lived in a household where English was spoken proficiently. To use a mROC safely, the child had to be able to maintain and tolerate a seated position with or without support while moving through space for 30 minutes.

3.2.2 Study Design

This study is a quantitative analysis that is part of a larger prospective, observational study. All families were given ROCs outfitted with custom dataloggers to use as they saw fit for a one-year period. This time period was selected to document the natural evolution of mROC use over time, and to our knowledge, is the longest deployment of ROCs in the field to date with use data being tracked consistently. Families were instructed on safe use of the mROC and encouraged to use them in both indoor and outdoor environments, however, specific dosage recommendations were not provided to observe family-selected mROC use patterns. All study procedures were approved by the Institutional Review Board at the University of Washington, and written informed consent obtained from the child's legal guardian.

3.2.3 Ride-On Car Specifications

The ROCs used in this research were modified by trained members of the research team using established protocols for mROC modification [9, 88]. The ROCs were rewired to be activated by a large, easy-to-push switch that is mounted on the steering wheel, and an emergency on/off switch on the rear of the vehicle.

Similar to prior research, custom seating supports (armrests and backrest) were added using materials such as PVC pipe (household water pipe), pool noodles, and kickboards (Figure 3.1). For additional safety and support, a seatbelt, or 5-point harness was added, as necessary.

3.2.4 Datalogger

ROCs were equipped with a custom datalogger behind the right front wheel [128]. The datalogger consisted of a voltage interrupt to record voltage changes from switch activation, a real-time clock to record date and time, a triaxial accelerometer, a magnetic contact (Hall effect) sensor to track wheel rotations, and a GPS mouse to track geospatial position (Figure 3.1). The horizontal positioning accuracy of the GPS mouse was 2.5 m. An Arduino Pro-Mini microprocessor was used to collect, sync, and save data to a secure digital (SD) card for the research team to access at mid-study and study completion. The data was sampled at 0.2 Hz, unless the switch or wheel rotation sensor was activated, at which the data was logged at 5 Hz. Families were able to keep the mROC after study completion, if they so chose, and all data collection equipment was removed from the mROC.

3.2.5 Data Analysis

The goal of this research was to evaluate mROC usage in the home and community environment, which relied on the data collected from the GPS, switch activation, and wheel rotation sensors from each mROC. We created custom MATLAB scripts for data analysis (MathWorks, Natick, Massachusetts). Play sessions were defined by a switch activation that occurred at least an hour after a previous switch activation (Table 3.1). To account for instances where the switch may have been jammed, we filtered the data to exclude any play sessions that were longer than an hour and the switch had been pressed for less than 10% or more than 90% of the play session duration.

GPS Data

GPS data were used to determine whether each play session was inside or outside of the child's home. GPS sensors can be impacted by the number of visible satellites and the presence of obstructions, such as buildings or trees [129, 130]. As such, GPS data was filtered to reduce the number of outliers in the GPS data, and improve data reliability. We removed erroneous points that were outside of two standard deviations (2 standard deviations = 95% confidence interval) of the mean geospatial location for each play session or had a difference of 0.001 degrees ($\sim$ 100 m) between consecutive datapoints as ROCs are unable to travel this distance in less than 5 seconds. We also filtered out geospatial coordinates that were infeasible, such as a

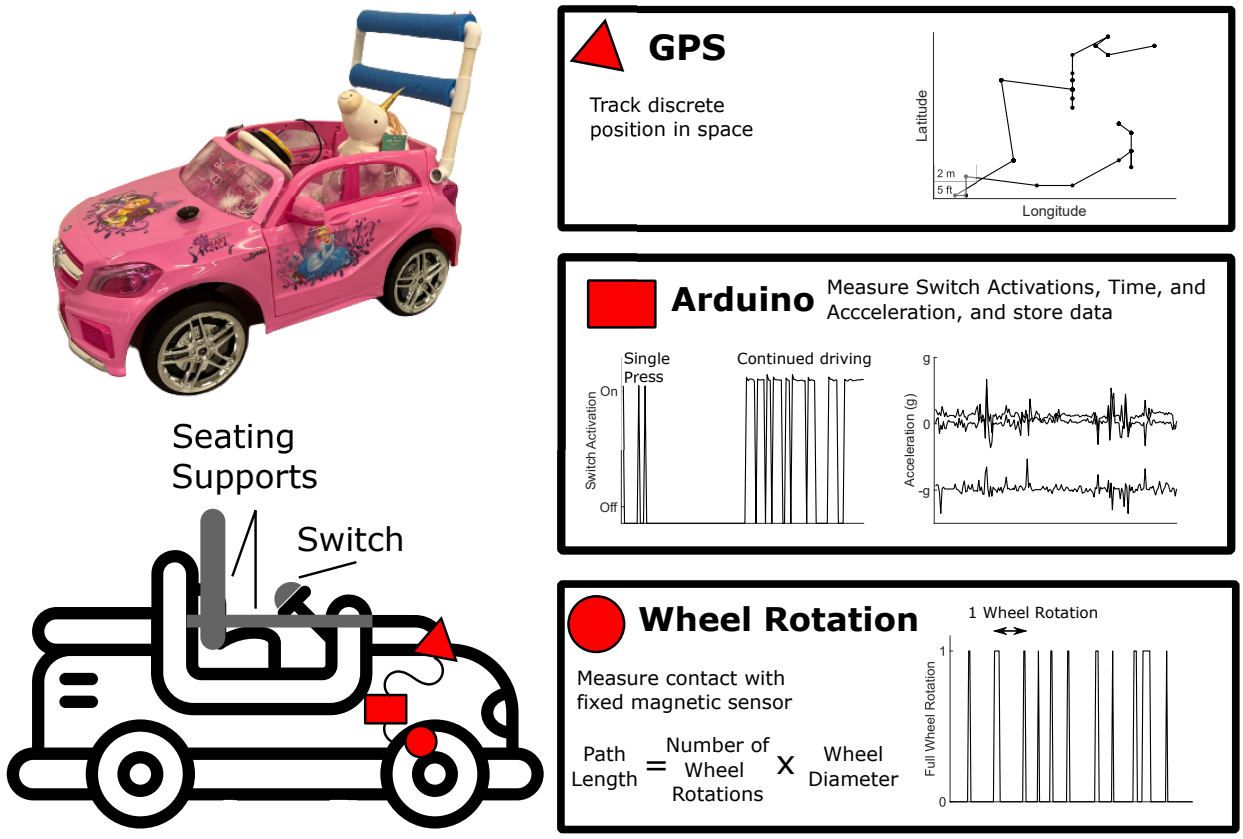

Figure 3.1: An adapted ride-on car (mROC) with the three different components of the datalogger. The GPS mouse is located on the hood, the main body of the datalogger is located behind the front wheel, and the magnetic contact sensor to measure wheel rotations is located on the right front wheel.

latitude greater than 90 degrees or latitude or longitude equal to zero. At the sampling rate utilized by the datalogger, the child would be unable to move more than a few meters between samples. We defined play sessions inside the home as the presence of no GPS data or more than 20% of the data points for a drive session were within the manually defined boundaries of the participant's home (Table 3.1).

Descriptive Data

To describe a child's usage of their mROC, we calculated the number of play sessions, play session duration, active drive time, and path length from the wheel rotation and GPS position for outdoor play sessions (Table 3.1).

Table 3.1: Terms and metrics used to describe modified ride-on car (mROC) usage.

Term	**Definition**
Play session	A period in which there was at least one switch activation and at least one hour had elapsed since the prior switch activation.
Switch activation	The voltage input from the switch exceeding a predefined high-voltage threshold.
Indoor play session	A play session in which no GPS data were present or no more than 20% of geospatial data points were located outside the boundaries of the participant's residence.
Outdoor play session	A play session in which 80% or more of geospatial data points were located outside the boundaries of the participant's residence.
Active drive time	The total time, in minutes, during which the child actively engaged the switch during a play session.
Play session duration	The total time from the first switch activation to the last switch activation within a single play session.
Geospatial path length	The distance a child travelled during a play session, calculated as the summed Euclidean distance between adjacent GPS points [131].
Path length	The distance a child travelled during a play session, calculated as the number of wheel rotations multiplied by the wheel circumference.
Drive radius	The maximum Euclidean distance from the participant's residence to the furthest geospatial coordinate recorded during a single play session.
AccessScore	A measure of sidewalk accessibility for a given street segment, derived from Project Sidewalk accessibility data.
Walk Score	A measure of pedestrian friendliness based on the availability of community amenities within walking or rolling distance.

3.2.6 Environmental Factors

To evaluate the effect of environmental factors on mROC usage, we combined mROC sensor data with sidewalk accessibility scores from Project Sidewalk and the proximity of community locations to their home.

Project Sidewalk is an open-source crowdsourcing platform that uses Google Street View to identify sidewalk accessibility issues, such as surface problems or missing curb ramps. We used the *AccessScore* from Project Sidewalk's API [132] which gives a score from 0=inaccessible to 1=accessible depending on the number of environmental barriers to mobility (e.g., lack of curb cuts, poles in the way) [133]. This data was only available for three participants (P5, P10, P17) who lived in Seattle-proper, as the accessibility data is manually gathered by volunteers through Project Sidewalk's platform [132]. We also evaluated how pedestrian-friendly the environment near each participant's home would be for mROC usage with the Walk Score (walkscore.com) [127, 134]. The Walk Score is scaled from 0 to 100 with 100 being the most walkable; scores less than 50 means that most or all errands require a car. For example, a score of 91 means that an individual can walk in their neighborhood to accomplish all daily errands, such as grocery shopping, picking up dry cleaning, or stopping at the local bakery; and is representative of living in a downtown area or main street. We selected this as a metric because it helps to indicate the quantity of amenities nearby that the family could walk to. Finally, we looked at the proximity of family-friendly third spaces — tertiary location that an individual would frequently visit that is not home or work. We identified parks and elementary schools as family-friendly third spaces as both locations may have an area for a family with young children to play and socialize, and as such may increase the frequency at which a child would use a mROC. Logan et al. [94] indicated that driving around the neighborhood led to more socialization both for the child and the caregivers, as their child was able to engage with children in the neighborhood. We manually looked up the nearest park and elementary school to each participant's home using Google Maps. Using the geospatial location of the third spaces, we observed participant's drive maps to see if they visited these spaces.

3.2.7 Statistics

We used Wilcoxon rank sum tests with an alpha of 0.05 to compare differences in the number of sessions, session duration, active driving time, and distance traveled between the indoor and outdoor play sessions. This test was selected because our data did not follow a normal distribution, and we were conducting a comparison between two independent groups. We also calculated pooled mean and pooled standard deviation (Table 3.3) for a weighted picture of the entire group based on the number of play sessions for each participant. We conducted a linear regression between path length and Walk score to quantify the relationship between community amenities and distance travelled.

3.3 Results

Nineteen participants and their families enrolled in the study. Fifteen participants completed all study procedures, with one data logger failure, resulting in fourteen complete data sets (Table 3.2) and included 8 males and 6 females (aged 2.5±1.45 years [Ave ± SD] at the start of the intervention). From the original 19 participants, two participants withdrew from the study due to moving out of state and intensive therapy schedules, and two were lost to follow-up. Families were located throughout Western Washington, within a 2-hr drive radius of Seattle. Three of the participants' primary residence were apartments during the course of the study, and three participants moved between enrollment and study completion. For these participants, we used the geospatial location of the primary residence where they were for the majority of the study for all calculations based on the participants' travel from home.

Table 3.2: Participant demographics.

Participant	**Age (years)**	**Gender**	**GMFCS**[a]
1	4	M	III
2	2	F	IV
3	3	F	III
5	4	M	III
6	5	M	II
7	3	M	IV
8	3	F	IV
9	4	F	III
10	1	F	III
13	3	F	II
15	1	M	II
17	1	M	II
18	2	M	IV
19	1	M	III
N = 14	**2.5 ± 1.45**	**8 M : 6 F**	**II: 4, III: 6, IV: 4**

[a] GMFCS = Gross Motor Function Classification System level.

3.3.1 Inside vs. Outside Driving

We quantified the driving patterns of families using ROCs in their home and community environments for a year. We found that children drove for a longer period of time and a further distance when the child was driving outside versus inside of their home (Table 3.3). On average, families used the cars for a total of 20 (range: 0 - 57) play sessions inside and 15 (range: 0-52) outside of the home (Figure 3.2A) over the course of a year. However, the children played with the ROCs for a longer period of time during outside play sessions, with an average play session duration of 10.4 min (Figure 3.2B) and active drive time of 6.9

min (Figure 3.2C) outside, compared to 7.5 min play session duration and 2.9 min of drive time inside ($p \ll 0.01$). Children also drove a further distance when play sessions were outside (Figure 3.2D), with an average path length of 214 m, compared to 53 m inside ($p \ll 0.01$).

Table 3.3: Play session counts, active drive time, play session duration, and path length for each child.

Participant	N	N_o	N_i	t_o	t_i	T_o	T_i	L_o	L_i
1	15	1	14	0.07	3.23	0.10	11.69	0.00	35.56
2	76	19	57	0.95	0.89	3.57	4.14	9.57	9.61
3	70	34	36	3.10	2.32	7.63	8.24	27.75	17.62
5	31	22	9	13.66	9.41	34.96	12.95	269.06	288.26
6	23	4	19	1.18	0.32	1.24	2.61	1.53	3.18
7	7	0	7	0	1.72	0	8.65	0	6.88
8	20	6	14	0.54	0.91	1.47	3.82	8.59	8.09
9	14	6	8	14.30	4.31	18.64	12.21	152.24	94.38
10	65	52	13	15.41	6.47	19.71	13.11	311.05	85.25
13	7	2	5	1.28	2.55	2.08	8.50	1.70	11.67
15	56	15	41	3.76	1.63	4.82	1.90	85.15	31.15
17	5	5	0	19.46	0	22.36	0	1230.92	0
18	1	1	0	5.47	0	7.25	0	293.01	0
19	38	26	12	10.14	1.37	11.16	2.27	393.06	38.38
Ave	31	15	20	6.87	2.93	10.38	7.51	214.12	52.50
SD				6.51	3.56	22.16	8.31	252.14	91.98

Abbreviations. N = total play sessions; N_o/N_i = sessions outside/inside; t_o/t_i = mean active drive time (min) outside/inside; T_o/T_i = mean play session duration (min) outside/inside; L_o/L_i = mean path length (m) outside/inside.
Pooled averages (Ave) and standard deviations (SD) are shown.

Looking at the driving patterns of individual children inside versus outside of the home illustrates different usage patterns. For example, P15 had similar driving patterns whether driving inside and outside, while P10 actively drove for more of the play sessions outside than inside (Figure 3.3). P5 also had similar driving patterns when they were outside and inside, but actively drove for a higher percentage of the play session inside. In comparison, P19 actively drove for most of their sessions outside of their home, but actively drove for less of the play sessions inside their home.

3.3.2 Distance from Home

The majority of participants drove their cars inside and near their homes (Figure 3.4). The average maximum distance travelled from home for outside play sessions was 181.4 m (range: 2.38 m - 253.98 km, Figure 3.4). However, some families took their child's mROC with them while traveling. Most notably, one family took the mROC with them on a ferry and another family took their mROC camping with them. The furthest distance that one family travelled with their mROC was 253.98 km from their home.

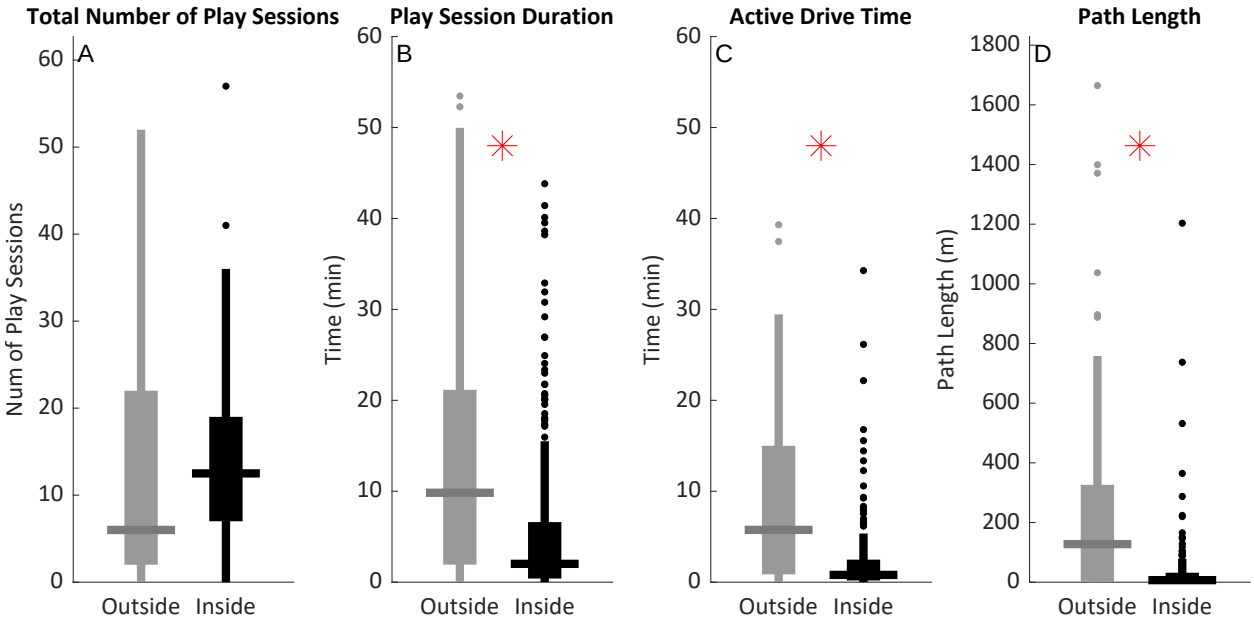

Figure 3.2: The (a) total number of play sessions, (b) total play session duration, (c) active drive time for each play session, and (d) total length driven for each play session when the participants were driving outside and inside their homes. The children actively drove for a longer time and distance, and the play sessions lasted longer when they occurred outside than inside. However, there were a higher number of play sessions inside than outside. Significance is shown by a red asterisk for play session duration, active drive time, and path length.

As illustrated in Figure 3.4, some families had a large variation in the distance that they drove each day, while others were fairly consistent in the distance they drove. For example, P9 and P10 tended to drive a similar distance every day (Figure 3.5), which indicates that they drove a similar path. However, other participants, such as P17 and P19, drove a varied distance, and hence must have altered their drive path between play sessions. Every child and family used the mROC in a different way, and this is reflected in their drive distances. P3 shows us that a child may consistently drive a short distance during each play session, but then go on a few longer adventures to explore their neighborhood.

3.3.3 Measures of Neighborhood Accessibility

mROC usage was decreased in inaccessible outdoor environments. Participants who lived in areas with higher Walk Scores traveled further during outside play sessions ($R^2 = 0.35$, Figure 3.6). The number of play sessions and the average duration of play sessions increased as Walk Score increased. The average distance traveled outside increased as the Walk Score increased, which may indicate that there were more areas to stroll and roll on the sidewalk. However, all of our families were able to identify a region in which they could use their mROC.

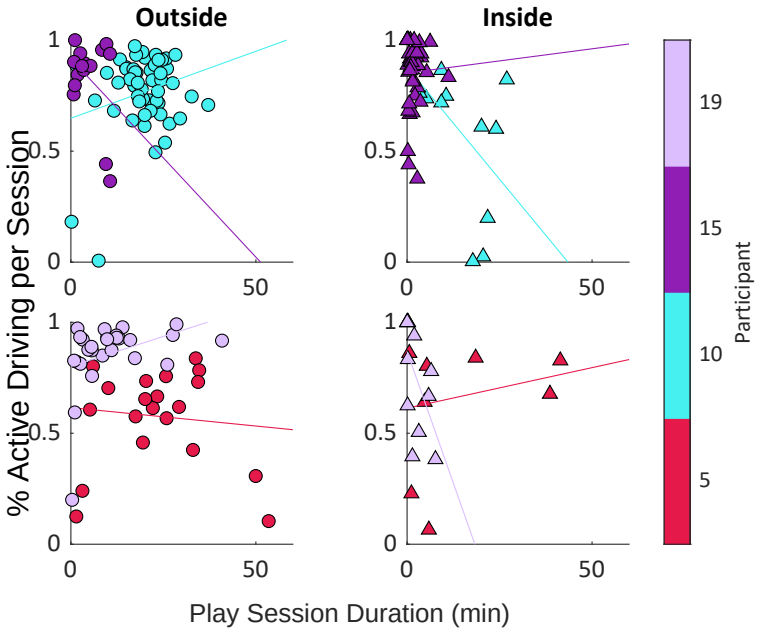

Figure 3.3: The ratio of active total drive time for each session to play session duration as a function of the total play session duration for four participants (P5, P10, P15, and P19). Each participant is represented as a different color. Play sessions outside are demarcated as a circle and inside as a triangle. Each child used their cars for a varied amount of time, with some actively driving during the entire play session and some for only a short time. For plots for additional participants see Supplementary Material.

The drive paths of four participants who lived in regions with Walk Scores lower than 50 show that each family used their mROC differently (Figure 3.7). P2 only used their mROC to drive in their driveway and backyard. P9 consistently drove up and down their street and in their driveway. P3 primarily drove just outside of their home, but on a few occasions drove their mROC to a nearby park. P19 varied their drive route each time, driving in the court by their home, and venturing to neighboring streets to explore their neighborhood.

Mapping initiatives, like Project Sidewalk, can provide further insight into environmental barriers and usage patterns [132, 133]. For the three participants (P5, P10, and P17) who lived in regions with sufficient Project Sidewalk accessibility data to calculate AccessScores, we found that participants primarily travelled on accessible paths (Figure 3.8). The sidewalks bordering P5's home were rated as highly accessible, however, they primarily drove their mROC in the immediate vicinity of their home. P10 lived close to an elementary school with a playground. They drove on accessible paths to and around the elementary school over 50 times, and only changed their route once to travel on a sidewalk that was less accessible. Three out of four of the streets surrounding P17's home were classified as inaccessible, and as such, we observed P17 primarily driving in the alley behind their home.

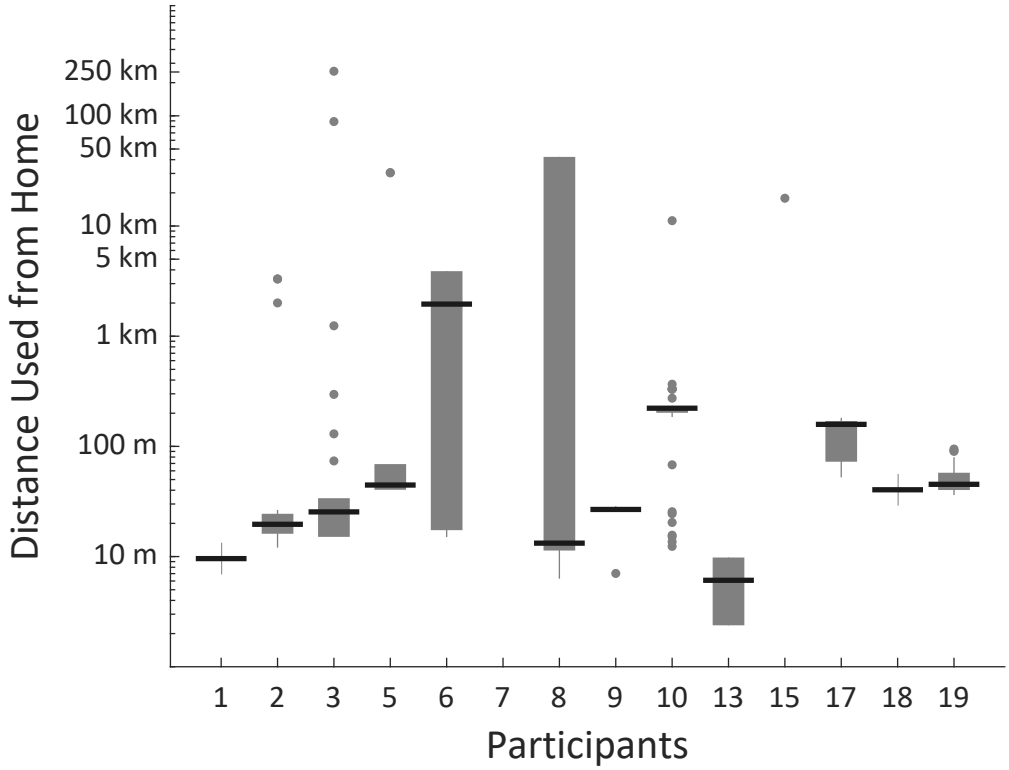

Figure 3.4: Each boxplot shows the drive radius, or the furthest distance a participant actively drove during a play session from the participant's home, for each participant. Most of the participants drove in the very near vicinity of their home (within a few hundred meters from home).

3.4 Discussion

In this study, we analyzed mROC usage patterns of 14 children and their families in their homes and local neighborhoods over a year-long deployment. Using a custom datalogger, we quantitatively measured switch activation, device usage duration, geospatial position, wheel rotations, and device acceleration. There was a wide breadth in the frequency to which each family used the device, but most families used the device within a few hundred meters of their home, and we observed that neighborhood features, such as walkability and accessibility of sidewalks, influenced usage and chosen routes.

The ROCs were used more outside the home than inside. Pritchard et al. 2019 showed similar results with 3 out of 4 participants using the mROC outside more than 70% of the time (100%, 92%, 29%, 73%) [96]. However, we observed that our participants spent an increased amount of time driving inside than in other studies [94, 96]. This could be a result of the families using the device over the course of a year in Western Washington, a region known for higher rainfall [96], or our use of GPS to define indoor driving, which may have over-classified indoor play sessions near the home.

One of the most significant observations from this study was that families that used the mROC the

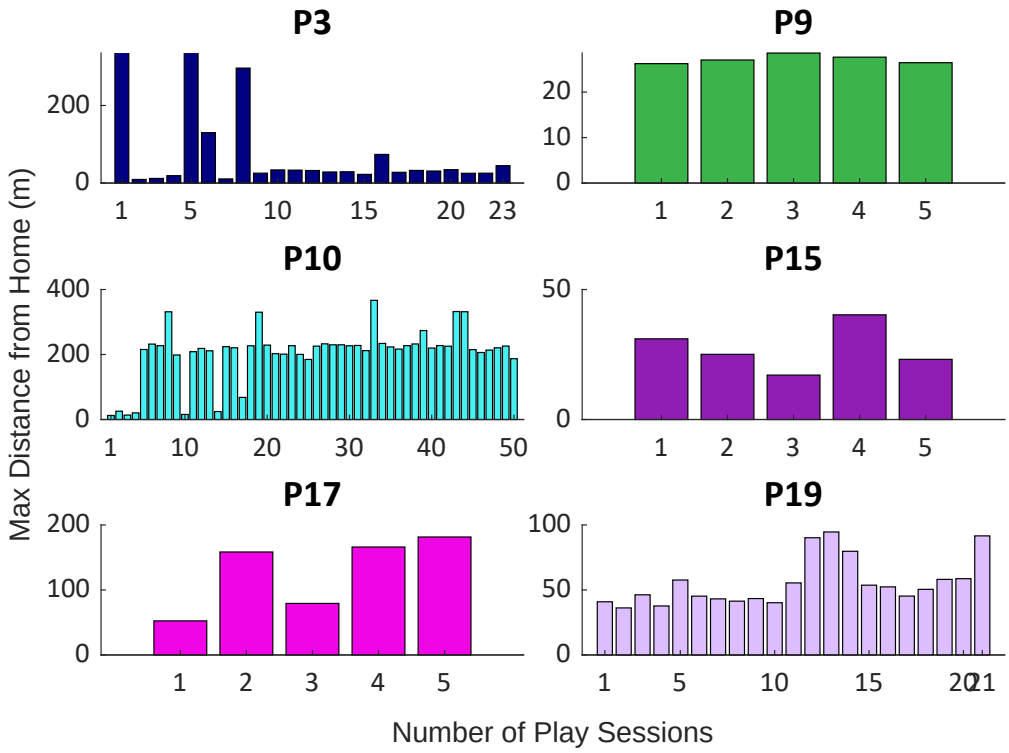

Figure 3.5: The maximum distance traveled from home for each play session for six participants. Some children consistently drove the same path, while others drove a slightly different path each time. For plots for additional participants see Supplementary Material.

most tended to drive a similar route each play session (P03, P10, P17, P19). Families seemed to identify an accessible area and/or path and stick with it. It should also be noted that the majority of families lived in areas with a lower Walk Score, which means that they would need to drive to accomplish most tasks of daily living (e.g., grocery shopping, doctor's visits). Hence, families in areas with lower Walk Scores may have had fewer community amenities within walking or rolling distance that they could easily travel to with their mROC, which may have impacted motivation to use the mROC. Future work could examine the impacts on mROC usage when families are provided with custom driving routes or other environmental supports to help families identify and find accessible routes in their neighborhood. These custom driving routes could also include paths to third spaces, such as parks, within walking and rolling distance. Previous studies have also noted the challenge of finding large enough spaces for a child to drive an mROC and have suggested that researchers and clinicians assist in identifying places, such as indoor community play spaces, to increase mROC usage [12, 13, 120, 135].

The accessibility of the physical environment in which the children are living and using their mROC is a major factor in the provision of power mobility devices. If a child does not have a suitable place to maneuver a device, they may not be provided one [122, 124]. Three of the participants in our study lived in

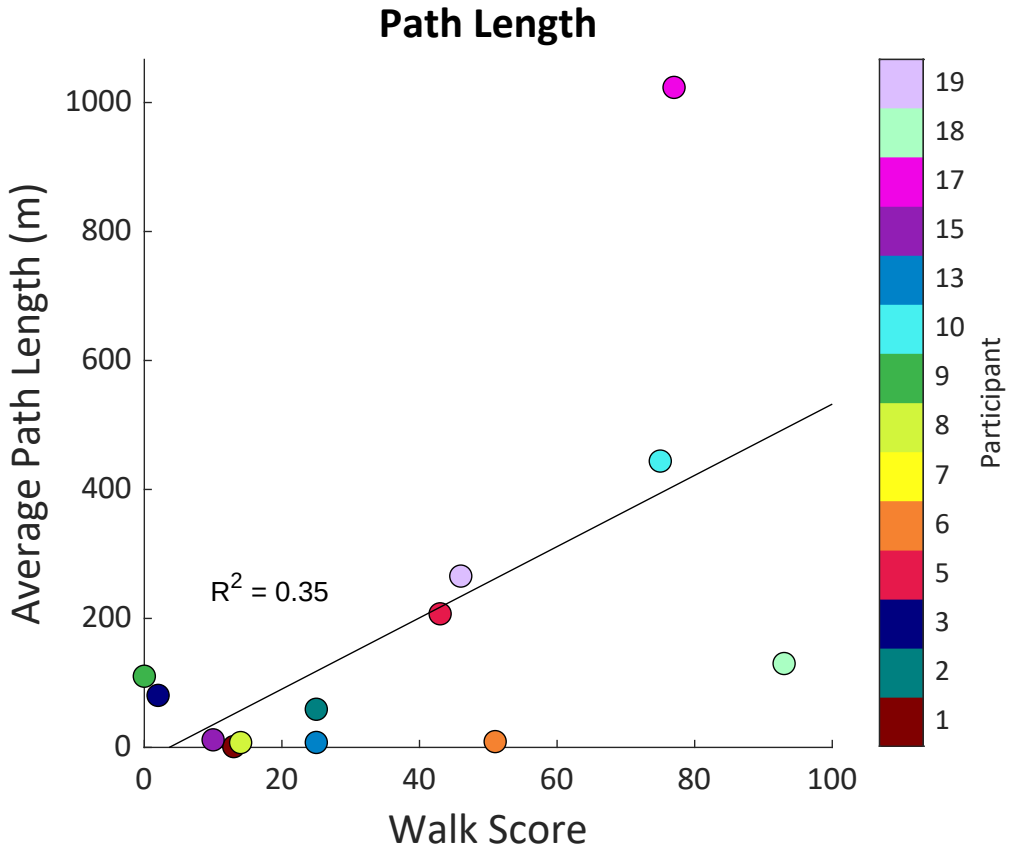

Figure 3.6: The average path length increased when the children was using their mROC outside of the home as the walkability — a measure of pedestrian-friendliness of a neighborhood — increased.

apartments, which can have less driving space. If an apartment or home does not have elevators or stairs to get to the sidewalk, these environmental barriers can further hinder outside mROC usage. For three of our participants, we were able to identify the accessibility of the streets in their immediate neighborhood. The resulting drive maps starkly parallel the accessibility of the space, with the participants driving the routes that were most accessible and avoiding inaccessible regions. P10 had more outdoor play sessions than any other child, which may be in part due to the identification of an accessible path in their neighborhood to a third space of interest. However, P10's drive map (Figure 3.8) indicated they drove on an inaccessible street bordering the elementary school once and then never returned to that path for future sessions, which may be due to difficulties encountered driving the mROC. Similarly, three out of four of the streets surrounding P17's home are classified as inaccessible, and as such, we observed P17 primarily driving in the alley behind their home. P5 also lived near a large park, but we did not observe them venturing there, possibly due to the high grade of the route, which is un-navigable for an mROC [96].

The children in our study mainly used the mROC within the vicinity of their home, with only one family taking it with them when they were traveling. Although ROCs are relatively lightweight for a power mobility

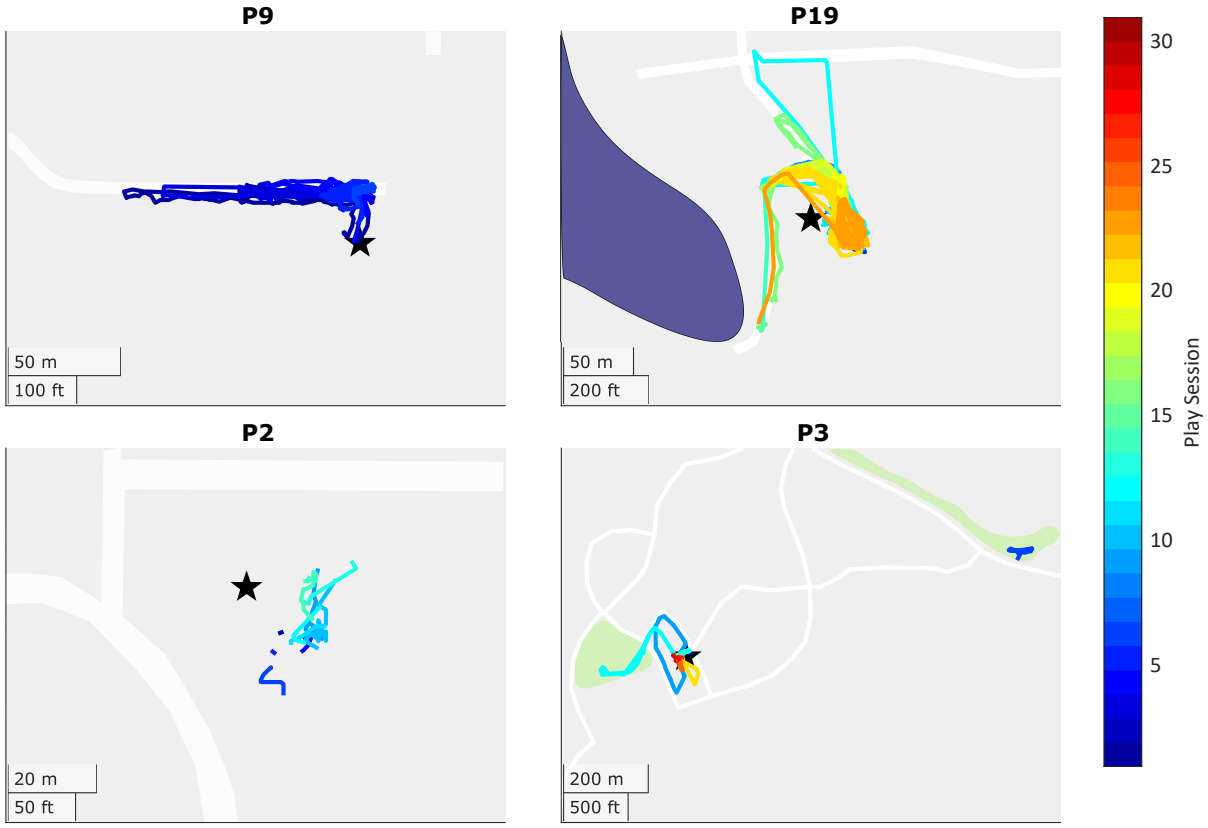

Figure 3.7: The drive paths for each participant for each play session. The star represents the participant's home. Each child had a unique drive path, with some driving just outside of their homes, while others went up and down the street or around the block.

device, they are still bulky, heavy, and cumbersome to transfer [13]. There is a low likelihood that families in our study have a wheelchair-accessible van (yet), which could make it easier to transport the mROC [136, 137].

A common limitation in mROC studies is the small sample size, with many of the studies being case studies or case series. This study is one of the largest and longest mROC studies (N=14 over one year), however, the relatively small number of participants means we are unable to generalize or evaluate the impact of specific factors like age, diagnosis, or home environment [91]. Another limitation of this study is that the Walk Score does not include metrics, such as sidewalk quality or dropped curbs, in its calculation, and hence, may not fully show pedestrian accessibility of a neighborhood [138]. The AccessScore metric was only available for three participants, due to the limited but growing deployment of Project Sidewalk. Project Sidewalk is currently deployed in ten cities, including six in the US, three in Mexico, and one in the Netherlands. Ideally, we would have accessibility information for each participant. To learn more about Project Sidewalk and label

Figure 3.8: The accessibility scores for the sidewalks near each participant's (P5, P10, P17) home on the left and the drive path of the participant on the right. Participants generally avoided driving on streets that were not accessible.

obstacles to exploration visit sidewalk-sea.cs.washington.edu. Future research that uses Project Sidewalk, or other open-source accessible mapping initiatives is important to understand and dismantle environmental barriers that may hinder participation and mobility options. Recently, Project Sidewalk has examined using machine learning to identify environmental barriers from Google Street View, which may make this data more widely available [139, 140]. Future collaboration with the Project Sidewalk team could also help us to get data specifically for the regions where the families in our studies live. Additionally, the *AccessScore* may not be fully representative of the environmental conditions our participants faced as Project Sidewalk data is collected using Google Street View, which is only updated every 18 months. The *AccessScore* also does not account for the grade of a slope, which is a factor that likely impacts a child's ability to drive their mROC. Another limitation of this study is that we cannot verify whether the child was driving or the caregiver was driving (activation and steering) while the child was in the mROC. Previous studies have led us to believe that most likely a child would have activated the switch and held it while their caregivers intervened to steer

the mROC. We observed a wide range of usage patterns, with many participants rarely using the car and others with 20+ play sessions (see Supplementary Material for individual data). This may be in part due to us not providing recommendations for frequency and duration of use. However, it does reflect the realities of usage patterns when technology is deployed with families. Future studies may recommend mROC dosage (e.g. 3 times a week for 15 minutes) or periodic reminders to support the families in fitting technology into their community and lifestyle. This study focused on environmental factors, but there are likely many other factors that contribute to a young child's usage of a powered mobility device. Other factors, such as age, mobility level, family lifestyle, and resources available likely impact frequency of use [13]. Seasonal changes and weather patterns also likely impact a child's outdoor usage of their powered mobility device [13, 125]. These represent important areas for future investigation.

We conducted a year-long geospatial observation study on fourteen families utilizing an adapted mROC. Each family and child utilized their mROC, albeit with varying frequencies and usage patterns. Our findings revealed that the presence of a driving route significantly increased the utilization of ROCs. Therefore, future studies should investigate how the provision of accessible driving routes impacts mROC usage. This research sheds light on the diverse usage of ROCs by families across different environments and over time. We aspire for this work to facilitate policy advancements and advocacy efforts aimed at enhancing accessibility to mobility technologies for children with disabilities during critical developmental stages [3, 91]. The accessibility of the surrounding neighborhood plays a pivotal role in promoting mobility for both children and their families, regardless of the mobility device being utilized. Future research throughout the lifespan should examine both the destinations individuals frequent and those they do not, as this will help identify barriers to freedom in the built environment.

3.5 Acknowledgments

We would like to thank the children and families that participated in this study for sharing their time and lived expertise with our research team. We would also like to thank Michelle Chuang, Joseph St. George, and Winston Lowe for their assistance in creating and integrating the custom data loggers used in this study.

Chapter 4

COMPARISON OF THREE TRACKING METHODS TO ASSESS USAGE OF TWO PEDIATRIC POWERED MOBILITY DEVICES FOR YOUNG CHILDREN WITH CEREBRAL PALSY

Assistive Technology

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Abstract

Powered mobility devices are underutilized for promoting self-initiated mobility in young children with cerebral palsy due to prioritization of walking, caregiver effort, device characteristics, and environmental factors. Understanding device usage patterns is important to assess the impact of powered mobility interventions on child outcomes. As part of clinical trial (NCT04684576), three objective tracking methods including integrated loggers, Global Positioning System trackers (GPST), and caregiver reported activity logs (CRAL) were compared to provide insights into device usage patterns. Metrics included play session frequency, session duration, total usage minutes, and unique usage days for two powered mobility devices: Modified Ride-on Cars (mROC) and the Permobil Explorer Mini (EM). Twelve children with cerebral palsy used each device for eight consecutive weeks in home and community settings (16 weeks total), with device order randomized. Results showed no significant differences among tracking methods for the mROC. For the EM, only session duration differed between GPST and CRAL. Correlation analysis revealed variable relationships amongst tracking methods for both devices. The EM was used more frequently than the mROC, with significantly greater total usage minutes and session duration via CRAL, not GPST. The findings highlight the need for reliable tracking technologies that can be used across powered mobility devices.

4.1 Introduction

Powered mobility enhances self-initiated mobility and supports developmental outcomes in young children with cerebral palsy (CP) [93, 104]. Research describes benefits in physical, cognitive, social, and emotional development, including increased exploration, engagement, and participation [85, 98, 104, 120, 141, 142, 143]. Despite these positive outcomes, powered mobility usage for children under age three remains limited due to numerous barriers. Barriers include device characteristics, accessibility challenges, environmental factors, caregiver effort, prioritization of walking over powered mobility, and a lack of standardized clinician training [3, 11, 13, 16, 92, 135, 144, 145]. In addition, the lack of reliable methods to track device usage makes it difficult to understand and optimize how powered mobility devices are utilized across real-world settings.

Reliable tracking methods are critical for assessing how powered mobility devices are used. Such methods provide insights into device utilization patterns across various settings and help ensure adherence to study protocols. Current tracking methods for pediatric powered mobility devices include integrated loggers, Global Positioning System trackers (GPST), and caregiver-reported activities logs (CRAL) [19, 146, 147, 148]. However, these methods remain underdeveloped, particularly for devices used by young children with disabilities, with no consensus on the most effective approach.

In adult populations, advancements in tracking technologies, such as apps (e.g., SmartDrive PushTracker) and wearables (e.g., Apple Watch), have demonstrated potential to monitor manual wheelchair usage [149, 150]. Additionally, complex rehabilitation technologies such as powered wheelchairs for older children or adults often include built-in digital sensors that automatically and continuously collect usage data, providing valuable insights into real-world mobility patterns [151]. Emerging technologies like the pluggable joystick control sensing device [152] and the LUCI smart wheelchair system, which includes time-in-seat tracking via the MyLUCI app, [153] further demonstrate the potential of advanced tracking solutions. However, these technologies are not yet compatible with devices designed for very young children, highlighting the need for alternative tracking methods to support research and clinical practice in pediatric populations. Two commonly used powered mobility devices for young children with disabilities are modified ride-on cars (mROC) and the Permobil Explorer Mini (EM). mROCs are adapted toy cars tailored to children's individual needs, offering a cost-effective ($250-300 US) and temporary solution to promote mobility, participation, and socialization through environmental exploration and play [9, 89, 94, 98]. The EM, introduced in March 2020, is the first Food and Drug Administration cleared powered mobility device specifically designed for children aged 12-36 months with disabilities and priced at less than $3000 US. Emerging research on the EM highlights its potential benefits for mobility and engagement, [103] with a recent clinical trial showing improvements in development and participation for children with CP [104, 106]. Tracking usage for these devices remains a challenge, with existing methods often limited by feasibility, accuracy, or compatibility.

Although CRAL remains the most widely used tracking method for powered mobility in pediatric populations [91, 93, 94, 95], its reliance on caregiver documentation often results in frequent misreporting and low completion rates [154]. Integrated loggers offer more objective measures but face challenges with device compatibility and data collection failures [145, 154]. One study found no significant differences between an integrated logger (the Feather Interface Tracking (FIT) System) and CRAL over three months, though families often misreported usage and six out of 14 families did not complete the CRAL [145]. Another study used the Arduino Pro-Mini microprocessor as an integrated logger and found consistent trends with CRAL over 12 months, despite one datalogger failure [154]. Similarly, GPST provide valuable insights into movement across settings but shows limited accuracy indoors and challenges with environmental obstructions, such as tall buildings [19, 155]. One study examined general movement patterns and found that CRAL misclassified locations 48% of the time compared to data collected using child-worn GPST [155]. In contrast, another study used GPST to monitor mROC usage over a year and found more frequent indoor use but longer outdoor play sessions near the families' homes [19].

Livingstone and Field [122] compared the use of multiple powered mobility devices within a single 60-90 min play session involving mROC and three other devices [122, 135]. Children's performance varied depending on the device and access method, with caregiver preferences influenced by device characteristics and the level of postural support provided [122, 135]. These findings highlight how selecting the most appropriate device can improve mobility for each child. However, while device selection is important, it is also important to reliably track usage across different devices. Currently, there is no clear consensus on the most effective tracking method for assessing usage, which highlights challenges to fully understanding and optimizing powered mobility use. Establishing consensus on effective tracking methods is needed to develop evidence-based guidelines for device selection, training, and implementation in clinical settings. This study aims to address this gap by comparing three tracking methods: integrated logger, GPST, and CRAL across two pediatric powered mobility devices, the mROC and EM, to inform best practices for assessing powered mobility usage in young children with disabilities.

4.2 Objectives

The objectives of this chapter include 1) compare three different tracking methods: integrated logger, GPST, and CRAL, for two powered mobility devices (EM and mROC), 2) understand the relationships among these three tracking methods for both devices, and 3) compare usage differences between the EM and mROC using GPST and CRAL (since the integrated logger could only be installed in the mROC, it could not be compared between devices).

4.3 Methods

4.3.1 Study Design

This study was part of a larger multi-site (Oregon, Washington, Michigan), mixed-methods, randomized AB crossover clinical trial [156]. Children (N=24) used a mROC or an EM for eight consecutive weeks each in home and community settings (16 weeks total) in a randomized order without a washout period [156]. Researchers conducted in-person visits at baseline (T0), device crossover (T1), and study completion (T2) to measure outcomes and provided two virtual check-ins for support and problem-solving during each device trial [156]. Families were encouraged to integrate the devices into their daily routine without providing specific usage recommendations, to understand real-world usage [156]. All study procedures were approved by the Univerity of Washington Institutional Review Board. This study was registered at clinicaltrials.gov, NCT04684576. Informed consent was provided by all adult participants, who also provided permission for their children.

4.3.2 Participants

Participants were recruited through flyers, social media, word of mouth, and emails to local community therapists. Inclusion criteria for children were: 1) children between 12-32 months of age, 2) diagnosis of CP, Gross Motor Function Classification System (GMFCS) Levels II-V, or high probability of CP based on birth history and current developmental status, and 3) ability to sit with or without support. Caregivers had to be at least 18 years of age, the child's legal guardian, and proficient in English.

4.3.3 Powered Mobility Devices

For the mROC, we selected the Fisher Price Lil' Lightning McQueen ROC, which is suited for children 12-36 months old, with a child's maximum weight of 18.1 kg. This model has a 6-volt battery, 0.89 m/s maximum speed, and multiple speed options. Modifications included a larger, mechanical switch on the steering wheel, a potentiometer for speed options, and standard postural supports (Figure 4.1). The Permobil EM was designed for children 12-36 months old, with a child's maximum weight of 15.8 kg. This device has a 12-volt battery, 0.67 m/s maximum speed, and five speed options. It can be used in sit or supported stand mode and features a midline joystick with a 360-degree turning radius for steering (Figure 4.1).

Figure 4.1: Two powered mobility devices were compared in this study: the Permobil Explorer Mini (EM) and modified ride-on cars (mROC).

4.3.4 Tracking Methods

Powered mobility device usage was tracked using three methods (Figure 2): integrated loggers (mROC only), GPST (both mROC and EM), and CRAL (both mROC and EM).

mROC integrated logger

The Feather Interface Tracking (FIT) System is comprised of an Adafruit Feather M0 Adalogger, Precision Real Time Clock FeatherWing, and Quicrun 60A 2S-3S Waterproof Brushed Electronic Speed Controller (Figure 4.2). The tracker systems were hard-wired and activated automatically when the mROC was on. The system recorded the date, timestamp, and duration of switch activation (milliseconds) each time the switch was pressed and released. Data were stored on a micro-SD card and downloaded after 8 weeks. Metrics included number of sessions, average session duration, total usage in minutes, and unique days (4.1).

GPST

This battery-powered, commercially available tracker (iTrail H600 GPST, KJB Security) recorded geospatial location, direction, and time (Figure 4.2). This tracker has motion activated operation, is accurate within three meters, and startup Satellite Acquisition time of <35 sec. GPST sampling frequency varied depending on the speed and distance the device moved. The GPST was attached via Velcro to the back of either device, and caregivers turned the tracker on and off. Trackers remained with each participant throughout the study and were collected at the final visit. Data extraction was performed at device crossover. Metrics included number of sessions, average session duration, total usage in minutes, unique days, total distance, and unique locations (4.1).

Table 4.1: Terms and metrics used to describe powered mobility device usage.

Term	Definition	Int Log	GPST	CRAL
Play session	For analysis purposes, a play session was defined as at least two minutes of device use, identified either computationally (via switch activation or geospatial position) or through caregiver report. To account for intermittent movement, sessions are separated by at least 10 minutes without device activity.	X	X	X
Number of Sessions	The total count of play sessions completed by a child.	X	X	X
Unique Days	The count of individual calendar days on which a child completes at least one play session.	X	X	X
Session Duration	The time from the start of the first device use to the end of the last device use within a single play session, marked by at least 10 minutes of inactivity.	X	X	X
Total Usage in Minutes	The aggregate duration of all play sessions completed by a child for each device, measured in minutes.	X	X	X
Total Distance	The cumulative geospatial distance travelled by a child across all play sessions.		X	
Unique Locations	The number of distinct geographical positions where a child completes at least one play session. Caregivers recorded the locations where their child used the device, and the unique locations (GPST) were determined computationally using the Density-based Spatial Clustering of Applications with Noise (DBSCAN) algorithm, with a minimum number of samples per cluster as one and a maximum distance between two samples for them to be considered in the space cluster as 3 km.		X	
Fun Index	A caregiver-rated Likert scale ranging from one to 10 (with 10 indicating the highest level of perceived fun) of the child's enjoyment while using the device.			X

Abbreviations. MROC = modified ride-on car; GPST = geospatial tracker; CRAL = caregiver-reported activity log; Int Log = MROC integrated logger.

CRAL

Caregivers also tracked how often their child used the mROC and EM device on a paper log (Figure 4.2). Caregivers recorded usage data, including start/stop times, total minutes engaged, location, activities, and their child's enjoyment during device use, measured using the Fun Index [94] (a subjective caregiver assessment of the child's enjoyment, rated on a scale from 1-10). The logs were collected at device crossover and at the final visit. Metrics were generated from these caregiver logs and included the number of sessions, average session duration, total usage in minutes, unique days, and unique locations, in addition to the Fun Index score (4.1).

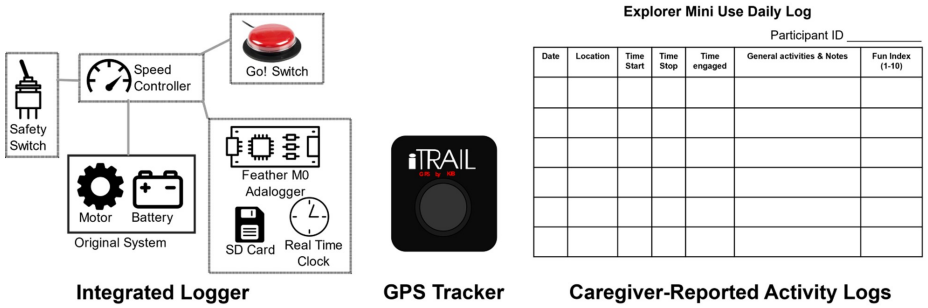

Figure 4.2: Child's usage of powered mobility devices was tracked using a) an integrated logger (mROC only), b) commercially available GPS Tracker (GPST, both devices), and c) caregiver-reported activity logs (CRAL, both devices).

4.4 Data Analysis

Analyses were conducted using participant-level data, with each observation representing usage metrics (e.g., number of sessions, unique days, total usage in minutes, and average sessions duration) collected from three tracking methods: mROC integrated logger, GPST, and CRAL for individual participants (4.2).

Descriptive statistics were calculated using custom Python scripts. Due to the presence of outliers, median and interquartile range (IQR) were reported to provide robust summaries of the data. For GPST, additional analyses were required to account for erroneous points caused by signal scatter or signal loss. Geographic coordinate outliers were identified and removed on a session-by-session basis using a z-score threshold of three standard deviations [157].Analysis was further restricted to play sessions where the device was moving, identified by an approximate velocity (total session distance/ total session duration) below 2 m/s (4.47 mph) and a geospatial standard deviation less than 0.001° (100 m). These thresholds were selected to align with device speeds and the expected movement range of a play session.

Table 4.2: Descriptive statistics for each tracking method per powered mobility device.

Outcome metric	Tracking method	Powered mobility devices						p^{c}
		EM			MROC			
		Median	IQR	p^{a}	Median	IQR	p^{b}	
Average Fun Index (1–10)	CRAL	5.44	2.02		5.38	3.60		0.583
Average session duration (min)	CRAL	23.4	14.8	0.002*	13.1	6.11	0.385	0.046*
	GPST	8.66	3.95		8.94	4.47		0.583
	Int Log				9.69	5.10		
N sessions	CRAL	24	12	0.524	16	17.3	0.371	0.099
	GPST	14	29.5		8	11.3		0.078
	Int Log				9.5	16.5		
Total distance (m)	GPST	9927.5	22 991.1		3680.3	6398.5		0.215
Total usage (min)	CRAL	456.5	686.3	0.707	107.5	435	0.128	0.023*
	GPST	367.5	1196.1		228.5	386.6		0.215
	Int Log				55.9	219.6		
Unique days	CRAL	23	10.75	0.148	16	15.25	0.149	0.112
	GPST	10	17.75		7	8.75		0.064
	Int Log				6	14		
Unique locations	CRAL	1	0	0.137	1	1	0.538	0.362
	GPST	1.5	1		1	0.25		0.166

Abbreviations. MROC = modified ride-on car; EM = Explorer Mini; GPST = global positioning system tracker; CRAL = caregiver-reported activity log; Int Log = MROC integrated logger.
Statistical notes. [a] Between tracking methods (Mann–Whitney U test). [b] Between tracking methods (Kruskal–Wallis test). [c] Between-device comparison (Mann–Whitney U test).
* Statistically significant at $p < 0.05$.

4.4.1 Objective 1: Compare usage metrics from three tracking methods

Separate one-way Kruskal-Wallis tests were conducted for each dependent variable (number of sessions, unique days, total usage in minutes, and average session duration) to compare differences across the three tracking methods (mROC integrated logger, GPST, and CRAL). For comparisons limited to two tracking methods (GPST and CRAL), Mann-Whitney U tests were performed for the same metrics.

4.4.2 Objective 2: Understand relationships among usage metrics of the three tracking methods

To assess the relationship between usage metrics for the three tracking methods, a correlation matrix was generated. Analyses were conducted separately for mROC usage and EM usage (GPST and CRAL). Correlations were interpreted using thresholds: high correlation $r \geq 0.8$, moderate correlation $0.4 \leq r < 0.8$, and poor correlation $r < 0.4$ [158].

4.4.3 Objective 3: Compare usage between the EM and mROC

To evaluate differences in usage metrics between the EM and mROC, Mann-Whitney U tests were conducted using data collected via GPST and CRAL. These comparisons aimed to determine whether usage patterns differed significantly between the two devices. For all objectives, statistically significance was identified at $\sigma < 0.05$.

4.5 Results

Twelve participants had complete data across all three tracking methods and were included in the analyses. Twelve participants, out of the total 24 participants who completed the clinical trial, were excluded because the iTrail unexpectedly discontinued the GPST and access to relevant data processing software, mid-study. Of the included participants, seven children used the EM during the first 8 weeks, while five children started with the mROC. Individual usage patterns varied substantially across participants and devices. For example, total session minutes as measured by CRAL for the EM ranged from 165 to 1,270 minutes, while mROC usage ranged from 20 to 571 minutes. This variability was also evident in the number of sessions (EM: 6–57; mROC: 2-38) and average session duration (EM: 8.4–36.1 minutes; mROC: 5.0–27.8 minutes) as measured by CRAL. The data presented visually in the figures is also included in Supplemental Table A for accessibility and detailed reference.

4.5.1 Objective 1: Compare usage metrics from three tracking methods

For the mROC, no significant differences were found in usage metrics across the three tracking methods (4.2). For the EM, a significantly lower average session duration was observed for the GPST compared to the CRAL (p=0.002, 4.2, Figure 4.3). All other usage metrics for the EM showed no statistically significant differences between tracking methods. Visual analysis (Figure 4.3) revealed variability across participants, with some showing consistent measurements across tracking methods, while others exhibited large discrepancies, highlighting potential differences in how each method captures use.

4.5.2 Objective 2: Understand relationships among usage metrics of the three tracking methods

The correlation matrix demonstrated positive but variable relationships between tracking methods for both the mROC and EM (Figure 4.4). For the mROC, the GPST and integrated logger showed a high correlation for total usage in minutes (r= 0.83, p=0.00093) and moderate correlation for the number of sessions and

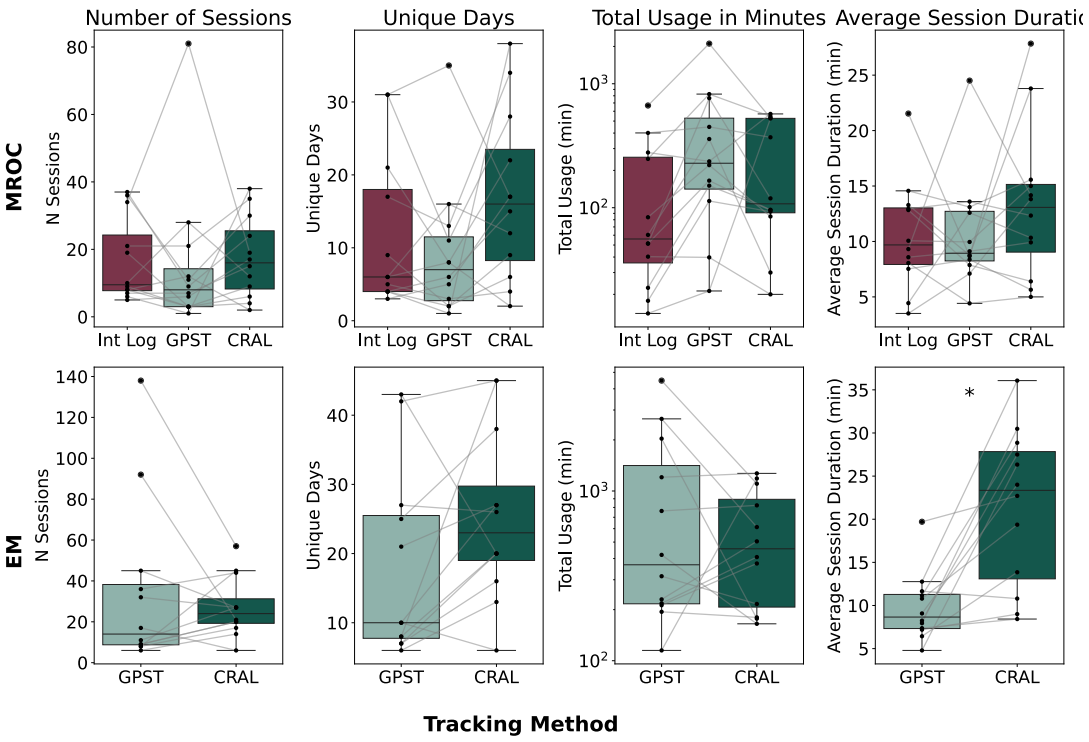

Figure 4.3: Boxplots show the number of sessions, unique days, total usage in minutes, and average session duration (minutes) for each tracking method per powered mobility device. Grey lines connect the usage metric for each participant as measured by each tracking method; if values were the same for each tracking method a horizontal line would be observed. *mROC=modified ride-on car, EM= Explorer Mini, GPST = geospatial tracker, CRAL = caregiver reported activity log, Int Log = mROC integrated logger.* * indicates significant differences between tracking methods.

unique days (r = 0.69, p=0.014). In contrast, correlations between the GPST and CRAL were poor for three out of four metrics, and correlations between the integrated logger and CRAL were poor for two out of four metrics. For the EM, the GPST and CRAL were moderately correlated for the number of sessions and unique days but poorly associated for total usage in minutes and average session duration. Correlations between GPST and CRAL were stronger for the EM compared to the mROC.

4.5.3 Objective 3: Compare usage between the EM and mROC

The EM was used more frequently than the mROC throughout the study, however this difference was only statistically significant for the total usage minutes (p=0.023) and average session duration (p=0.046) via CRAL (Figure 4.5. Both tracking methods recorded more play sessions and unique days for the EM compared to the mROC, and total usage in minutes was consistently higher for the EM. For unique locations tracked, the GPST recorded more locations for the EM, while the CRAL captured more for the mROC. Across both

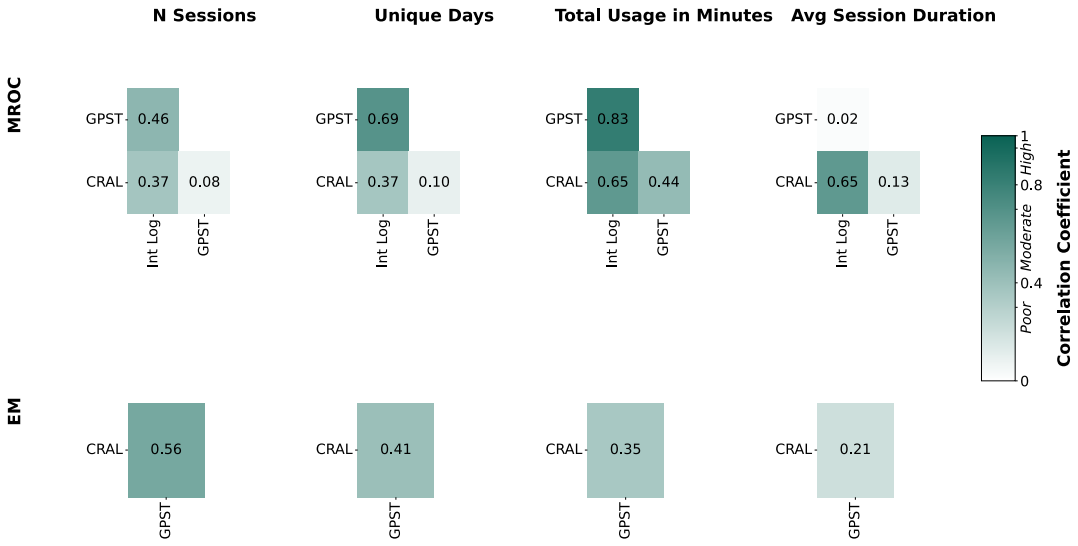

Figure 4.4: The correlation matrix represents the association between the usage metric as measured by each tracking method. The top row compares the tracking methods for the mROC, and the bottom row compares the tracking methods for the EM. A dark green value of 1 represents a higher correlation between tracking methods. mROC=modified ride-on car, EM= Explorer Mini, GPST = geospatial tracker, CRAL = caregiver reported activity log, Int Log = mROC integrated logger. * indicates significance.

devices, the CRAL consistently measured more unique locations than the GPST. For total distance, tracked only by the GPST, the EM covered more distance than the mROC. Despite these differences in usage, the Fun Index measured via CRAL indicated that caregivers perceived children's enjoyment with both the EM and mROC to be similar.

4.6 Discussion

This study is the first to compare integrated logger, GPST, and CRAL tracking methods for reporting community-based powered mobility usage. The only significant difference between tracking methods was for average session duration of the EM, which may be due to differences in usage definitions between quantitative measures and caregiver-report. Caregivers were not given a specific definition of a play session, leading to broader interpretations of device usage recorded in the CRAL, such as sitting in or playing near the device without actively moving or engaging with it. This contrasts with the GPST's movement-based definition, and the integrated logger's switch-activated definition. Other usage metrics showed no significant difference between tracking methods, similar to previous findings that reported no significant differences in session duration and total driving time as measured by CRAL and an integrated logger [145]. This non-significant

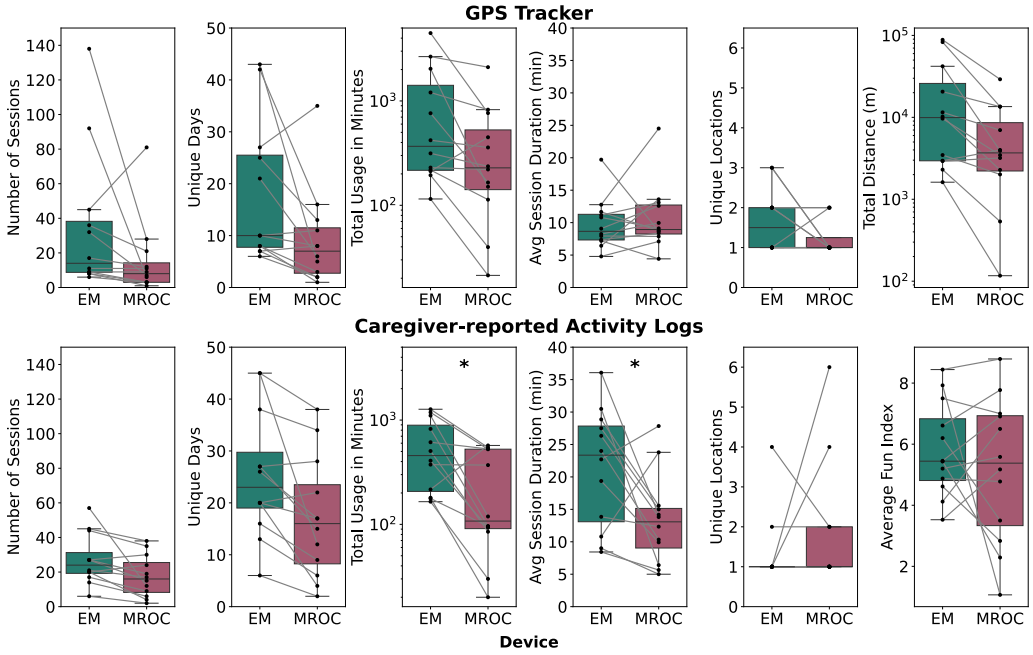

Figure 4.5: Comparison of usage metrics between the EM and mROC collected only by GPST and CRAL. Individual data is represented by black points. Grey lines connect the usage metric for each participant per mobility device. *mROC=modified ride-on car, EM= Explorer Mini, GPST = geospatial tracker, CRAL = caregiver reported activity log.* * indicates significant differences between devices.

difference suggests that all tracking methods in the study demonstrated concurrent validity in measuring community-based powered mobility usage, providing different but complementary perspectives on device usage.

The mROC integrated logger and GPST showed the highest correlation for most metrics, including number of sessions, total usage minutes, and unique days. However, the GPST algorithm underestimated play session duration, likely due to its movement-based play session definition, which lacks input from switch activation or caregiver determination and focuses on motion-based activity, potentially missing stationary periods where children engage with their environment, such as interacting with objects or playing with caregivers. Similarly, integrated loggers recorded play session duration that aligned moderately with CRAL, suggesting that caregiver input remains valuable in understanding the full context of mobility device usage. This finding reinforces the importance of combining quantitative and qualitative tracking methods to capture a more complete picture of device usage, particularly the stop and go nature of children's play and exploration. Device use variability may also help explain why only one statistically significant difference was found between CRAL and GPST for the EM. According to CRAL, the EM was more often used indoors, where GPST performance is limited but possible. Caregivers may have recorded longer play sessions in CRAL

that included seated or stationary time [159]. The potential underreporting by GPST and overreporting by CRAL may have canceled each other out, making it harder to detect significant differences between tracking methods.

Children and families used the EM more frequently than the mROC. CRAL indicated significantly higher average session duration and total usage minutes for the EM compared to the mROC. Most participants used the devices at home, with a few using them at different locations, like prior research [19]. The perceived fun (i.e., Fun Index) was similar between both devices (median: EM 5.44, mROC 5.38), aligning with prior research (average: 5.8) [145].

Outside our research team's work on this study, there are currently no prior reports of EM usage [106]. On average, participants in this study used both the EM and mROC more frequently than reported in prior mROC studies [19, 145, 154]. The number of sessions per month was higher (EM: 7, mROC: 4) compared to earlier mROC reports (2.58 sessions/month) [19]. Similarly, children used the devices on more days per month (EM: 5, mROC: 3.5) than in prior mROC studies (1.33 [154] and 2.43 [145] days/month). Average monthly usage was 178.75 minutes for the EM and 114.25 minutes for the mROC. EM usage was comparable to the group average mROC usage reported in a three-month study (182.5 minutes/month [154]), while mROC usage was between this prior report and the average reported in a study that evaluated usage over a 12-month period (57.1 minutes/month [145]). These results may be due to the increased frequency of check-ins and ongoing support provided to families throughout the device trial period. The study team contacted families every two weeks to discuss barriers to usage of the device and provide recommendations on ways they could increase usage [145]. This contrasts with the previously mentioned studies that only checked in with families at 3 months and every 6 months Outside our research team's work on this study, there are currently no prior reports of EM usage [106]. On average, participants in this study used both the EM and mROC more frequently than reported in prior mROC studies [19, 145, 154]. The number of sessions per month was higher (EM: 7, mROC: 4) compared to earlier mROC reports (2.58 sessions/month) [19]. Similarly, children used the devices on more days per month (EM: 5, mROC: 3.5) than in prior mROC studies (1.33 [154] and 2.43 [145] days/month). Average monthly usage was 178.75 minutes for the EM and 114.25 minutes for the mROC. EM usage was comparable to the group average mROC usage reported in a three-month study (182.5 minutes/month [154]), while mROC usage was between this prior report and the average reported in a study that evaluated usage over a 12-month period (57.1 minutes/month [145]). These results may be due to the increased frequency of check-ins and ongoing support provided to families throughout the device trial period. The study team contacted families every two weeks to discuss barriers to usage of the device and provide recommendations on ways they could increase usage [145]. This contrasts with the previously mentioned studies that only checked in with families at 3 months [145] and every 6

months [154].

Although device order was randomized, prior work from the overarching clinical trial suggests that the sequence in which devices are introduced may affect usage patterns, potentially due to learning effects or family preferences [104, 106, 156, 159]. To assess potential order effects in our randomized crossover design, we compared CRAL outcome measures between participants who received each mobility device first versus those who received it second. No significant differences were observed between randomization groups, suggesting minimal carryover or order effects. Given the recognized validity of CRAL as a benchmark for evaluating other tracking methods, we focused our exploratory analysis on this measure. Specifically, we examined total number of sessions and total session minutes, reducing the number of comparisons to four (adjusted significance threshold: $\sigma = .0125$). None of these comparisons reached statistical significance, further supporting the consistency of outcomes across randomization groups.

4.6.1 Clinical Pearls: Strengths and Challenges of Each Tracking Method

While CRAL provides rich qualitative data, it relies on caregivers' time and mental effort to complete. In the larger study of 24 participants, one caregiver did not complete the CRAL; which reflects an improvement over a previous study where 42% of caregivers did not complete CRAL indicating greater adherence [145]. However, CRAL data were often incomplete; for instance, 17.1% of caregiver-reported play sessions lacked location information. A key challenge with CRAL is that caregivers were not provided with a clear definition of a play session, which led to variability in how caregivers reported device use. Some caregivers, for example, interpreted play sessions as sitting near the device while it was not moving, such as watching a movie or sitting in the car. This variability highlights the importance of providing families with a clearer definition of what constitutes a play session to improve consistency in tracking.

The integrated logger and GPST required minimal to no caregiver effort. However, integrating the integrated logger into the device's electronics increased the risk of device failure. In this study, several mROCs failed due to integrated loggers, which caused the mROCs to be switched out during the trial period, leading to longer breaks in device use and tracking data. This issue was not unique, as a previous study also reported one integrated logger failure [19]. Externally-mounted GPST are potentially highly accurate, quick to set up, and can provide detailed metrics such as distance traveled, which are essential for clinicians and researchers [148]. However, GPST accuracy depends on a strong satellite signal, which can be challenging indoors or in areas with dense tree coverage or tall structures. In this study, several participants in rural areas were unable to use the GPST due to unstable satellite connections. The effectiveness of GPST could be enhanced with better algorithms and integration with an inertial measuring unit (IMU). The IMU could help initiate device start-stop sequences, similar to a previously reported method that identified periods

Table 4.3: Summary of the strengths and challenges of each tracking method.

Tracking method	Cost	Set-up time & effort	Implementation time & effort	Multi-device use	Reliability
Int Log	$50–100	Three hours by 2–3 engineers	Easy during deployment; risk of device malfunction or failure	No	Activated by device electronics; high reliability
GPST	∼ $150–200	∼10 minutes; requires reliable GPS signal	Easy during deployment; caregiver turns device on and off	Yes	High reliability when used outdoors
CRAL	Free	∼10 minutes to prepare printed forms	Approximately two minutes per use; caregiver must remember to complete	Yes	Prone to under- or over-reporting; incomplete entries possible

Abbreviations. GPST = geospatial tracker; CRAL = caregiver-reported activity log.

of walking in combination with GPST [160].

4.6.2 Limitations and Future Directions

This study has several limitations. First, integrated trackers were not incorporated into the EM due to concerns of disrupting the commercial devices, thereby preventing consistent tracking across both devices. Additionally, the iTrail GPST and software were discontinued mid-study, requiring the use of two different software platforms for data extraction. As a result, only a subset of the 24 participants from the larger clinical trial could be included in this secondary analysis. This small sample size may have limited statistical power to detect some differences between tracking methods, despite observed trends. Differences in device characteristics, such as using a joystick versus a switch-and-steering-wheel configuration, or driving from a seated versus a standing position, may have influenced participants' ability to access and engage with the device across settings, contributing to variability in overall usage patterns. Future research should use tracking methods compatible across multiple devices and aim for larger sample sizes.

4.7 Conclusions

This work is the first to quantitatively compare a young child's use of multiple powered mobility devices over a multi-week loan. This study highlights the importance of tracking both device usage periods and the stop-and-go moments of play and interaction, which are crucial for young children's development. Future advancements in data tracking should integrate movement-based metrics with caregiver-reported insights to capture the multifaceted nature of young children's mobility experiences. This integrated approach will

provide a more comprehensive understanding of the learning and social opportunities that powered mobility devices offer young children.

Acknowledgements

Funding

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Chapter 5

UP AND DOWN: ANALYZING PHYSICAL ACTIVITY AND POSTURE WITH WEARABLE SENSORS DURING PARTIAL BODYWEIGHT SUPPORTED PLAY FOR YOUNG CHILDREN WITH DOWN SYNDROME

Developmental Neurorehabilitation

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Abstract

Children with Down syndrome experience delays in motor development. Open-area partial bodyweight support (PBWS) systems can help support motor development, but no study has objectively reported motor behaviour changes, such as increased leg activity or time spent upright. This study quantified changes in physical activity and posture during exploratory play with a PBWS system for pre-ambulatory children with Down syndrome. We hypothesized that PBWS would increase both physical activity levels and upright posture duration. This randomised, multisite crossover trial included children with Down syndrome who could sit independently but were not yet walking. Each child completed nine 30-minute play-based sessions with and without PBWS. Physical activity and posture were measured using shank-worn accelerometers, capturing the percentage of time spent in high physical activity and upright. Nonparametric Mann-Whitney U tests compared outcome measures between PBWS and non-PBWS conditions. Fifteen children (mean age: 19.4 months, range: 12-31 months) completed study procedures. Across all participants, high physical activity did not noticeably increase from the first to last session. The median change was -5.0% (IQR: -13.4- +9.05%) with PBWS and -2.53% (IQR: -13.7- +12.9%) without PBWS. Time spent on feet showed a median increase of +2.38% with PBWS (IQR: –0.96 – +12.24) and a decrease of -1.08% without PBWS (IQR: -7.70 - + 1.02%). A statistically significant difference between conditions (p=0.042) indicated greater improvements in time on feet during PBWS sessions versus without. PBWS did not increase time spent in high physical activity, but did support increased upright posture over time. These findings suggest PBWS systems may provide a supportive environment for practicing upright postures in early motor development for children with Down syndrome. Longer interventions may be needed to evaluate the full impact of PBWS on motor development. This study adds to growing evidence supporting early, engaging, and accessible motor interventions for children with DS. This study was registered at ClinicalTrials.gov (CT # NCT05307523).

5.1 Introduction

Children with Down syndrome (DS) commonly experience delays in motor milestones, such as pulling to stand and walking, due to musculoskeletal factors associated with DS like hypotonia and ligament laxity [25, 69, 70, 71, 161, 162]. These body structure and function-level factors impact postural control and trunk stability, affecting developmental progress in prone, sitting, and standing positions. These musculoskeletal factors also hinder development of self-initiated mobility, which is crucial for achieving social, cognitive, and other developmental gains that begin when a child starts rolling, crawling, or walking [3, 11]. Diminished physical activity in children with DS is evident as early as six months of age [161, 163] and impacts gross motor and cognitive development [164]. Interventions like treadmill training or mobility aids can be used to support self-initiated movement and physical activity at the same time as typically developing peers [3, 74, 91, 94]. Additionally, increased time in upright standing postures has been shown to increase bone density, improve antigravity strength, and support bowel function for children with neuromuscular disorders [17]. Therefore, understanding how to support age-appropriate motor exploration while increasing movement, physical activity and upright time is essential for optimizing developmental and health outcomes in young children with DS.

One widely used method for measuring physical activity is wearable accelerometery. These small wearable sensors, which measure acceleration in one to three dimensions, are typically worn on the hip, wrist, or ankle. Prior research has recommended shank placement near the ankle for toddlers to capture kicking and walking movements [165, 166]. Accelerometery data is converted into movement counts, and then segmented into time intervals, or epochs. The amount of movement within each epoch is then classified into physical activity levels, such as low and high, using experimentally-determined cut points, or movement count thresholds [167]. Beyond monitoring movement, accelerometers have been used to assess overall health and evaluate interventions for young children. For instance, infants with DS have been shown to have lower intensity physical activity compared to typically-developing peers [168]. In another study, leg movement rate measured by a shank-worn accelerometer increased in infants with DS following play with a toy gym that encouraged kicking [169]. This play-based intervention is promising, as increased leg activity has been associated with earlier walking onset for young children with DS [161, 170]. However, there remains limited understanding of how other play-based motor interventions, such as partial body weight support (PBWS) systems, may impact children with DS's activity levels [163].

Motor development in infancy emerges through new experiences and repeated actions, and can be supported through both structured play activities designed to build specific skills and unstructured play which promotes self-initiated exploration and movement variability [36, 45]. PBWS systems offer a play-based context that can reduce physical demands, while maintaining an unstructured environment in which children

can choose how and when to move, potentially supporting motor learning[114]. PBWS systems typically consist of a tent-like frame with low-friction mobile support bars that allow for multi-positional, 360^o exploration in a bounded play area, providing body weight offset through a soft harness connected to the frame via bungee cords or a weighted pulley system (Figure 1a) [117]. The optimal proportion of body weight support for facilitating motor development has not been empirically established, and prior studies report a wide range of support levels (e.g. 20-40% offset) that may enable more advanced motor behaviors under supported conditions [171]. Preliminary research suggests that play in PBWS systems can support motor development for children. A case study involving a child with spina bifida showed increased locomotor activity and engagement in adaptive sports with an in-home PBWS system [111]. Similarly, an infant with DS who used a PBWS system at home averaged 28 minutes of daily use and achieved milestones such as pulling to stand, independent standing, and independently walking earlier than expected for children with DS [69, 172]. Other studies have shown that PBWS in conjunction with socially assistive robots enabled children with developmental disabilities, including DS and cerebral palsy, to perform motor actions, such as taking steps, beyond their current capabilities [113, 173]. In a user evaluation with 16 infants, including five with DS, families reported positive experiences with in-home PBWS systems, including observations of infants' increased confidence in their motor behaviour, such as climbing stairs [117]. Although initial work with in-home portable PBWS systems have demonstrated their usefulness and efficacy, no studies to date have combined PBWS intervention with wearable sensors to objectively verify reported motor behaviour changes, such as increased leg activity or time spent upright, associated with PBWS use.

This study aimed to quantify changes in physical activity and posture during exploratory play with PBWS for pre-ambulatory children with DS. We hypothesized that children's physical activity levels would be elevated with PBWS assistance, potentially due to reduced physical demands during transitional movements. Additionally, we hypothesized that children would increase the amount of time spent in upright postures with PBWS assistance, as reduced load demands and external trunk support may facilitate standing. Understanding the impacts of PBWS on physical activity and posture can inform early intervention strategies that promote mobility, independence, and physical health for children with DS.

5.2 Methods

5.2.1 Design

This pilot study was a multi-site, prospective, randomized crossover clinical trial, with repeated measures at the start, middle, and end of the study (ClinicalTrials.gov # NCT05307523). The Institutional Review Boards at all participating sites, the University of Washington, University of Puget Sound, and Texas

Women's University, approved the research protocol. This chapter evaluates the impact of PBWS on posture and physical activity as measured by accelerometers, while primary outcomes of gross motor development and mastery motivation are reported elsewhere [112].

5.2.2 Participants

We enrolled a total of 17 children with DS under the age of 36 months. Two participants withdrew from the study due to scheduling demands and illness unrelated to the study; a total of 15 participants completed all study procedures. To be included in the study, the child needed to be able to maintain a sitting position without support and not yet be taking independent steps. Children with uncontrolled seizures or other medical conditions that would prevent them from tolerating PBWS, as reported by caregivers, were excluded from the study. Informed consent and permission were obtained from the caregivers, who were required to be over the age of 18 and possess proficient English communication skills to complete study surveys. Participants were recruited through word of mouth and flyers shared with the researcher's clinical contacts, local DS organizations, and inclusive preschool programs. Gross motor function was assessed using the Gross Motor Function Measure (GMFM)-88, a reliable and valid scale for children with DS [174]. Using the benchmarks established in Palisano et al., 2001, children were classified into two groups based on the most advanced major motor milestone that was observed during their initial GMFM-88 assessment [69]. This categorization resulted in nine children being included in the sitting group and six children being included in the crawling group (Table 1).

5.2.3 Procedure

At all sites, the study took place over nine weeks using a single-subject randomized crossover study design. The first-, fifth-, and ninth- weeks involved a single assessment visit during which a paediatric physical therapist completed the GMFM-88 [112]. During weeks 2-5, children and their families participated in three, 30-minute intervention sessions per week, either with or without PBWS based on randomization order (Figure 1b). After the mid-study assessment, participants switched conditions and completed an additional three 30-minute intervention sessions per week for three weeks in the opposite condition. Nine children were randomly assigned to the PBWS intervention first, and six children second. Accelerometery data were collected at each intervention session. Sessions were conducted in a clinical lab setting.

Each intervention session was guided by an experienced paediatric physical therapist and standardized using a fidelity checklist. Guidelines for session structure were established to provide standardization across sites while preserving developmentally meaningful opportunities for exploration. The framework for sessions

Table 5.1: Participant demographics ordered by initial GMFM-88 scores.

Participant	Age (mo)	Mobility at Entry	PBWS Order	GMFM Initial
UPS02	20	Sitting	2	25.8
UW06	15	Sitting	2	29.6
TWU02	12	Sitting	2	35.5
UPS04	17	Sitting	2	36.1
UW03	17	Sitting	1	38.8
UW01	31	Sitting	1	39.7
UPS03	19	Sitting	1	41.1
TWU04	26	Crawling	1	44.1
TWU03	15	Sitting	1	47.1
TWU06	14	Sitting	2	48.0
UPS01	14	Crawling	1	48.6
UW02	20	Crawling	1	48.9
TWU01	17	Crawling	1	49.3
UPS05	25	Crawling	1	56.0
TWU05	29	Crawling	2	56.1

Abbreviations. PBWS: Partial Body Weight Support protocol order, GMFM: Gross Motor Function Measure (GMFM)-88.

was informed by early intervention and motor learning principles[45], with approximately 10 minutes of play in upright positions (e.g., kneeling or standing at benches or toys), 10 minutes of mobility exploration (e.g., crawling, rolling, cruising), and 10 minutes of child-led exploration. The framework was applied flexibly to support self-initiated movement in all conditions while maintaining consistency across sessions. Children were guarded appropriately (i.e. using contact guard assist for safety) during self-initiated upright positioning but received no additional manual support. Caregivers and siblings were encouraged to interact and play with their child and the research team during the sessions. Children were given breaks as needed if the child was fussy and could not be redirected or calmed within one minute, fell asleep, or a break was requested by their caregiver. Standardized toys and equipment, such as nesting benches, a walker push toy, a floor piano mat, and various manipulative toys, were used to encourage mobility and exploration.

5.2.4 PBWS system

The Portable Mobility Aid for Children (PUMA; Enliten LLC, Newark, DE) is a collapsible system providing passive PBWS for a child wearing a harness (Figure 5.1a). It features an overhead support structure with two parallel rigid beams and a perpendicular mobile beam, allowing movement in one direction. A network of pulleys in the mobile beam connects the harness to a counterweight, enabling movement in the opposite direction and providing a passive vertical force to counterbalance gravity. The counterweight was initially

set to provide approximately 20% of each child's bodyweight, consistent with support levels from prior literature [171]. However, support levels were adjusted as needed during sessions to effectively support standing behaviours and exploratory movement. Weight offsets varied by no more than a pound between sessions for all but three participants, as determined by the site's physical therapist, to ensure successful initiation of transitional movements. The PUMA provides mobility support over 81 ft^2 (9 ft x 9 ft) floor space. The overhead bar connects to a child-worn harness at four attachment points, ensuring stability during all intervention sessions with PBWS. Children wore a harness during all sessions, with and without PBWS assistance, to maintain consistent conditions.

5.2.5 Actigraph

During each session, children wore a triaxial Actigraph GT3X+ accelerometer (Actigraph, Pensacola, Florida, USA) on their right shank (Figure 1c). Accelerometery data were collected at 100 Hz. The shank accelerometer was attached with disposable wristbands and covered with a soft athletic wrist band to maximize comfort and reduce distraction. The shank location was selected to capture lower-limb movement typical of pre-ambulatory children, consistent with prior studies in infants with Down syndrome [164, 170].

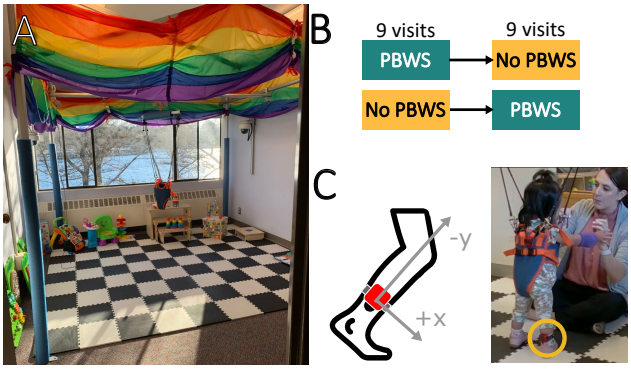

Figure 5.1: (A) The enriched exploratory play space with the PBWS system (B) Actigraph GT3X+ triaxial accelerometers were placed on a child's right shank. (C) This study used a randomized crossover study design. Nine children had PBWS assistance first, and 6 children second. Each intervention period lasted 3 weeks. (D) The accelerometers were used to calculate physical activity and upright posture.

5.2.6 Outcome measures

Physical activity levels

Physical activity levels were calculated using the vertical axis of the sensor aligned with the shank, capturing movement in 15-second epochs [166]. We identified periods of low and high activity using cut points previously identified in research with infants with DS [161, 170]. Specifically, counts of 0-131 movement units/15 s epoch was defined as periods of low activity and more than 131 movement counts/15s epoch was defined as periods of high activity (Figure 5.2). Movement counts were calculated from raw accelerometery data in Python using ActiGraph's open-source algorithm [175].

Posture identification

Upright and horizontal postures during play were also differentiated using the shank accelerometer. This methodology was adapted from the Actigraph algorithm, which uses a triaxial accelerometer as an inclinometer [176, 177]. When mounted on the thigh or waist, Actigraphs are valid for assessing standing and lying postures [178, 179]. The orientation angle of the accelerometer's y-axis aligned with the shank relative to vertical was calculated as [176]:

$$\theta_y = cos^{-1}(\frac{y}{\sqrt{x^2 + y^2 + z^2}}) \tag{5.1}$$

The inclination angle identifies standing postures as $\theta_y < 17°$, lying postures as $\theta_y > 65°$, and in between as sitting postures. As specified by ActiGraph's inclinometer function, we classified vertical positioning of the shank as "on feet" when $\theta_y < 17°$. The term "on feet" encompasses static standing, cruising, squatting and walking.

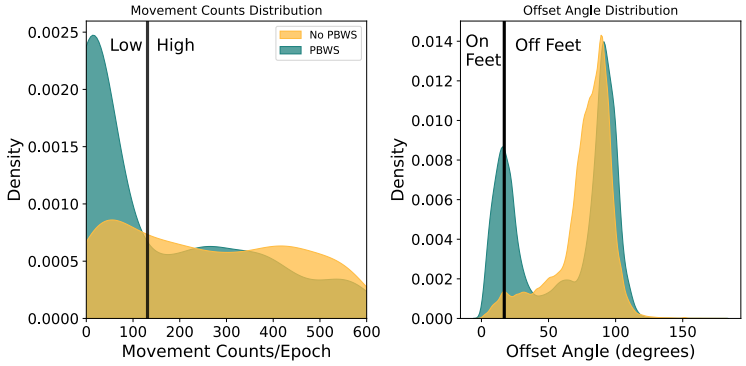

Figure 5.2: Distribution of movement counts per 15 second epoch (left) and offset angle (right) for a representative subject (UPS04). A threshold of 131 counts/15s distinguishes low from high physical activity, while On Feet postures were defined as an offset angle less than 17°.

5.2.7 Data analysis

The changes in the percentage of session time spent in high physical activity and time spent on feet were calculated by comparing the differences between the first and ninth session of each experiment block separately with and without PBWS. Additionally, we analysed the relationship between time on feet and high physical activity levels using accelerometer measurements by assessing their correlation (R^2). This analysis aimed to determine whether an increase in time spent upright was associated with higher levels of physical activity, given that both variables were recorded through the same accelerometer data. To compare the outcome measures with and without PBWS, nonparametric Mann-Whitney U tests were conducted using an alpha level of 0.05. Data were analysed using a custom Python script. To assess potential carryover effects, outcome data were stratified and compared by intervention randomization order (PBWS-first vs. No-PBWS-first). To assess baseline equivalence between randomized groups and evaluate potential carryover effects inherent to the crossover design, we conducted a pre-crossover analysis using only data from the first study session for each participant. Participants were stratified by randomization order, and outcome measures were compared between groups at this initial session prior to exposure to both conditions. As this was a pilot study designed to assess feasibility and provide preliminary estimates of effect, a formal power analysis was not conducted.

5.3 Results

All fifteen children in the study tolerated both the PBWS system and wearable sensors. The average age of the participants was 19.3 months at study onset (range: 12-31 months), consisting of nine females and six males (Table 1). An average of 24% (SD: 4%) of bodyweight support was provided during each session. Children played during intervention sessions with their caregivers, siblings, and the interventionists. Play activities included dancing along to music, knocking down cup towers, and chasing after balls. Six children took breaks (<2 mins) during the intervention sessions, both with and without PBWS. One child fell asleep during one intervention session for an extended period. Five participants had one Actigraph data session missing, and one participant had two missing data sessions. The absence of this data stemmed from issues such as children experiencing discomfort with the Actigraph sensors or challenges related to file transfers. No significant differences were observed between randomized groups at the first study session prior to crossover (Figure 5.3).

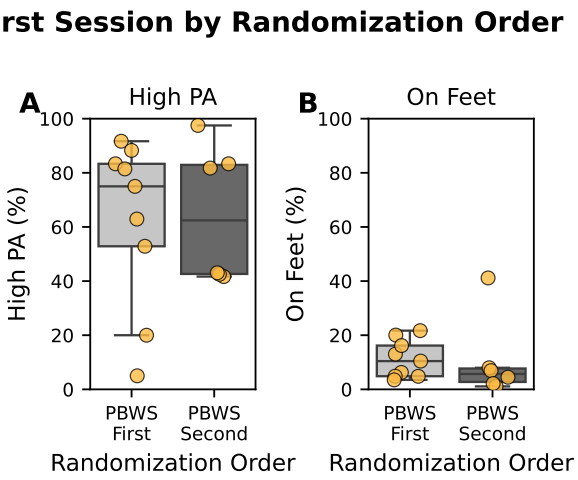

Figure 5.3: Percentage of session spent in (A) high physical activity and (B) On Feet during the first study session prior to crossover stratified by randomization order, to assess baseline equivalence between groups.

5.3.1 Physical activity levels

The amount of each session spent in high physical activity (> 131 movement counts/15s epochs) was similar with and without PBWS. The median physical activity level was 263.9 counts/15s (IQR: 174–411) with PBWS and 301.1 counts/15s (IQR: 190–431) without PBWS. Children had high levels of physical activity during the first session both with (median: 62.9%, IQR: 48.5–-82.4) and without PBWS (median: 68.3%, IQR: 42.8–-73.7; Figure 5.4a). Across all fifteen participants, there were no noticeable increases in high physical activity from the first to last session: the median change was -5.0% (IQR: -13.4– +9.05%) with PBWS and -2.53% (IQR: -13.7– +12.9%) without PBWS.

High physical activity levels were similar when the data were stratified by motor ability at study entry (Figure 5.5). Children who were sitting at study entry spent a median of 60.0% of the initial session in high physical activity with PBWS (IQR: 30.9–72.3%) and 56.4% without PBWS (IQR: 42.5–81.8%). Children who were crawling at study entry maintained high physical activity levels, with a median of 78.2% of the initial session with PBWS (IQR: 58.4–-82.9) and 71.6% without PBWS (IQR: 69.1–-72.8). Changes in high physical activity from the first to last session were modest across groups. For children who were sitting, the median change was –6.7% with PBWS (IQR: –15.5 –- +9.3) and –13.5% without PBWS (IQR: –20.8 –- +13.4). For children who were crawling, the median change was –4.8% with PBWS (IQR: –9.6 –- +5.5) and –1.8% without PBWS (IQR: –3.1–- +8.5). There were no noticeable differences in average physical activity levels whether the nine sessions with PBWS were first or second in the protocol .

There were no clear differences in high physical activity between participants based on randomization

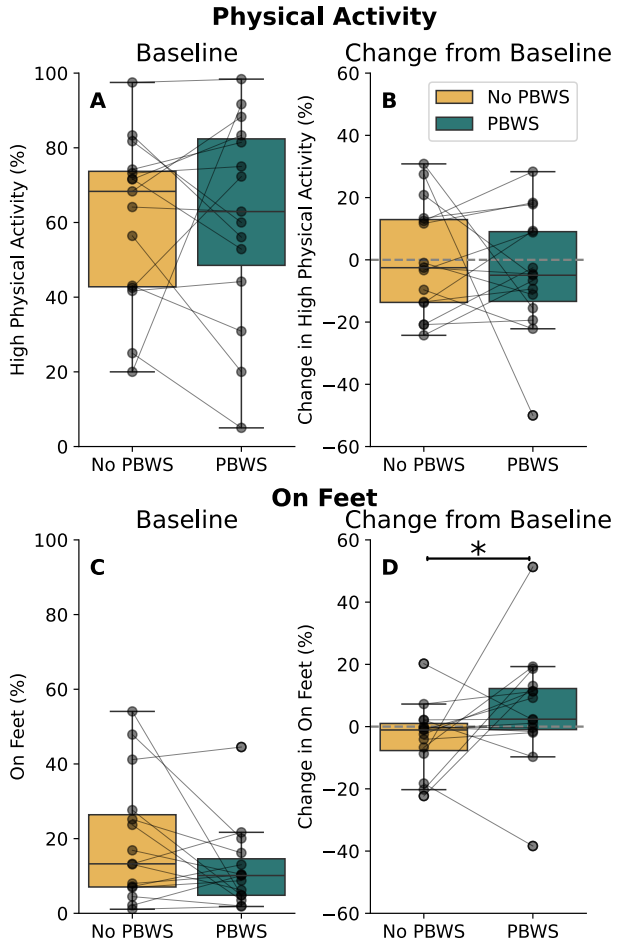

Figure 5.4: Percentage of session spent in high physical activity at (A) baseline and (B) change between first and final session with and without PBWS. Percentage of session spent On Feet at (C) baseline and (D) change between first and final session with and without PBWS. Significance is indicated by a *.

order (Figure 5.6). For the PBWS first group, participants spent a median of 75.0% (IQR: 42.9-93.3) of their first session with PBWS in high physical activity, compared to 68.3% (IQR: 56.4-71.7) during their first session without PBWS. The median change in high physical activity for the PBWS first group was -5.0% (IQR: -11.2 - +8.8) during the PBWS condition and -2.5% (-9.6 - +12.5) during the no-PBWS condition. For the PBWS second group, participants spent a median of 58% (IQR: 47.1-69.2) of their first session with PBWS in high physical activity, and 62.4% (IQR: 42.6 – 82.9) of their first session without PBWS in high physical activity. The median change for the PBWS second group was -4.6% (IQR: -13.3 - +12.7) during the PBWS condition and -4.6% (-20.8 - +12.9) during the no-PBWS condition.

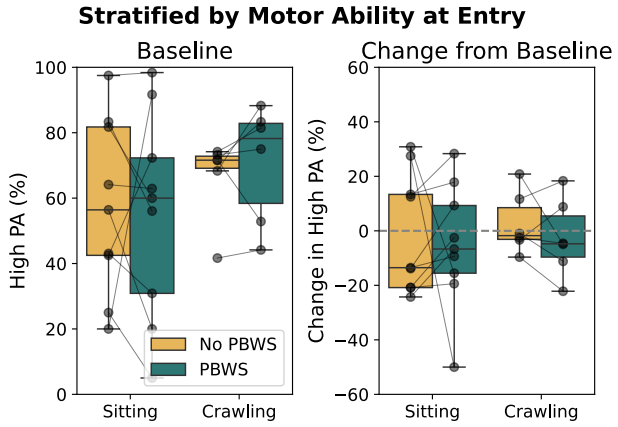

Figure 5.5: Percentage of session in high physical activity at baseline and change between first and last where data is stratified by motor milestone group.

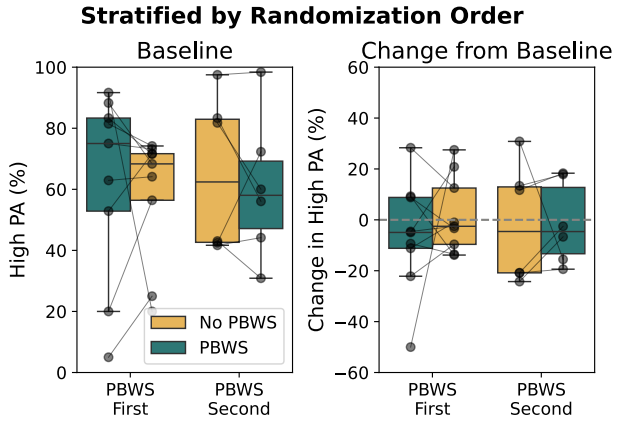

Figure 5.6: Percentage of session in high physical activity at baseline and change between first and last where data is stratified by randomization order.

5.4 Posture identification

Children spent a median of 10.1% of the first session on their feet with PBWS (IQR: 4.8–14.6) and 13.3% without PBWS (IQR: 7.1–26.4) (Figure 5.4c). The median change in time spent on feet from the first and last session was +2.38% with PBWS (IQR: –0.96 – +12.24) and -1.08% without PBWS (IQR: -7.70 - + 1.02%, Figure 5.4d). There was a significant (p=0.042) difference in the change in time spent on feet from the first to last session between conditions, with greater improvements observed during PBWS sessions.

Children who were sitting at study entry spent a median of 10.1% of their first session on their feet with PBWS (IQR: 4.8–16.2) and 8.0% without PBWS (IQR: 4.5–25.2, Figure 4). For children in the sitting group, there was a significant increase in time on feet between their first and last sessions with PBWS (p = 0.034). These children had a median increase of +11.3% in time spent on feet with PBWS (IQR: +1.1 –

+13.1), compared to a median decrease of –2.5% without PBWS (IQR: –6.7— +0.1, Figure 5.7). Children who were crawling at study entry spent less time on feet during their first session with PBWS (median: 8.3%, IQR: 5.2–12.4) than without PBWS (median: 20.3%, IQR: 14.0–26.6, Figure 5.7). On average children in the crawling group showed no noticeable increase in time on feet from the first to last session, regardless of PBWS use. The median change was +1.0% with PBWS (IQR: –7.4–7.5) and –0.7% without PBWS (IQR: –14.0–1.5).

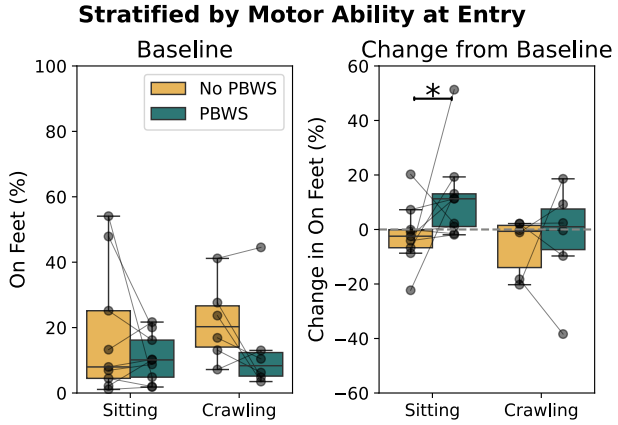

Figure 5.7: Percentage of session on feet at baseline and change between first and last where data is stratified by motor milestone group. Significance is indicated by a *.

For the group that received PBWS first, there was a significant difference (p=0.017) in time on feet between the first session of the PBWS block and the first session of the no-PBWS block (Figure 5). These children spent a median of 10.4% of their first PBWS session on their feet (IQR: 4.8–16.2), compared to 23.7% during their first session without PBWS (IQR: 13.2–27.6, Figure 5). In contrast, the PBWS second group showed relatively consistent baseline performance, with a median time on feet of 5.7% during their first session without PBWS (IQR: 2.7–7.7) and 9.4% during their first session with PBWS (IQR: 3.7–10.2) This discrepancy suggests a possible carryover effect in the PBWS first group. On average, the PBWS-first group showed a median increase of +9.2% in time on feet during the PBWS condition (IQR: +1.1– +13.1), followed by a median decrease of –0.8% during the no PBWS condition (IQR: –8.7– +2.1) (Figure 5.8). This statistically significant change (p = 0.027) indicates that increased upright activity was largely maintained after PBWS exposure. In contrast, the PBWS-second group showed minimal changes across conditions, with a median change of +0.3% with PBWS (IQR: –1.8– +9.1) and –3.3% without PBWS (IQR: –6.1— +0.7).

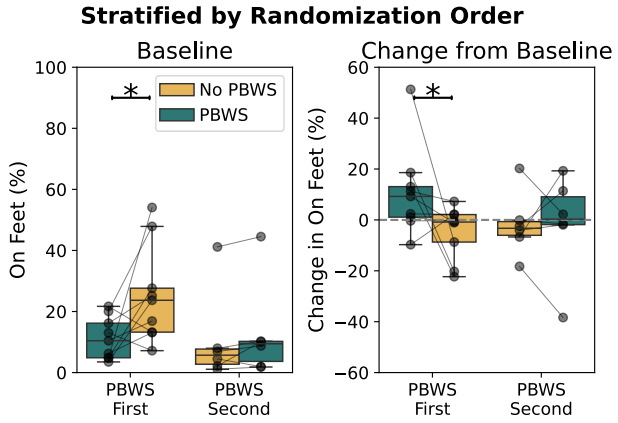

Figure 5.8: Percentage of session on feet at baseline and change between first and last where data is stratified by intervention randomization group. Significance is indicated by a *.

5.4.1 Relationship between measures

We observed an inverse relationship between high physical activity and time on feet (Figure 5.9), with stronger negative associations in the PBWS condition. The correlation between high physical activity and time on feet had an R of -0.64 with PBWS and -0.36 without PBWS. Regression analyses further supported this pattern, showing steeper declines in time on feet with increasing physical activity in the PBWS group. Across both randomization orders, seven of the 15 children demonstrated decreased physical activity but increased time on feet with PBWS. Without PBWS, only four of the 15 children showed decreased physical activity with increasing time on feet.

5.5 Discussion

We hypothesized that physical activity levels would increase with PBWS assistance. However, children with Down syndrome maintained relatively high levels of physical activity during play across both conditions, indicating that PBWS did not enhance engagement in physical activity. Secondly, we hypothesized that time spent in upright postures would also increase with PBWS, which was supported by our findings. PBWS appeared to support increased time spent in upright postures, particularly among children who were not yet crawling at study entry. These results suggest that PBWS may offer an encouraging environment for practicing upright postures without reducing physical engagement.

Children with Down syndrome in this study demonstrated elevated physical activity levels during play-based sessions, exceeding those typically observed in daily life and aligning with levels reported in previous structured interventions. Children in this study averaged 326 counts/15s during play-based sessions. These

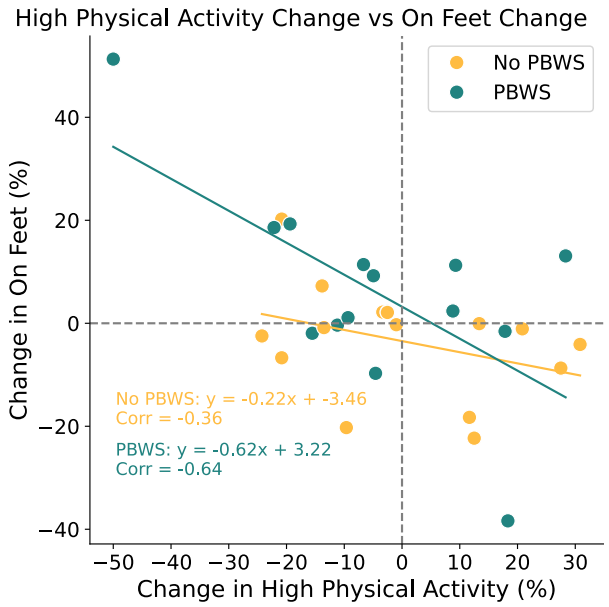

Figure 5.9: The relationship between changes in time on feet and changes in high physical activity for each participant between the first and last session for PBWS and no PBWS conditions. Linear regression lines for each condition indicate a negative correlation between the two outcome measures, such that participants who had greater time spent in high physical activity at the last session also had less time on feet.

values are comparable to those reported by Angulo-Barroso et al. [170], where children with DS (average age: 10.0 months) participated in supported treadmill training and averaged 245 – 295 counts/15s during high physical activity periods within 24-hour recording periods during daily home life. While the physical activity levels are similar, PBWS play allowed for more varied movements including crawling and climbing compared to the linear motion of treadmill walking. The children in our study were older on average (12 – 31 months), which may have influenced activity levels. Compared to typical daily activity levels for children with DS reported by Hauck et al. [164], 103.5 counts/min at 12 months and 131.5 counts/min at 18 months, participating children demonstrated elevated activity during the 30-minute play sessions, with a median of 1122 counts/min across sessions. This suggests that these play-based sessions promoted higher physical activity than typically observed in daily routines.

In alignment with prior research, the findings in this pilot study show that PBWS systems may support motor development in pre-ambulatory children with motor delays. Children playing with PBWS showed increases in upright postures after nine sessions, though benefits were observed most strongly in children who were sitting at study entry. This finding highlights the substantial variability in motor development among children with Down syndrome of similar chronological ages and may suggest that baseline motor stage may influence responsiveness to PBWS. PBWS may be particularly beneficial for children at earlier motor

stages by reducing postural and strength demands required for transitions and upright activity, whereas children who were already crawling may already have existing motor repertoires that lead to less change in upright behaviors, but further empirical research is needed to examine this hypothesis.

Several studies have demonstrated improvements in mobility and developmental milestone acquisition with PBWS assistance [111, 117, 172, 180, 181]. One case study involving a young child with DS found that mobility in all sessions was consistently higher during PBWS sessions and developmental milestones were achieved faster than expected [172]. Caregivers observed quicker transitions and increased step attempts outside the PBWS system, potentially due to increased confidence or practice [117]. In a study of typically developing, pre walking infants using PBWS, unweighting revealed more advanced motor behaviors that were not yet present under baseline conditions, with longer durations of unsupported standing observed at both 20% and 40% unweighting and a greater number of independent steps observed at 40% unweighting [171]. These results suggest that different levels of bodyweight support may afford distinct motor behaviors rather than a single optimal level of support. Other studies using ankle-worn accelerometers found variable, but generally increasing ankle movement counts across PBWS sessions [113, 182]. To build on these findings, future research should incorporate wearable sensors to measure physical activity and posture both during PBWS play periods and throughout the rest of the day to identify any carryover effects.

An inverse relationship was observed between high physical activity and time spent on feet, likely reflecting a new balance between stability and mobility during developmental transitions. When a child transitions from sitting to crawling behaviours, there is likely an increase in physical activity as measured by a wearable accelerometer as there is more movement [183]. However, when a child progresses to standing statically after pulling to stand, these actions are categorized as low physical activity since minimal acceleration is detected. The trend likely shifts once more as a child gains confidence in their movements, engaging in upright physical activity through cruising and walking. This inverse relationship between physical activity levels and upright posture aligns with broader developmental insights gleaned from our GMFM-88 data. As reported in Abuatiq et al. [112], both conditions showed statistically significant improvements in average GMFM-88 total scores. However, greater changes in motor performance were seen following the PBWS assistance condition (7.22% with PBWS versus 4.31% without PBWS), regardless of randomization order.

Family-centred and play-based early intervention to support children's motor and cognitive development is most often conducted in a natural setting [45]. Previous studies with similar PBWS systems were conducted at home with family involvement 19,21 [117, 172]. In contrast, our study was conducted in a clinic-like environment led by paediatric physical therapists, demonstrating that the open-area PBWS system is also feasible and translatable to clinical settings. PBWS provided a safe and comfortable bodyweight offset, allowing therapists to focus on engaging the child and facilitating play. Also, children playing in

PBWS can work on transitions between positions, a challenging skill for young children with DS [68]. Our findings highlight the versatile potential for open-area PBWS systems like the PUMA across settings and environments to safely support children with DS in exploring new motor skills during play.

Despite promising findings, this study has several limitations. The small sample size makes it challenging to evaluate the interplay between motor skills and PBWS effects but represents an important area for future study. While the crossover design provided preliminary insight into the effects of PBWS-supported play, a fully powered randomized controlled trial is needed to verify these findings and establish standardized intervention procedures. Our intervention periods, though intensive at three times/week, lasted only three weeks, which may impact PBWS outcomes for children with DS. Longer intervention periods, as seen in studies with children with cerebral palsy, may be beneficial [180, 181]. Similarly, the one-week washout period between interventions may not have been sufficient, as there was an observable difference between the baseline intervention values for the PBWS first group. Footwear was not standardized during play sessions, which may have influenced sensory input and lower extremity mechanics during motor exploration, particularly for children with Down syndrome [79, 80].

Sensor-based challenges also warrant consideration. While wearable sensors offer a quick means to assess motor behaviour, validated methods for pre-ambulatory young children, especially those with DS, are scarce. We used previously published cut-point metrics to calculate physical activity levels, aligning with prior research on treadmill training with young children with DS [184], and comparable to a cut-point validated for pre-ambulatory children with cerebral palsy [185]. However, other literature indicates that the use of cut-point based metrics are not recommended for infants and toddlers [165, 185, 186]. To enhance physical activity measurement, we used an ankle-worn accelerometer to identify postural changes, facilitating a quick assessment of gross motor ability in each session without time-consuming video coding. However, the published Actigraph angle threshold (of 17^o) that was used to determine "on feet" has not been validated in this age group. During in-lab calibration testing, we found that positions could be distinguished at an angle threshold of 40^o, hence more testing and validation is needed depending on the population and mobility contexts. Future research should consider employing inertial measuring units with both accelerometers and gyroscopes to enhance precision [187], and expanding sensor placement to the thigh could enable the identification of multiple postures. During the intervention, activity guidelines recommended 30% of each session involved upright play. While our trained paediatric physical therapists demonstrated high fidelity to these guidelines, future studies should explore child-led play in mobility interventions without imposing structured guidelines to understand natural motor skill progression better.

5.6 Conclusions

This study evaluated the potential of a portable PBWS system to promote physical activity and support motor development in pre-ambulatory children with DS. Using a single-subject randomized crossover study design, we found that children maintained high physical activity levels with and without PBWS. On average, children spent 17% of each session in upright postures, though there may have been a carryover from PBWS for the group that received it first. Children increased their time in upright postures between first and last PBWS sessions. These findings support the integration of portable PBWS systems into both home and clinic environments as a tool for play-based therapy. Unlike other interventions that may limit movement variety, PBWS-enabled play encouraged diverse motor behaviours such as crawling, climbing, and standing. Additionally, the use of ankle-worn sensors to quantify upright time offers a promising method for generating objective, real-time progress reports—empowering families and clinicians with actionable data. Beyond individual outcomes, this research contributes to a growing body of evidence that emphasizes the importance of early, engaging, and accessible motor interventions for children with DS. By enabling more naturalistic, self-directed movement in safe environments, portable PBWS systems may help reduce barriers to participation in physical activity, an important factor in long-term health, independence, and inclusion for young children with DS. These findings underscore the need for continued research into scalable, family-centred technologies that support early motor development and promote equity in early intervention services.

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Chapter 6

PATHWAYS TO PLAY: BIOMECHANICS AND EXPLORATION DURING YOUNG CHILDREN'S FIRST INTERACTIONS WITH PEDIATRIC MOBILITY DEVICES

In preparation for Developmental Medicine & Child Neurology

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Abstract

Access to self-initiated mobility is often delayed for young children with developmental disabilities. Mobility aids can support on-time mobility; however, there is limited evidence comparing different device types to inform clinical selection. This study quantified exploration, muscle activity, and posture across four conditions: unassisted mobility (UA), partial bodyweight support (PBWS), and powered mobility using a static (PMD-static) and dynamic (PMD-dynamic) seat configuration. Sixteen children with developmental disabilities (12–50 months, 7 M / 9 F) participated in four randomized play sessions in a laboratory playroom. Movement patterns were assessed using multi-camera motion capture, muscle activity using wearable electromyography sensors, posture using inertial measurement units, and caregiver perceptions through technology and implementation surveys. Children explored significantly larger areas during PMD use than during UA and PBWS. Muscle activity in the biceps femoris and quadriceps was greater during UA and PBWS than during PMD conditions, though PMD-dynamic elicited greater quadriceps activation than PMD-static. Relative time spent in an upright posture varied across conditions, but was most frequently greatest during PMD-dynamic. Caregivers reported higher overall satisfaction and intervention feasibility for the PMD relative to PBWS. These findings demonstrate that different mobility aids and powered mobility configurations support distinct movement patterns and can be strategically selected to align with therapeutic and developmental goals.

6.1 Introduction

Independent, self-initiated mobility in early childhood is a powerful driver of development, supporting learning across cognitive, social, and motor domains [6, 36]. As infants gain locomotor experience, changes in posture and movement alter how they interact with their environment, influencing exploration opportunities, object interaction, and caregiver engagement [2, 6, 36, 188]. When mobility is delayed or limited, young children with motor disabilities have fewer opportunities for self-initiated exploration and participation, which may have downstream effects on other developmental domains [3, 189, 190]. Additionally, infants with developmental disabilities spend less time sitting and standing than their typically developing peers [33]. During early childhood, many children with disabilities require support to move independently and, as they grow, may alternate between walking, wheeled mobility, and assisted mobility depending on their age and environment [27, 56]. Large cohort studies show that motor ability does not necessarily reflect movement in daily life, as mobility methods vary widely by context, environment, and age [54, 59]. To support movement and participation, children may use mobility aids such as walkers, gait trainers, and powered mobility devices (PMDs). These devices provide different levels of postural support and control, shaping movement strategies and opportunities for environmental interaction [3, 18]. Furthermore, results from studies in which children trialed multiple PMDs suggest that differences in postural support and control interfaces influence caregivers' preferences for specific devices [20, 135]. However, there is limited quantitative evidence to guide how specific device features influence children's movement and postural experiences.

A growing body of work suggests that mobility aids can influence children's posture, movement patterns, and opportunities for exploration. For example, a case study of a young child with Down syndrome using an open-area partial-bodyweight support (PBWS) system demonstrated increasing distances traveled with PBWS over time [172]. Similarly, studies of a commercially-available powered mobility device for young children, the Permobil Explorer Mini, have shown increases in distance traveled across sessions [108]. The Explorer Mini also supports multiple seating configurations, and work with this device has shown that taller seat heights with more extended legs, increase muscle activations and alter joystick activation relative to lower seat heights [109]. Consistent with these findings, randomized controlled trials by Huang and colleagues indicate that modified ride-on cars, particularly using standing postures, can enhance mobility skills, social function, and mastery motivation in toddlers with motor delays [191, 192]. A complementary case study reported increased peer interaction when a child used a standing-enabled modified ride-on car compared to their typical mobility aid [101]. Despite this growing literature, prior work has largely focused on individual devices and often relied on case studies or single-group designs. As a result, it remains unclear how young children's movement patterns differ across types of mobility aids and how engagement with these devices compare to not using a mobility aid.

The purpose of this study was to quantify changes in children's movement patterns and biomechanics across four mobility conditions: unassisted mobility (UA), PBWS, and the use of a powered mobility device with a static seat (PMD-static) and dynamic seat (PMD-dynamic). Our primary objectives were to evaluate how each mobility condition influenced children's movement patterns and muscle activity. We hypothesized that area explored would be greatest during PMD use, regardless of seating configuration, and lowest during UA. We also hypothesized that muscle activity would increase when using either mobility aid compared to UA. We assessed differences in posture across mobility conditions and caregiver-reported differences in device usability, appropriateness, and feasibility.

6.2 Methods

6.2.1 Study Design

This within-subject study included four mobility conditions: UA,PBWS, PMD-static, and PMD-dynamic. Condition order was randomized and counterbalanced using a Latin square design. Procedures were approved by the University of Washington Institutional Review Board (STUDY00018915) and caregivers provided written informed consent. The study was registered on clinicaltrials.gov (NCT06591559).

6.2.2 Participants

Participants were recruited via flyers and emails to clinical networks, previous research participants, community organizations, and social media. Children were eligible if they (1) had a condition affecting movement and muscle tone and were (2) 5 years of age or younger, (3) 35 lbs or less in weight, (4) 39 inches tall or shorter, (5) able to sit independently, and (6) not yet independently walking. Caregivers had to be at least 18 years old and able to complete study procedures in English. Data collection occurred between January 2025 and March 2026.

6.2.3 Devices

Children used the Portable Mobility Aid for Children (PUMA; Enliten LLC, Delaware, USA), a commercially-available device providing passive PBWS during floor-based play. The system consists of a freestanding, tent-like aluminum frame with an overhead harness suspended via a pulley, enabling 360° movement within a 9 ft $\times$ 9 ft area. Weight support was set at 20-30% of bodyweight based on prior work [112, 171].
Children used the Permobil Explorer Mini, a U.S. Food and Drug Administration–cleared PMD operated

via a proportional joystick. In the PMD-static condition, children used the standard Explorer Mini seating system. For the PMD-dynamic condition, the Explorer Mini was adapted with a soft gait trainer seat (Drive Medical, Port Washington, NY) to provide support while increasing postural challenge.

6.2.4 Protocol

Caregiver-child dyads participated in five in-person sessions. Families received financial compensation, and children were given a developmentally appropriate toy. During the first session, informed consent was obtained, study procedures were reviewed, and caregivers completed a demographic questionnaire. Children were sized to the PBWS harness and PMD. Additionally, a trained pediatric physical therapist administered the Gross Motor Function Measure (GMFM-88) to measure children's baseline motor abilities. The GMFM-88 is a valid measure for children with Down syndrome [174] and cerebral palsy [193].

In each of the four subsequent sessions, children completed one mobility condition (UA, PBWS, PMD-static, or PMD-dynamic). Sessions consisted of approximately 30 minutes of free play in a playroom designed to encourage movement and exploration. Some sessions were shorter if the child became fatigued or fussy. Children played with caregivers and study staff using a variety of toys (e.g., sensory toys, cause-and-effect toys, musical instruments). The environment and toy placement were adapted to the child's abilities and the mobility condition to promote engagement and exploration. Breaks were provided as needed. To support biomechanical analyses across conditions, children did not wear lower-extremity orthoses during sessions unless caregivers requested that they remain on for safety or comfort; these instances were recorded as protocol deviations.

6.2.5 Outcome Measures

Movement patterns

All sessions were video recorded using four synchronized cameras (25 Hz, resolution: 1280 x 720). The position of neon-colored tape markers placed on the child's upper body and/or mobility aid were tracked using a custom-developed motion capture pipeline built on the AniposeLib framework [194]. Area explored was calculated by partitioning the play space into square regions (0.2 m $\times$ 0.2 m) and identifying cells with 5 cumulative seconds of occupancy, then normalizing by the observable space defined by camera calibration (room areas: 14.8 m^2 and 11.2 m^2). Trajectories were also segmented into movement bouts based on sustained displacement ($\geq$ 0.45 m over 5 s), with bouts <1 s or >6 m excluded. Outcome metrics included total distance traveled, number of movement bouts, and bout duration and distance.

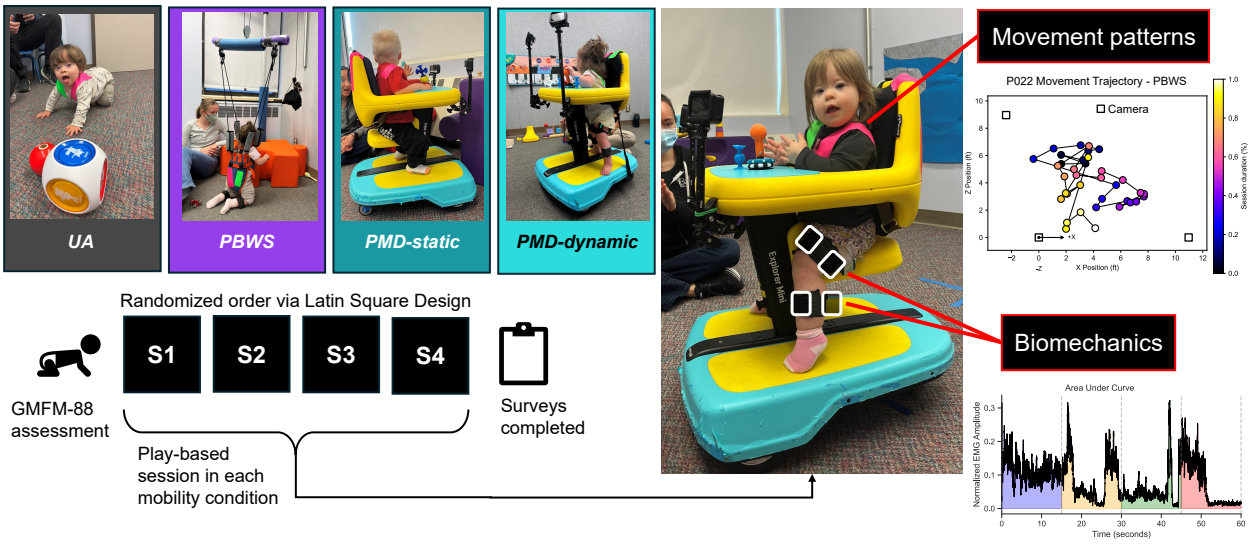

Figure 6.1: Children participated in four mobility conditions where the order was randomized across sessions. Movement patterns were tracked using motion capture, and wearable sensors measured muscle activity and body posture.

Muscle activity and body posture

Children wore wearable sensors (Delsys Inc, Natick, MA, USA) on the lower limbs and trunk that measured electromyography (EMG) activity and orientation using inertial measurement units (IMUs). Trigno Avanti sensors (sampling rate EMG 1778 Hz, sampling rate IMU: 74 Hz) were placed bilaterally on the biceps femoris (BF), quadriceps (QUAD), tibialis anterior (TA), and medial gastrocnemius (MGAS) following SENIAM guidelines [195]. Trigno Duo sensors (sampling rate EMG: 1926 Hz, sampling rate IMU: 74 Hz) were placed bilaterally on the cervical paraspinals (CERV) and erector spinae (ES), with IMUs positioned on the lower and upper trunk. Data were synchronized and annotated in real time, and periods of adult assisted mobility or signal artifact were excluded. TA and MGAS sensors were not placed on one participant (P18) because of serial casting. EMG data were unavailable for both EM sessions for one participant (P21) and for the EM-dynamic session only for another participant (P04).

EMG signals were bandpass filtered (4th order Butterworth filter, 20 – 450 Hz), rectified baseline-corrected using a 10-second calibration period, and normalized to the 95th percentile amplitude across sessions for each participant. EMG data were segmented into consecutive 15-second windows, and muscle activity was quantified using area under the curve (AUC). For each muscle and condition, the median AUC across windows was used as the summary outcome measure.

Time spent in standing posture was quantified as the proportion of time children maintained an upright body configuration using IMU-derived orientation estimates. For sensors providing quaternion orientation data, an initial reference orientation was established during supine calibration, when the sensor Z-axis was

approximately aligned with the global vertical direction. The sensor Z-axis, which was approximately aligned with the anatomical anterior-posterior direction and perpendicular to the segment's longitudinal axis, was transformed into the global coordinate frame. The inclination angle was subsequently quantified as the angle between the transformed sensor Z-axis and the global vertical direction, such that values near 0° corresponded to the supine calibration orientation and values approaching 90° indicated that the underlying body segment was oriented vertically. Sensors were classified as upright when the inclination angle was at least 60°. Due to kicking and other leg movements, standing posture was defined as the simultaneous upright classification of both shank sensors on the same leg, at least one thigh sensor on each leg, and at least one back sensor. When quaternion orientation data were unavailable, orientation was estimated from low-pass filtered accelerometer data using the gravity vector [196].

Caregiver-reported surveys

After all study visits, caregivers completed questionnaires administered via REDCap. Caregiver satisfaction with each mobility device was assessed using the eight technology-related items of the Quebec User Evaluation of Satisfaction with Assistive Technology, Children's Version 2.1 (QUEST) [197]. Caregivers also completed three validated implementation instruments: 1) the Acceptability of Intervention Measure (AIM), which assesses the perceived desirability of the device for their child; 2) the Intervention Appropriateness Measure (IAM), which assesses perceived fit or relevance of the device for their child; and 3) the Feasibility of Intervention Measure (FIM), which assesses the perceived practicality of using the device with their child in home and community settings [198]. For each instrument, a composite score was calculated by averaging item responses.

6.2.6 Statistical analysis

Differences in area explored and muscle activity across the four mobility conditions were assessed using Friedman tests for within-participant comparisons. When a Friedman test indicated a significant effect ($p < 0.05$), post-hoc pairwise comparisons were conducted using Wilcoxon signed-rank tests across conditions. A Holm–Šidák correction was applied to control for multiple comparisons. For each outcome, we report the Friedman test statistic and corresponding p-value. For significant post-hoc comparisons, we report the p-values. For EMG analyses, tests were conducted separately for each muscle group. Caregiver-reported survey scores were compared between the two devices using paired t-tests.

6.3 Results

Sixteen participants completed all study procedures (Table 6.1, Figure 6.2).Five children had Down syndrome, four had or were at high risk for cerebral palsy, five had other genetic disorders, one had a mitochondrial disorder, and one had spinal muscular atrophy type I. Mobility at study entry ranged from emerging independent sitting to crawling and brief independent standing, with GMFM-88 scores spanning 18.2 to 71.0 (Table 6.1).

Table 6.1: Participant demographics.

Participant	**Age (mo)**	**Gender**	**Diagnosis**	**Muscle tone**	GMFM-88	**Mobility**
P01	14	M	Down syndrome	Hypotonia	35.7	Sitting
P02	25	M	Down syndrome	Hypotonia	55.0	Cruising
P03	22	F	Down syndrome	Hypotonia	54.5	Crawling
P04	15	F	Down syndrome	Hypotonia	43.6	Cruising
P05	36	F	Cerebral palsy	Spastic	22.1	Rolling
P06	12	M	Genetic disorder	Hypotonia	19.8	Non-mobile
P07	17	F	At risk for CP	Hypotonia	52.6	Crawling
P08	17	F	At risk for CP	Hypotonia	50.5	Crawling
P11	50	F	Cerebral palsy	Spastic	42.0	Crawling
P14	25	F	Genetic disorder	Hypotonia	35.0	Sitting
P15	37	M	Genetic disorder	Hypotonia	44.9	Crawling
P17	30	F	Mitochondrial disorder	Hypertonic / spastic	43.7	Sitting
P18	24	F	Genetic disorder	Hypotonia	18.2	Sitting
P20	12	M	Spinal muscular atrophy type I	Hypotonia	27.9	Sitting
P21	18	M	Genetic disorder	Hypertonic	46.1	Crawling
P22	25	M	Down syndrome	Hypotonia	71.0	Standing

Summary: Age range: 12–50 months; gender distribution: 7 male / 9 female; GMFM-88 range: 18.2–71.0.
Abbreviations. GMFM: Gross Motor Function Measure (GMFM)-88.

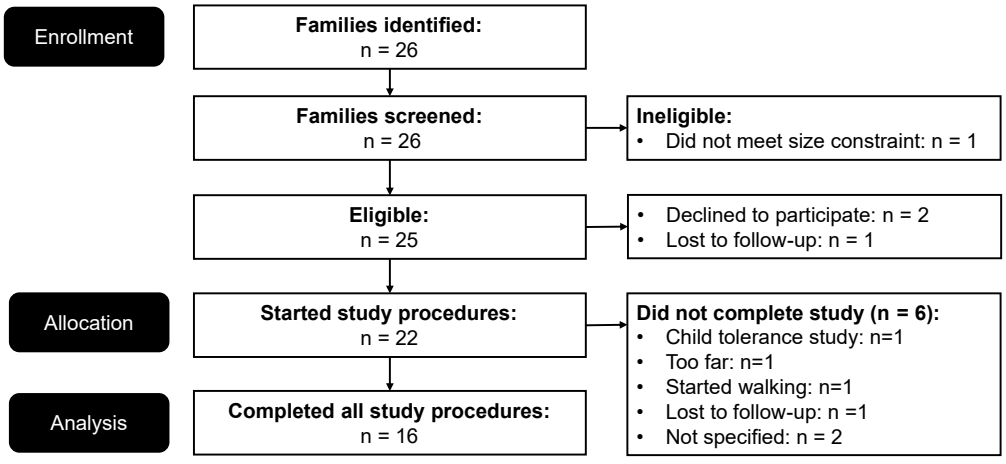

Figure 6.2: CONSORT diagram showing participant flow through study.

6.3.1 Movement patterns

Area explored was greater during PMD conditions than UA and PBWS (Friedman $\chi^2 = 15.9$, $p = 0.0012$; Figure 6.3, Table 6.2). Post-hoc tests indicated greater area explored in the PMD-dynamic condition compared to UA (p = 0.0003), PBWS (p = 0.0008), and PMD-static (p=0.0214). Area explored was also greater in the PMD-static condition than in PBWS (p = 0.0443), while differences between PMD-static and UA (p=0.0577) approached statistical significance. Most movement bouts were brief, with 82.6% lasting less than 5 seconds. The number of movement bouts was descriptively higher during the PMD conditions than during UA and PBWS (Table 6.2).

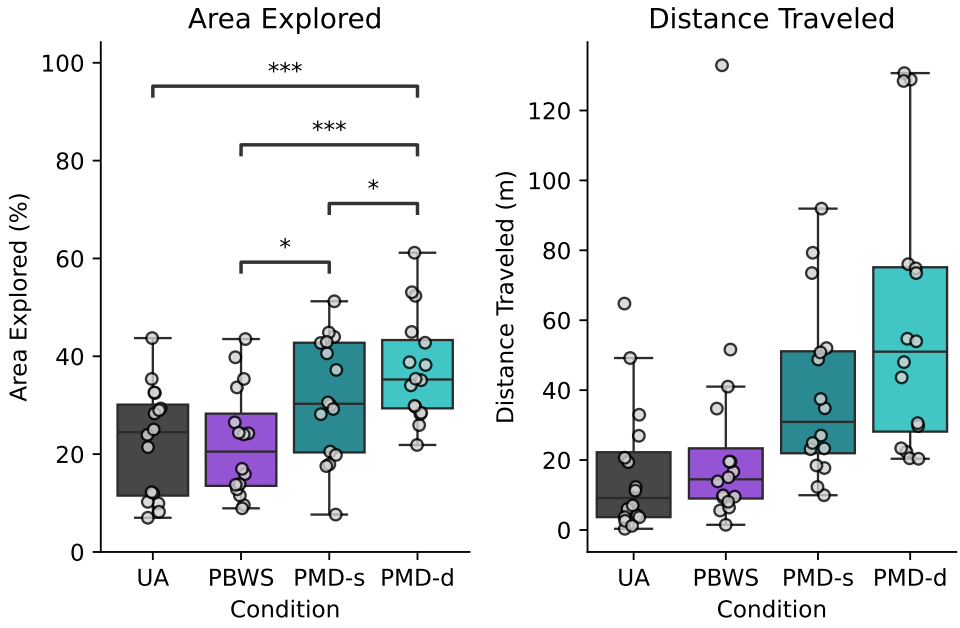

Figure 6.3: Boxplots show (a) the percentage of the room explored and (b) total distance traveled during each mobility condition. Percentage of area explored is normalized relative to the camera capture area. Significant differences are indicated by an asterisk (*).

6.3.2 Muscle activity

Muscle activity differed significantly across mobility conditions for the BF and QUAD muscle groups (Figure 6.4). Post-hoc pairwise comparisons indicated that BF activity during UA was significantly greater than during both PMD-static (p = 0.0006) and PMD-dynamic (p = 0.0203). In addition, BF activity during the PBWS condition was also significantly greater than during PMD-static (p = 0.0166) and PMD-dynamic (p = 0.0009). For the QUAD muscle group, UA elicited significantly greater activity than both PBWS (p

Table 6.2: Movement and biomechanical outcome measures across four mobility conditions, summarized as median (inter-quartile range).

Outcome Measure	**UA**	**PBWS**	**PMD-static**	**PMD-dynamic**	$\chi 2$	p
Movement outcomes						
Area explored (%)	24.5 (11.5–-30.1)	20.5 (13.5-–28.3)	30.3 (20.4-–42.8)	35.3 (29.4–-43.3)	15.9	0.0012
Total distance (m)	9.14 (3.67-–22.2)	14.5 (9–-23.4)	30.9 (21.9–-51.1)	51 (28.1–-75.2)		
Number of bouts	15 (4.5–-24.2)	19.5 (13.2–-31.8)	33 (24.8–-50.2)	47 (29–-62.2)		
Avg bout distance (m)	0.71 (0.54–-1.24)	0.78 (0.65–-0.95)	1.03 (0.82–-1.44)	1.03 (0.81–1.41)		
Avg bout duration (s)	3.66 (3.33–-4.65)	3.1 (2.43–-4.08)	3.26 (2.54–-3.98)	3 (2.74–-3.23)		
Max bout duration (s)	7.85 (5.25–-11.3)	6.68 (4.98-–10.2)	9.08 (7.73-–10.9)	8.93 (8.1–11.5)		
Muscle activity outcomes						
CERV	0.86 (0.21–1.1)	0.68 (0.21–2.75)	0.49 (0.39–1.14)	0.60 (0.07–1.26)	1.62	0.6559
ES	2.29 (0.64–3.44)	2.56 (1.3–2.92)	2.31 (1.9–2.87)	1.89 (0.57–2.37)	6.43	0.0925
QUAD	2.06 (1.3–3.16)	1.75 (1.11–2.27)	0.92 (0.57–1.5)	1.68 (1.13–2.49)	12.6	0.0056
BF	1.79 (0.64–3.0)	2.09 (1.24–2.85)	1.02 (0.66–1.74)	1.18 (0.78–1.61)	14.0	0.0029
MGAS	1.75 (1.46–2.78)	1.74 (1.41–2.24)	1.28 (1.03–1.91)	1.82 (1.24–2.1)	4.57	0.2062
TA	1.99 (1.69–2.98)	1.76 (1.37–2.53)	1.79 (1.4–2.15)	1.45 (1.23–1.75)	1.62	0.6559
Postural outcome						
Standing posture (%)	2.1 (0.6–8.8)	4.6 (0.5–7.1)	0.7 (0.0–8.3)	12.2 (1.5–19.0)		

= 0.0052) and PMD-static (p = 0.0023). QUAD activity was also greater during PBWS than PMD-static (p = 0.0353), and greater during PMD-dynamic than PMD-static (p = 0.0245). No statistically significant differences were observed across conditions for the TA, MGAS, ES, or CERV.

6.3.3 Body posture

Time spent in upright postures was highly variable across participants and generally limited across mobility conditions (Figure 6.5). Standing was not measured for one participant due to serial casting. Participant P22, who had the highest GMFM-88 score in the sample, spent the greatest proportion of session time upright (44.8%) during the PMD-dynamic condition. Across the four mobility conditions, the highest proportion of upright time occurred most frequently during PMD-dynamic (n = 9), followed by PBWS (n = 3) and UA (n = 2). The maximum proportion of time spent upright was 24.5% in UA, 16.7% in PBWS, 19.9% in PMD-static, and 44.8% in PMD-dynamic. More than 10% of session time upright was observed for two participants in UA, three in PBWS, three in PMD-static, and nine in PMD-dynamic.

Caregiver-reported surveys

QUEST ratings favored the PMD over the PBWS (Table 6.3, Figure 6.6). The largest item-level differences between devices were observed for device size, ease of moving the device, and setup time (Figure 6.7). Among respondents with complete data (n=12), composite QUEST scores were significantly lower for the PMD than the PBWS, indicating greater caregiver satisfaction with the PMD (Table 6.3). Both devices demonstrated

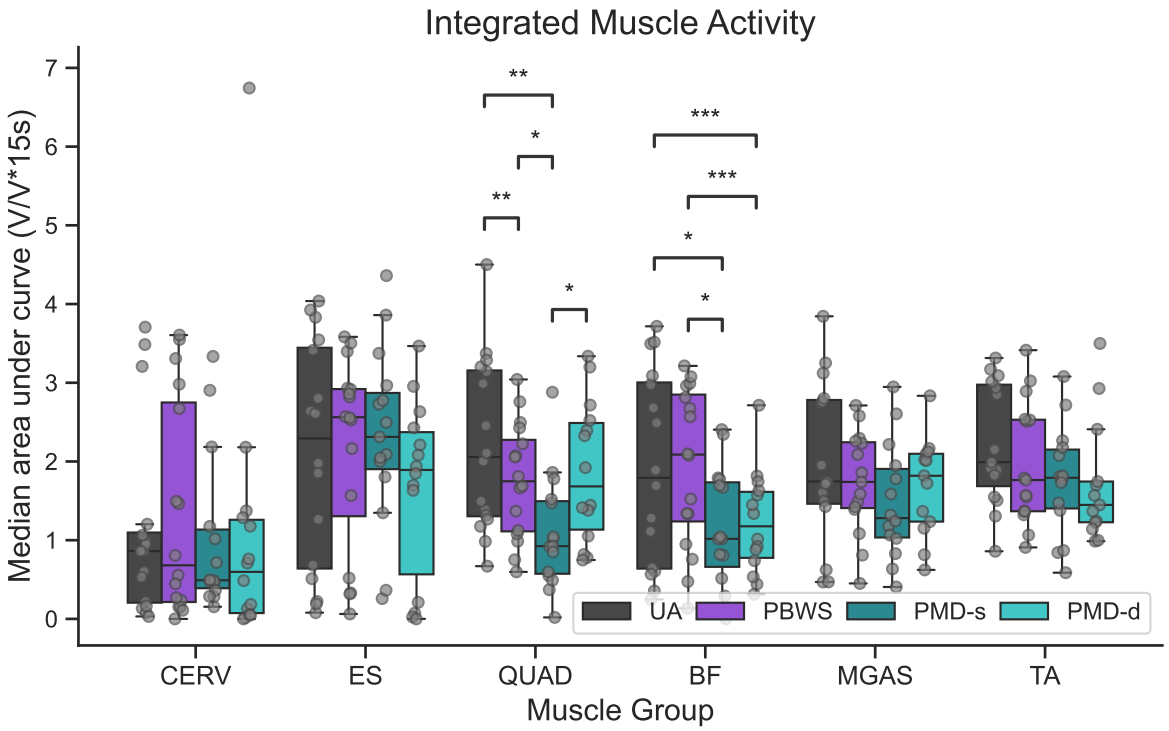

Figure 6.4: Boxplots show participant-level median area under the curve (AUC) values for each muscle group across mobility conditions. AUC was computed over 15-second windows, and median values are reported for each participant–condition–muscle combination. Muscle activity is normalized to the 95th-percentile maximum observed across all conditions. Significant differences are indicated by an asterisk (*). *PMD-static = PMD-s, PMD-dynamic = PMD-d*

high caregiver-reported acceptability and appropriateness, with no significant differences between them (Figure 6.6). Feasibility was higher for the PMD than PBWS ($p = 0.0044$), indicating that caregivers perceived the PMD as more feasible to use.

6.4 Discussion

This study examined how different mobility aids and configurations influence young children's movement patterns and biomechanics. Consistent with our initial hypothesis, use of a PMD enabled children to travel farther and engage in greater overall movement within the room compared to other mobility conditions. However, contrary to expectations, children explored a similar area during UA mobility and PBWS. Across all four mobility conditions, children demonstrated active muscle engagement, though muscle activity was lower during PMD use compared to UA and PBWS. As a secondary analysis, we found that children spent more time in upright postures during PMD-dynamic than during UA, supporting our initial hypothesis that mobility aid use promotes upright engagement. Finally, caregiver reports indicated high overall satisfaction

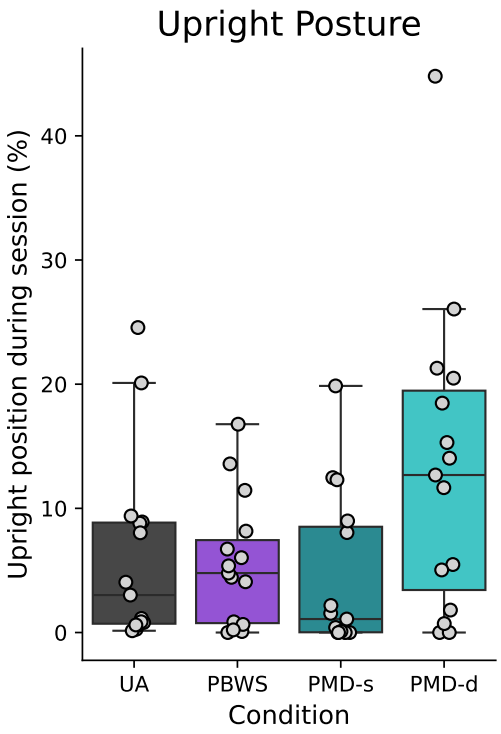

Figure 6.5: Boxplots showing the percentage of session spent in upright posture for each mobility condition. *PMD-static = PMD-s, PMD-dynamic = PMD-d*

for both devices, with higher scores for the PMD. While most caregivers considered both devices acceptable and appropriate for their child, PBWS was more frequently perceived as less feasible to use in practice.

During both UA and assisted mobility conditions, children actively moved throughout the playspace and engaged with toys and people. During UA, children spent an average of 3.9% of the session moving, which is slightly lower than the 6.8% of therapy sessions that young children with cerebral palsy spend [199]. However, this difference may be due to the requirement in Prosser et al. [199] that children be able to pull to stand. Prior work has also shown that powered mobility can increase children's self-initiated mobility. Butler [200] reported increases in independent, self-initiated position changes among six young children following powered wheelchair training relative to baseline independent mobility. These findings are consistent with the greater area explored and increased distance traveled observed in this study during PMD conditions compared to UA. However, independent mobility using the PMD may have continued to increase with additional experience, as prior work has shown progressive increases in children's locomotion across 12 sessions [108]. Movement patterns observed while children used the PBWS were consistent with prior studies. Two case studies indicate that children increased the distance traveled over successive PBWS sessions, with lower locomotion observed during initial exposure compared to later sessions [172, 182]. In

Table 6.3: Survey outcomes comparing powered mobility device and PBWS devices, summarized as mean (standard deviation).

Measure	PMD	PBWS	Independent samples t-test (p)
QUEST	2.28 (1.29)	3.64 (1.84)	0.0033*
AIM	4.32 (0.70)	4.07 (0.94)	0.3728
IAM	3.91 (0.96)	3.63 (1.02)	0.3894
FIM	4.32 (0.76)	3.25 (1.24)	0.0033*

AIM = Acceptability of intervention measure; IAM = Intervention appropriateness measure; FIM = Feasibility of intervention measure.

* Statistically significant at $p < 0.05$.

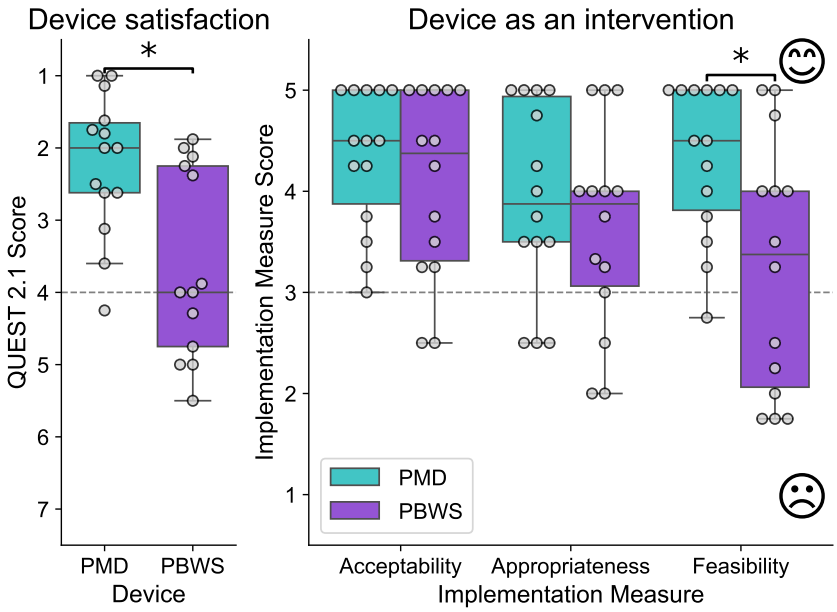

Figure 6.6: Caregivers' perceptions of the PMD and PBWS measured using (a) the QUEST and (b) implementation measures surveys. Lower QUEST scores indicate more positive perceptions, whereas higher implementation measure scores indicate more positive perceptions. Direction of positive and negative perceptions are shown by emoticon. Significant differences are indicated by an asterisk (*).

addition, another study reported substantial variability in distance traveled across PBWS sessions, ranging from approximately 10 to 50 m [113]. Together, these findings suggest that children may require multiple sessions to acclimate to the PBWS and to learn to sustain movement while using the system.

Muscle activity in the QUAD and BF was higher during PBWS and UA compared to PMD conditions. There were no significant differences between UA and PBWS, which contrasts with prior research showing that increasing bodyweight support reduces lower-limb muscle activity in nondisabled adults [201]. The level of unloading used (30%) in this study was less than prior work that showed larger reductions in muscle

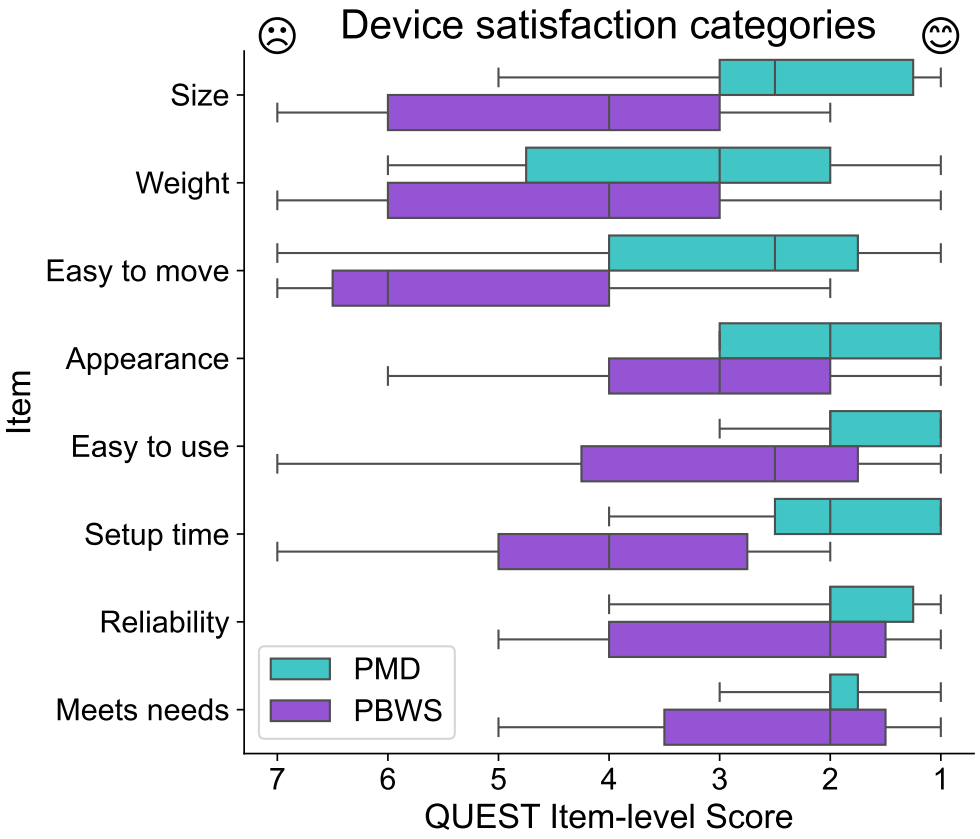

Figure 6.7: Caregivers' perceptions of the PMD and PBWS, assessed using item-level QUEST questionnaire scores. Scores range from 1 ("delighted") to 7 ("terrible"), which are represented by emoticons.

activity at unloading levels greater than 40% [171, 201, 202]. Consistent with our findings, a study of older children and adolescents walking in the Andago, a hands-free support walker, found that muscle activity in the hip abductors (gluteus medius) decreased significantly with increasing body-weight support, while activation of the plantarflexors (MGAS) and the quadriceps (vastus medialis) remained largely the same across unloading conditions [203]. While activation of the QUAD and BF was lower overall in PMD conditions compared to non-PMD conditions, QUAD muscle activity was nevertheless higher during PMD-dynamic than PMD-static, which indicates that device configuration can also impact muscle activation. Consistent with this finding, a previous case study by our group reported substantially greater QUAD activation during an unsupported standing posture in the Explorer Mini compared to a supported seated configuration [109]. Together, these findings suggest that while PMDs reduce overall lower-limb muscle demands, upright weight-bearing postures elicit greater muscle activation than seated configurations, particularly in muscles involved in postural support.

In this study, 78.6% of respondents reported composite QUEST scores indicative of high caregiver sat-

isfaction with the PMD, which exceeds child-reported satisfactions levels in a prior study in which only 50% of children reported high satisfaction with their PMD [84]. These differences may reflect variation in respondent perspectives, device type, and context of use. Scores for the PMD in this study were comparable to previously reported values in the literature, where devices were generally perceived favorably [104, 204]. Feldner et al. [104] reported higher AIM-IAM-FIM scores for the Explorer Mini than a modified ride-on car. Although prior work has reported highly favorable perceptions of open-area PBWS systems, including regarding ease of use, family experience, and feasibility [113, 115, 117], caregiver-reported surveys indicate reservations about the feasibility of home use, particularly related to device size. These concerns may reflect the use of the PBWS system in a clinical environment rather than in home or community contexts, as has been the case in prior studies [111, 114, 117, 172].

Several factors may have contributed to variability in outcomes. Children entered the study with differing prior experience with mobility devices, and each condition was assessed during a single session, which may not reflect performance with repeated use. In addition, variations in device setup (e.g., joystick toppers, adjustments to PBWS support) and participant dropout resulted in minor deviations from the intended balance across randomized conditions. Future work should examine learning trajectories and adaptation across repeated exposures. Technical limitations also influenced data quality. Variability in camera calibration and testing environments introduced inconsistencies in motion capture, and brief data loss occurred during high-frequency sensor collection.

The findings of this study suggest that mobility aids, depending on their design, configuration, and functional demands, may support different developmental priorities. Powered mobility devices enabled greater independent exploration, while unassisted and body-weight-supported mobility imposed higher neuromuscular demands, highlighting trade-offs between mobility and physical effort. Device configuration also influenced outcomes: the dynamic seat was associated with greater muscle activation and increased time spent upright compared to the static configuration, indicating that biomechanical demands can be adjusted to provide a "just-right challenge" without changing the underlying technology. Together, these findings suggest that mobility technologies may be most effective when selected and configured to align with specific goals and stages of learning. Clinically, these results support providing children with access to a range of mobility aids based on individuals goals, contexts, and developmental trajectory [3]. Caregiver responses further underscore the importance of considering feasibility and real-world use when selecting devices. Future longitudinal work is necessary to understand how experience, device configurations, and individual characteristics may shape mobility trajectories and inform more personalized, goal-directed clinical decision making.

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Chapter 7

"A PATH FORWARD": COMPARING FAMILIES' PERCEPTIONS OF MOBILITY AIDS FOR YOUNG CHILDREN WITH DEVELOPMENTAL DISABILITIES

Prepared for *Behavioral Sciences*

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Abstract

Caregivers' perceptions play a critical role in the selection and use of mobility aids for young children with developmental disabilities. This study examined caregivers' experiences with and perceptions of two mobility aids, a partial bodyweight support system (Portable Mobility Aid for Children, PUMA) and a powered mobility device (Permobil Explorer Mini), within the context of their overall experiences with mobility aids. Caregivers participated in interviews before (N = 21) and after (N = 15) a clinical trial evaluating children's initial interactions with these devices. Interviews were inductively coded and analyzed with the ON-Time Mobility framework used as a guiding analytic lens. Four themes emerged from caregiver interviews: 1) pressure to measure up to developmental expectations; 2) celebrating 'inchstones': growth and learning through mobility aids; 3) rightsizing devices and the realities of daily use; and 4) navigating new systems of care and access. Families were open to using mobility aids for their children while also balancing the path towards independent walking. Improving access to ON-Time mobility may require a broader range of device options, as well as systems that support affordability and short-term use, such as loan programs or shared community resources.

7.1 Introduction

The emergence of self-initiated mobility in early childhood supports a range of developmental outcomes, including language development, spatial understanding, problem-solving, and socioemotional engagement [2, 36, 205, 206, 207]. These developmental benefits occur with multiple forms of self-initiated mobility, including walking or wheeling [4, 104, 105]. Accordingly, clinical guidelines emphasize ON-Time mobility, access to self-initiated movement opportunities at developmentally-appropriate ages, to promote exploration, learning, and participation during periods of heightened neuroplasticity in early childhood [3].

Despite these guidelines, many young children with developmental disabilities have delayed access to self-initiated mobility. Children with Down syndrome typically begin walking one to two years later than their typically developing peers [25, 70, 71], while some children with cerebral palsy start walking in preschool or may use alternative forms of mobility [27, 56, 59]. Expectations surrounding walking readiness may shape whether mobility aids are introduced and which devices are considered appropriate, potentially limiting access to mobility opportunities for children with developmental delays [16, 66]. However, self-initiated mobility in any and all forms should be supported regardless of anticipated walking outcomes [3].Mobility aids such as gait trainers and partial bodyweight support (PBWS) systems can increase stability during overground movement and support gross motor development [18, 111, 112, 114]. Similarly, wheeled mobility devices, such as modified ride-on cars and other powered mobility devices, can support developmental growth across domains [91, 104, 105] and facilitate participation in play and social activities [94]. Thus, families of young children with developmental disabilities are often faced with decisions regarding multiple mobility options and interventions that differ in their functional goals, developmental implications, and day-to-day use [208, 209].

Disability is often experienced collectively within families of young children with disabilities [210, 211], and caregivers therefore play a central role in determining whether and how mobility aids are incorporated into their child's life. Caregiver perceptions, beliefs, and expectations influence whether devices are trialed, adopted, and integrated into daily routines [13, 20, 212]. These perspectives are shaped by factors such as concerns about safety, developmental appropriateness, independence, and family fit [13, 117, 135, 212]. However, they may also evolve through direct experience with mobility aids [213], interactions with early intervention professionals [212], and pervasive cultural narratives that link walking to independence and developmental success [214]. In addition to navigating decisions about mobility and development, caregivers of young children with disabilities frequently report elevated stress and poorer health relative to other families [215].

The purpose of this study was to understand caregivers' perceptions of different types of mobility aids for young children with developmental delays, with particular attention to a PBWS device and a powered

mobility device, and how caregivers evaluate these aids within the context of their broader beliefs and lived experiences. A substantial body of research has examined caregiver attitudes toward powered mobility for young children, documenting both initial hesitations and shifts toward more positive perceptions following direct experience [213, 216, 217], as well as evidence that powered mobility use may support caregiver well-being and reduce stress [98]. However, this literature has largely focused on powered mobility in isolation, even though families are often presented with multiple mobility options that serve different functional and developmental purposes. Far less is known about how caregivers perceive and compare different types of mobility aids, or how these perceptions evolve as families gain experience with multiple mobility options [209]. Understanding caregivers' perspectives can guide device selection and the development of family-centered interventions that promote self-initiated mobility, participation, and development across developmental stages.

7.2 Methods

7.2.1 Study Design

This study is part of an overarching, mixed-method clinical trial (NCT06591559) examining child outcomes and caregiver perceptions of two unique mobility aids, the Portable Mobility Aid for Children (PUMA, Enliten, LLC) and the Explorer Mini (Permobil, Inc) (Figure 7.1). This qualitative component used inductive thematic analysis of semi-structured interviews to explore caregivers perceptions' of mobility aids for young children with developmental delays. As part of the larger study, children participated in four randomized play-based mobility conditions: (1) PUMA, (2) Explorer Mini with a rigid seat, (3) Explorer Mini with a dynamic seat, and (4) no device (Figure 7.1). All study procedures were approved by the University of Washington Institutional Review Board (STUDY00018915).

The PUMA is a PBWS system that uses a soft fabric harness suspended from an overhead frame to provide passive support while allowing children to move freely in any direction. The Explorer Mini is a joystick-controlled powered mobility device. In this study, the Explorer Mini was used with either a standard rigid seat or a dynamic seat adapted from a gait trainer, allowing children to experience a range of postures and movement opportunities.

Before the pre-trial interview, children briefly interacted with both mobility aids and caregivers received information about their features and functions. Families were also offered an optional demonstration video. This initial exposure ensured that all caregivers had familiarity with both mobility aids prior to sharing their perspectives. Families then completed four play-based sessions in a randomized order, with children experiencing each mobility condition once (except P22, who repeated one condition due to illness). Child-directed

play was encouraged during the 30-minute session, with adults providing minimal hands-on assistance beyond safety support.

7.2.2 Participants

Participants were recruited using convenience sampling through emails to local clinics and community organizations, announcements on statewide listservs, and word of mouth. Children were eligible to participate if they (1) were 5 years of age or younger; (2) weighed 35 lbs or less, (3) were 39 inches tall or shorter, consistent with the manufacturer's size and weight indications for the Permobil Explorer Mini; (4) could sit or prop sit independently; (5) were not yet taking independent steps; and (6) had a diagnosed or suspected genetic or neuromuscular condition that impacted their movement and muscle tone. Caregivers were eligible if they (1) were the child's legal guardian, (2) were at least 18 years of age, and (3) could communicate proficiently in English during the interviews. Caregivers provided written informed consent for both their own and their child's participation. Families were compensated financially for their study participation, and children received a developmentally appropriate toy.

7.2.3 Positionality

The authors bring varied but complementary experience in pediatric rehabilitation and pediatric assistive technology, spanning rehabilitation engineering and pediatric physical therapy. Two members of the research team identify as disabled. We approach this work from a disability studies perspective that understands assistive technology as both an artifact and an enabler of participation. Throughout the analytic process, the research team engaged in reflexive discussions to consider how our professional and disability identities shaped interpretation of children's mobility experiences. In this study, we use the term *disability* based on children's documented diagnoses. We recognize, however, that the young children in this study, and their families, may use other terms such as developmental delay or may not identify with the label disabled as a political or personal identity.

7.2.4 Interviews

Interviews were conducted using a semi-structured interview guide (Table 7.1) following the intake and final play session. The interview guide was developed based on past responses of caregivers on mobility aid use for young children from this research team's previous studies [20, 77, 209, 213]. Interviews were conducted in person, except for four post-interviews completed via videocall, and ranged from 2 to 18 minutes. At

least one caregiver was involved in the interview, though up to three caregivers were involved. Although the protocol included both pre- and post-trial interviews, six families completed only the initial interview due to scheduling, child-specific, or other factors. All interviews, regardless of timing, were included in the qualitative dataset because they offered meaningful insight into caregivers' experiences and perspectives on early mobility aids.

Figure 7.1: The Portable Mobility Aid for Children (PUMA) and the Permobil Explorer Mini using the rigid seat and dynamic seat configurations.

Table 7.1: Semi-structured interview guide.

Pre-study	**Post-study**
• Tell me about your child and how they move around now. • What are your child's current mobility goals? • Have you had any conversations with your therapy team about using mobility aids with your child, even for a short period of time? • Why are you interested in participating in the mobility aids study? • Is there one device you are more interested in trialing? Why? • How do you think your child will react to using the [device]? • Do you have any concerns about using the [device]?	• Tell me about an experience during the study that made you excited. • Tell me about an experience during the study that made you frustrated. • How has this impacted your perception of your child's abilities? • What do you think are the benefits of the [device]? • What are the drawbacks of [device]? • What are your overall feelings about how mobility aids like these fit or don't fit into your child's participation and family life? • Which of the devices did you prefer? Why? • Which of the devices did your child prefer? Why? • Can you please describe your home, and how mobility aids may or may not fit?

7.2.5 Analysis

We conducted an inductive thematic analysis informed by the ON-Time mobility framework [3]. Although interviews initially focused on caregivers' perceptions of two mobility aids, caregivers consistently situated these devices within a wider landscape of mobility, including other mobility aids (e.g., walkers, gait trainers) and non-device forms of movement (e.g., crawling and cruising). In response, analysis expanded inductively to examine how caregivers understood mobility aids as part of a multi-modal, evolving approach to their child's mobility and development, consistent with the ON Time framework's emphasis on self-initiated mobility across modalities.

Interviews were audio-recorded, transcribed verbatim by AK and a professional service, deidentified, and managed using Microsoft Excel and Figma. The first two au-thors (MH, AK) independently coded each transcript, with secondary review by the senior author (HF). Analysis began with open coding using a phrase-by-phrase approach, and progress to focused codes representing recurring patterns across interviews (Table 2). Codes were iteratively refined and organized into themes using visual mind mapping, analytic memoing, and regular team discussions. Discrepancies were resolved through consensus. To ensure trustworthiness and credibility, a summary of themes and de-scriptors was shared with participants for feedback via member checking. Leaders of a local organization which serves people with intellectual and developmental disabilities, who were involved in recruitment and eligibility discussions, were invited to review the themes as an external stakeholder check. Reporting followed the SRQR guidelines [218].

Table 7.2: Example of coding process from caregiver quote (L) to the developed themes (R).

Quote	**Open Coding**	**Focused coding**	**Theme**
"I'd like her to not have to use anything [mobility aids]. I'd like her to be able to just **be independent as much as possible.** I recognize that that's probably not going to happen, but maybe she can be one of those people who can **walk a little bit and then just need something else to help**, but as much as possible because she has a lot of spunk. And I don't want to be the person that has to **hold her back.**" *P11, Pre*	mobility aids not needed, independence, mobility aids holding child back, unassisted	building independence; assistance vs reliance; caregiver feelings; walking, walking, walking	Pressure to measure up to developmental expectations
"I have to say, I really liked just how the mobility aids just helped P20 **explore his environment more**. Because he really wants to go around, and he asks us to give him toys and stuff like that. But he's unable to move his body that way, and so he gets frustrated sometimes. So it was nice seeing him be able to have that **freedom to play more**. And he was just **happy** about it, for sure. He was really **pleased that he was able to move himself** without having us help him, and get what he wanted and stuff. So that was really cool to see." *P20,Post*	mobility aids enabling independent mobility, self-initiated mobility, freedom with mobility aids, joy, frustration with current mobility, participation	towards self-initiated mobility, motivators and hinderers to move, autonomy, movement is fun	Celebrating "inchstones": Growth and learning through mobility aids
"I wish I could have **all the devices at home** so we can rotate in between them, mix it up, because again, at home, we kind of just do the same things. We have a stander, but it's not powered mobility. It's like, yeah, I got to push her with the stander. And even the gait trainer, it's like that's too advanced for her. So between the stander and the gait trainer, **there's nothing in between to help her move a bit.** And get the motion in. Because I'm like, OK, let's practice crawling, but it's like, either I gotta lift her and get her legs moving. **There's no in-between.** So I wish I could have all of it at home." *P14, Post*	multi-modal mobility, need for mobility aid options, device mismatch, in-between mobility aid	multi-modal mobility, getting first mobility aids, finding the just-right-device	Rightsizing and the realities of daily use
"I think that we're very **open to trying out different devices**, in addition to just letting him explore his body and on his own to build crawling. But I think with mobility devices like this, there's an accessibility aspect, not only if **it's $1,000 or whatever**, but also, accessibility in terms of **practicality**, I don't want to haul this heavy piece of equipment that's cumbersome to have – **we've got a million things on the plate already**. So whatever we add in, on top of many other therapies and other things we're working on, it doesn't even cover it." *P21, Post*	open to mobility aids, cost, weight, bandwidth of caregiver, multi-modal mobility	spectrum of "readiness", insurance & cost, feasibility	Navigating new systems of care and access

7.3 Results

Twenty-one families participated in the pre-interview, and fifteen families completed post-interviews (Table 7.3). One family had two children who participated in the study, and completed both interviews. Children were between 12 and 50 months old and ranged from not yet independently moving to taking supported steps (Table 7.4). Children's use of and exposure to mobility aids varied widely. Five children had no prior experience using mobility aids, whereas nine children had extensive experiences with devices such as standers, gait trainers, manual wheelchairs, and powered mobility. Children had a range of developmental and medical diagnoses that impacted their muscle tone and mobility, including Down syndrome, cerebral palsy, and genetic disorders (Table 7.4). The majority of interviews were conducted with a single caregiver (Table 7.3).

Table 7.3: Caregiver demographics.

Characteristic	Frequency (n)
Interview participant – pre (n = 21)	
Mother	14
Mother & Father	5
Primary caregiver (other)	2
Interview participant – post (n = 15)	
Mother	8
Father	1
Mother & Father	4
Mother & Grandparents	1
Primary caregiver (other)	1
Household income range	
$\leq$ \$49 k	3
\$50–74 k	1
\$75–99 k	3
$\geq$ \$100 k	14
Employment status	
Not employed	12
Part-time	6
Full-time	6
Highest level of education	
High school	2
Some college	2
Associate degree	1
Bachelor's degree	9
Graduate degree	6
Not specified	2
Ethnicity / race	
Caucasian	13
Asian	3
African American	1
Mixed	1
Not specified	3
Hispanic ethnicity	
Yes	2
No	18
Not specified	1

Table 7.4: Child demographics.

Characteristic	Frequency (n)
Age	
12–17 months	7
18–23 months	4
24–29 months	7
30–35 months	1
36 months and older	2
Diagnosis	
Down syndrome	6
Cerebral palsy	3
At risk for cerebral palsy	3
Autism spectrum disorder	2
Cardiofaciocutaneous (CFC) syndrome	1
Charcot Tooth Marie disease	1
Genetic duplication (2q)	1
Joubert syndrome	1
KAT6A syndrome	1
SCN2A-related disorder	1
Spinal muscular atrophy type I	1
Stroke	1
TRIT1 deficiency	1
TUBB3-related tubulinopathy	1
Current mobility	
Nonmobile	1
Rolling	2
Sitting	8
Crawling	6
Standing	2
Cruising	3
Use of mobility aids	
Lower-limb orthotics	12
Gait trainer or walker	8
Manual wheelchair	3
Powered mobility experience	7

1

Four themes emerged from the data: 1) “Pressure to measure up to developmental expectations”, 2) “Celebrating ‘inchstones’: Growth and learning through mobility aids”, 3)“Rightsizing and the realities of daily use”, and 4) “Navigating new systems of care and access” (Table 7.5).

Table 7.5: Summary of themes.

Theme	Definition
Pressure to measure up to developmental expectations	The emotional and social tension families experience as they navigate norms around "typical" motor development and independence, guided by a desire to support mobility and maximize their child's potential.
Celebrating "inchstones": Growth and learning through mobility aids	Families' experiences of how mobility aids foster confidence, participation, and joy, alongside the developmental learning involved as children acquire new mobility skills.
Rightsizing and the realities of daily use	Families' considerations of how mobility aids fit their child's sensory, physical, and environmental needs, and the practical adjustments required to integrate devices into daily routines and spaces.
Navigating new systems of care and access	The process by which families learn about, access, and navigate complex systems to obtain and trial mobility aids, shaped by their resources, openness to their child using a mobility aid, and readiness for action.

Table 7.6: Quotes from families.

Index	Quote	Interview
Theme: Pressure to measure up to developmental expectations		
Q1	"A path forward to getting caught up. I mean, we're super proud of the progress they've made. But they're behind their 'peers,' quote, unquote, babies that are younger than them. So we have several yardsticks that we in our lives to compare them to."	P07/P08 - Pre
Q2	"My big goal participating in this study was trying to see if some of these help towards our goal of walking. But I don't know if– with P12, if you give her the support, she'll take it. So I'm seeing that there is a lot of support available in Explorer Mini. So I don't know if that's going to encourage her to stand and walk. I think she'll probably sit in it."	P12 - Pre
Q3	"I think since we have gait trainers, I think for us, maybe something like the PUMA would help create an environment where P17 would be able to use more lower extremities more often if we were to pick between the two. But I think they're very different modalities. I think because P17 is in a space where she is strong and she's developing her balance and her overall mobility, for her, something like the PUMA will help her get to make momentum in that direction. If at one point, P17 wasn't so mobile, I think the little zippy, 'wheelchair' would be great to be able to get her around. I think they both have their space, and they both do very different things."	P17 - Post

Index	Quote	Interview
Q4	"For the longest time, he just wasn't interested in moving. So it was really hard to gauge what his capabilities were. So that's where the Explorer Mini really came in handy when we had it, kind of. I don't think it really clicked with him. But it was a way for him to realize he could move himself. And since then, like when he started crawling, we stopped using Explorer Mini because crawling is a better developmental skill."	P15 - Pre
Q5	"Well, the Explorer Mini was less work, so I think he probably preferred the Explorer Mini."	P15 - Post
Celebrating "inchstones": Growth and learning through mobility aids		
Q6	"I feel like when he's shown that he can move and given those opportunities, I do feel like it sparks and motivates him to want to move more. Because I feel whether it's with a gait trainer that we started trying at home or letting him practice like cruising or with these mobility devices, I feel like it's sparked something in him to be like, oh, I want to move my body. I experienced movement and wanting to move a bit more."	P21 - Post
Q7	"She'll be in the gait trainer, but not really want to move away from me or anything. And on Monday night, we were at the tot services for Rosh Hashanah. And all the kids were running around, being little kids. And all of a sudden, she takes off. At first, it's slowly, slowly, gone. And she was all over the place, up in the aisle, and whatever other kids– it was amazing. It was like, everybody was– some of us were watching the services or listening. And some of us were just going, yay. Yeah. So I think the main goal for her is to be able to be as independent as possible."	P11 - Pre
Q8	"We got that mini wheelchair for him. And it's really helpful, because we put him on the floor and then he has his own way of scooting by pushing his arms back to get places. But he can't go very far, and it takes a long time. So it's just really important for him to also have autonomy of doing what he wants, because most kids his age would just crawl places and he can't do that. So I think the study has showed me how important it is to give him devices like this as he's growing, to develop other skills. It's not like it's preventing him from learning crawling or walking. But for some part of the day, you can give him a chance to roam around himself, too, in conjunction with other exercises. A little bit of both."	P20 - Post
Q9	"As much independence as possible. That's pretty much it. And then what she what she wants to do is what we want. So if she wants to use her gait trainer, we'll use her gait trainer. If she wants to use her wheelchair, we'll use her wheelchair."	P05 - Post

Index	Quote	Interview
Q10	"I think that thing (PUMA) was awesome… I thought that thing was pretty cool, just 'cause you could see her standing on her own. Whereas you know at home it's always she's either holding one of our hands, or holding on to something. Whereas with that she could like, hold herself up a lot better."	P04 - Post
Rightsizing and the realities of daily use		
Q11	"Like, there's some time that it's going to take to get used to how the straps feel, because it seems– clunky is not the right word, but it just felt like there's take some time to get used to the weights and the balancing and how everything feels and for them how it feels."	P07/P08 - Post
Q12	"And then, I love that Explorer Mini. I wish we had had that. I wish I had heard about it last year when she was just a little bit smaller, so she can– you just even learn that joystick, how to go. And then we have been trialing at PT powered wheelchairs, but they're huge. So– –it's like we gotta just kind of strap her in there, and it's kind of iffy on the safety, but just to get that practice. So yeah, that Explorer Mini is perfect just to learn how to use the joystick in a safe way."	P14 - Post
Q13	"Our home is a little bit of a nightmare for mobility aids."	P05 - Post
Q14	"Well, I mean, the Explorer [Mini] can fit, but I don't know how the other one [PUMA] would fit in. [..] I don't know if that's going to work. But the Explorer mini would work in my little apartment, two bedroom apartment with my son and I and my daughter. And yeah, I think it'll work. The Explorer Mini got space for it."	P18 - Post
Q15	"Just because it's not something you could like, oh we're going to go to the grocery store, let's take the PUMA like [laughing] you know. You know, not as mobile I guess."	P02 - Post
Q16	"Um I mean I'm planning on making a PUMA in the basement. [laughs] So it's going to be an every night thing pretty shortly."	P01 - Post
Navigating new systems of care and access		
Q17	"Yeah. Again, P13's unique– his rare disorder. And my goal as his mom is to get him anything I can to help make his life better and help him reach all his goals and his fullest potential. And so if this can help with that and give me an idea of what we could be doing differently, or if we could introduce a different mobility aid, I'm all for it."	P13 - Pre
Q18	"We've kind of worked on getting that stander. But insurance giving us a hard time right now because some guy came to check it out while she's on it [...] Just to see if she's able to handle it. [..] So he said that she wasn't able to be on it for 10 minutes. [..] So that's why we're having a hard time getting that."	P18 - Pre

Index	Quote	Interview
Q19	"I think a lot of the time, they say it's [mobility aids] not medically necessary because, technically, some non-disabled babies their age still have a little bit of delay or aren't fully walking, but showing that—P16 has a lot of developmental delays in consequence of their not being able to be mobile on their own. And so showing that they make a lot of improvements and can be more social, and also have more play skills and things like that because they're able to be independent and be more in a upright position at eye level with other kids."	P16 - Pre
Q20	"We found a family in Wisconsin, actually, that had one [Explorer Mini] that their child outgrew, and they were selling it. And we were able to have a family friend drive to Wisconsin and bring it all the way to us."	P16 - Pre
Q21	"And that's just understanding what [mobility aids] is around and available but also whether or not he'd be a good candidate for them. And at this point in time, his physical therapist didn't think that they were necessary even if they might be helpful."	P09 - Pre
Q22	"We're really lucky to be part of the Birth to three program. And so they've let us take things home. I will say, we just got our own gait trainer a week ago. So we're still ramping up there. But we had the– we were borrowing the Permobil from [clinic name]. And so everything he's tried in PT he's also been able to try at home, which has been awesome. But he definitely gets the focus and attention on it in his clinical environments."	P15 - Pre
Q23	"I think that if you had a facility that you could go to where you could go and do this stuff somewhere, it would be very beneficial to support kids who also are in early learning and support physical therapy programs like we are, because we were NICU kids. I don't know how much this stuff would cost, and it's hard to know sometimes if insurance would cover it. And also just the space perspective, I would see this– I have a hard time seeing families putting these products into their home. I think if there were like a center or a practice where you could go and utilize all this with professionals, I could see that being extremely beneficial, even once a week where you could go and have an hour's worth of time in both of them and have it like in conjunction with the physical therapy program."	P07/P08 - Post

7.3.1 Pressure to measure up to developmental expectations

Caregivers described balancing their desire to support their child's independence with concerns about making choices that might limit future possibilities. Although care-givers expressed pride in their child's progress, many also compared their child's development delays to peers or siblings (Table 7.6, Q1). Across interviews, walking was consistently described as a primary developmental goal and a motivating factor guiding therapy decisions and study participation (Table 7.6, Q2). This perspective shaped how caregivers evaluated mobility aids. Many caregivers preferred mobility aids that provided *assistance* without fostering *reliance*, while

encouraging emerging gross motor skills and contributing to the longer-term goal of independent walking (Table 7.6, Q2). Within this context, many caregivers viewed the PUMA favorably, describing it as offering "just enough" support to encourage active engagement and ongoing motor development (Table 7.6, Q3). In contrast, caregivers expressed greater uncertainty about how the Explorer Mini aligned with their long-term developmental goals. Some caregivers questioned whether it supported motor development or reduced opportunities for active, strength-building movement (Table 7.6, Q2).

Caregivers described mobility devices as existing within a developmental hierarchy, in which certain devices were viewed as more appropriate at specific stages of motor ability (Table 7.6, Q3). This tension between immediate mobility access and longer-term developmental priorities was exemplified by P15, who described how the Explorer Mini initially helped their child understand self-initiated mobility, but was discontinued once crawling emerged, as crawling was perceived as a "better developmental skill" (Table 7.6, Q4). Despite these concerns, caregivers reported that their children often preferred the Explorer Mini, as it required less physical effort and enabled faster or farther movement (Table 7.6, **??**).

7.3.2 Celebrating "inchstones": Growth and learning through mobility aids

Families described movement itself as inherently joyful for their child, and mobility aids were widely characterized as facilitators of self-initiated mobility and engagement with the world (Table 7.2). Several caregivers described how giving their child opportunities to move, across multiple modalities, sparked motivation and curiosity, encouraging them to want to move more (Table 7.6, Q6). For families who already used mobility aids, caregivers described moments of joy and pride as children engaged more fully with peers and their surroundings. One caregiver recounted watching their child independently navigate a gait trainer during Rosh Hashanah services, joining other children who were running through the space (Table 7.6, Q7).

Access to new devices were described as supporting autonomy, independence, and decision-making (Table 7.6, Q8), with some caregivers explicitly adopting child-led approaches to device use based on their child's interests and preferences (Table 7.6, Q9). One caregiver reflected that mobility aids provided opportunities for their child to roam independently for parts of the day, offering autonomy that would otherwise be inaccessible, while explicitly emphasizing that this access complemented, rather than hindered, ongoing gross motor development (Table 7.6, Q8). Caregivers also celebrated perceived gross motor gains associated with mobility aid use. Several described moments of first-time hands-free standing with the PUMA, highlighting how the device allowed children to support themselves more independently than they typically could at home (Table 7.6, Q10).

7.3.3 Rightsizing and the realities of daily use

Families emphasized that identifying the "just-right" required balancing their child's needs and abilities with the realities of daily routines and home environments (Table 7.2). A recurring theme was that adjusting to new mobility aids often took time, particularly when devices introduced unfamiliar sensations and environments. Several caregivers described how the PUMA's harness, weight distribution, and cords within the child's personal space initially felt confusing or overwhelming, requiring an adjustment period before children became comfortable using the device (Table 7.6, Q11). Beyond this adjustment period, caregivers described an iterative process of 'right-sizing' mobility devices for their children's functional abilities. One caregiver described how the size of the Explorer Mini felt safer and more appropriate for their child than a powered wheelchair they were trialing that they had to "just kind of strap her in" (Table 7.6, Q12). Other families described owning multiple devices, yet still feeling that none fully aligned with their child's needs or daily routines (Table 7.2). Rather than finding a single ideal device, caregivers described managing ongoing tradeoffs between support, safety, and usability.

Families also spoke at length about integrating mobility aids into real-world physical spaces, particularly within their homes. One caregiver described their home as a "nightmare for mobility aids", capturing the spatial constraints and stairs many families faced (Table 7.6, Q13). The Explorer Mini's smaller footprint was frequently viewed as better suited for apartments or crowded households (Table 7.6, Q14), though descriptions of home use often included rearranging furniture or child-proofing spaces. In contrast, the PUMA was frequently described as too large or cumbersome for daily home use, raising concerns about feasibility and frequency of use (Table 7.6, Q14). Portability emerged as a key consideration when evaluating mobility devices, as caregivers valued devices that could easily be incorporated into everyday outings and viewed the PUMA's limited portability as a barrier to routine use (Table 7.6, Q15). At the same time, other families expressed enthusiasm about making space for mobility devices at home, with one caregiver even describing plans to "make a PUMA in the basement" (Table 7.6, Q16). Overall, caregivers described device selection as an ongoing process of finding the best fit between the child's abilities, the family's routines, and the environments in which the device would be used.

7.3.4 Navigating new systems of care and access

Families entered the study with varying degrees of mobility aid "readiness", reflecting differences in how they considered, explored, and integrated mobility devices into their child's life. Some families were early in this process, while others were already trialing or using multiple mobility aids at home. Across readiness levels, caregivers expressed a strong desire to explore any option that might support their child's mobility

and independence. Many described advocating for access to orthotics, gait trainers, standers, wheelchairs, and other mobility devices, while remaining open to learning about new forms of support (Table 7.6, Q17). However, caregivers also described how openness to new mobility aids was shaped by practical and systemic constraints, including cost, physical burden, and competing demands (Table 7.2).

Families described the struggles faced obtaining and trialing mobility aids, many of which came down to insurance and cost. Insurance evaluation processes delayed or prevented access to mobility devices, including a case where coverage for a stander was denied because the child was determined unable to tolerate it for a sufficient duration (Table 7.6, Q18). In some cases, age-based developmental expectations limited access to equipment despite caregivers' perceptions that mobility limitations were likely to be lifelong (Table 7.6, Q19). When formal acquisition pathways failed, families pursued alternative strategies, including purchasing used equipment and coordinating transportation across multiple states to obtain it (Table 7.6, Q20).

Clinicians also played important roles in mobility aid access. Some families described providers who discouraged or delayed device use by questioning whether equipment was necessary (Table 7.6,Q21). In contrast, other families highlighted providers who facilitated access through equipment loans, trials, and integrating device use across clinic and home settings (Table 7.6,Q22).Given barriers related to cost, space, and uncertainty about long-term use, caregivers envisioned continued access through shared or clinic-based models rather than individual ownership. Families imagined community centers or clinical practices where children could engage with multiple mobility devices under professional guidance, supporting sustained learning without the logistical burden of fitting equipment into homes (Table 7.6, Q23). Overall, caregivers described mobility aid access as requiring not only awareness of available devices, but also the ability to navigate the systems that enabled or constrained access.

7.4 Discussion

Through conversations with caregivers of young children with developmental disabilities across the spectrum of mobility aid "readiness", we observed a tension as caregivers navigated providing on-time mobility opportunities for their child while simultaneously focusing on their child's development of walking. Caregivers celebrated small developmental gains, and described mobility aids as facilitators of growing independence, confidence, and motor skill development. At the same time, caregivers engaged in a continual process of "rightsizing" mobility aids to fit their child's abilities, their homes and lifestyles. Most families were new to navigating the landscape of disability, learning about available options while advocating for resources to support their child's development.

The ON Time Mobility framework highlights the importance of providing multimodal mobility opportu-

nities, ensuring that children have access to mobility at the same time as their peers while also supporting ongoing motor development [3]. Consistent with this framework, families in our study described a dual focus: they wanted to foster independence through mobility aids while still viewing walking as the primary and most socially valued motor milestone. This tension mirrors prior work documenting the cultural and clinical emphasis placed on walking, as well as caregiver's mixed feelings with mobility aids that may be perceived as alternatives to walking rather than complementary pathways to participation [3, 214, 219, 220]. Similar patterns have been noted across mobility interventions, with caregivers in pow-ered mobility trials expressing resistance to the devices even while acknowledging the benefits [213], while those involved in robotic gait trainer trials framed walking as central to their child's well-being and identity [221]. At the same time, a growing body of evidence demonstrates that using supportive mobility technologies to access mobility at the same time as peers promotes cognitive, social, and motor development for young children with developmental disabilities [72, 222].

Rightsizing involved the fit between the child, the device, and the daily environments in which mobility would occur [223]. Caregivers considered their child's sensory preferences, motor abilities, and tolerance for new sensations or movement patterns, describing reactions to donning the PBWS harness, experiencing new forms of movement, and unexpected sounds, as factors in determining whether a device felt "just right". These child-specific observations parallel findings from other mobility aid studies demonstrating that sensory processing and emerging motor skills influence how quickly children adjust to powered or supported mobility [7]. Caregivers often drew on their child's experience with infant positioning equipment to assess whether mobility aids provided an appropriate level of safety, support, and developmental fit, emphasizing the value of devices consistent with products families al-ready use [9, 11, 224]. The learning curve associated with new mobility aids was also discussed by families, particularly with powered mobility devices, as caregivers expressed concerns about the time required to learn joystick control and whether their child could effectively maneuver the device in tight spaces [20]. These concerns echo findings from earlier work showing that joystick-based control can be cognitively demanding for beginning users and may require substantial time to learn [7, 108, 109]. These concerns raise important questions about whether alternative control interfaces, such as weight-shifting platforms like the WeeBot [225, 226], may offer more intuitive access for young learners.

Ease of integration into daily routines and their home environment was also central to families' evaluations of devices. Families valued portability, including a small footprint that would not limit their child's interaction with the environment and a lightweight design that could be transported between floors of the home and community settings. Caregivers in the present study expressed concerns about the PUMA that were similar to those reported previously, with many describing the device as too large or cumbersome and

suggesting a need for either a smaller frame or a larger supported walking area depending on their child's needs [117]. Although devices were trialed in a controlled setting, families also considered how they would function within real-world environments, raising concerns about navigating stairs, uneven surfaces, and other features of the built environment. These findings align with prior work showing that environmental constraints remain a pervasive challenge for families of young children with motor disabilities, limiting mobility aid use in homes and community spaces [12, 13, 15, 19, 20, 227].

Families' experiences navigating mobility aids are shaped not only by the devices themselves, but by the broader systems through which access is granted. Caregivers described clinicians as critical gatekeepers, functioning as either enablers or disablers within the mobility aid landscape. Some families encountered professionals who discouraged mobility aid use or suggested that devices were unnecessary, practices that have been previously documented in the literature [211, 228]. Others described early intervention providers who actively facilitated access, shared knowledge about mobility aids, or provided equipment loans, reflecting the enabling practices of providers [229]. Beyond provider practices, families also encountered systemic barriers related to cost and insurance coverage, with funding requirements and approval processes often limiting timely access to mobility aids. Structured trial opportunities, such as those documented during Powered Mobility Days, can help inform proper selection of a device [135, 230]. Across interviews, families in our study expressed a clear desire for ongoing access to mobility aids, even when their long-term goal remained walking. Many saw mobility aids as supporting participation, exploration, and motor learning during a transitional period. These perspectives indicate a need for early intervention systems to incorporate mobility aid access more intentionally. Integrating trial opportunities and mobility aid related goals directly into Individualized Family Service Plans may help ensure that children receive on-time access to mobility aids aligned with developmental frameworks [3]. Addressing provider, funding, and policy barriers will be critical to ensuring that access to mobility aids is determined by children's developmental needs rather than by the systems through which families must navigate.

7.4.1 Limitations and Future directions

One limitation of this research was that families used the mobility devices for a single session each in a controlled research setting, with equipment set up and adjustment completed by the study team. This may limit the generalizability of the findings, as families did not interact with the devices in their natural home environments; the study experience may therefore have been more akin to trialing equipment in a clinical or home setting. Adjusting to both the study environment and novel devices simultaneously may have impacted children's reactions to the devices and caregivers' subsequent perceptions. Additionally, multiple children had prior exposure to the Explorer Mini through home use, therapy sessions, or school, whereas none had

previous experience with the PUMA. These differing levels of familiarity may have influenced children's comfort and learning, as well as families' perceptions of the devices. Six families did not complete study procedures, resulting in different sample sizes for the pre- and post- interviews, which may have shaped the range of perspectives captured. Participation requirements may have introduced selection bias. The time commitment associated with traveling to five data collection sessions may have posed a burden for busy families and restricted participation to those with greater schedule flexibility or access to personal transportation. Additionally, requiring English proficiency may have excluded families who speak other languages, particularly given that some conditions represented in the sample, such as Down syndrome, are more prevalent in Hispanic communities.

The results of this study suggest that families are eager to access mobility aids for their young children, recognizing these devices as valuable supports for exploration and independence across a range of mobility trajectories. However, this work also highlights critical systemic gaps related to how families access mobility devices, including limitations within insurance pathways and a lack of short-term trial opportunities. Future re-search should explore partnerships with local early intervention systems, community centers, or library-based lending programs to provide time-limited access to mobility aids, allowing families to trial devices in everyday contexts. Families also emphasized a need for lightweight, multimodal mobility aids that can fit within typical home environments without requiring dedicated storage or extensive setup. Design-focused re-search should build on these priorities by engaging families through co-design approaches to develop mobility devices that can transition alongside children as their skills evolve and adapt across multiple environments, including home, classroom, and outdoor settings, to support peer participation. Additionally, future longitudinal studies should examine how specific device characteristics, such as size, control interfaces, configurability, and setup demands, influence learning curves for both children and caregivers. Understanding how device design affects ease of learning and engagement could inform strategies to reduce initial barriers to use and improve early adoption, particularly for families seeking short-term or transitional mobility solutions.

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Chapter 8

CONCLUSION AND FUTURE WORK

8.1 Summary

The emergence of self-initiated mobility supports a child's independence and learning, contributing to growth across multiple developmental domains [2]. For young children with disabilities, mobility aids can reduce barriers to independent mobility, enabling age-appropriate opportunities for exploration [3, 4]. Accordingly, this dissertation aimed to use an engineering lens to understand how the environment of use, type, and design of mobility aids impacts self-initiated mobility and engagement for young children with developmental disabilities.

One objective of this dissertation was to measure children's use of mobility aids in community and clinical settings. Chapter 3 reported on an observational study of 14 children with developmental disabilities using modified ride-on cars (mROC) for a year in a natural setting, where use was measured with integrated dataloggers and geospatial tracking. The results of this study showed that children engaged with the mROC for longer durations and traveled further distances when using the mROC outside compared to inside their home. Chapter 4 built on this work by comparing the use of two powered mobility devices by 12 children with cerebral palsy for 8 weeks each in a natural setting, as part of a larger clinical trial [156]. The findings from this study indicated that usage was similar between devices, though the Explorer Mini usage duration was higher than the mROC. Chapter 6 measured movement patterns of 16 children with developmental disabilities across four mobility conditions, and found that children traveled farther distances when using the Explorer Mini compared to both bodyweight-supported mobility and unassisted mobility. These are some of the first studies to quantitatively measure mobility by children with disabilities, offering comparable metrics to those reported in the literature on infant development for typically developing children.

Though a growing body of evidence emphasizes the importance of ON-Time mobility through mobility aids, many providers are still under-utilizing powered mobility in their clinical practice [16]. Additionally, multiple qualitative studies have indicated that caregivers are hesitant around powered mobility usedue to concerns about motor development as well as societal stigma surrounding powered mobility [213, 231]. As such, an objective of this dissertation was to show how mobility aids benefit children's motor development.

Chapter 5 measured children's physical activity levels and time in upright postures during play with and without bodyweight-support. Results showed that children increased their time upright while playing with bodyweight support compared to unassisted play. Similarly, Chapter 6 showed that children spent more time in upright postures when using a powered mobility device in a configuration that enabled standing than during unassisted mobility. This study also showed that muscle activity was similar between bodyweight-supported play and unassisted play. Together, these results provide evidence that mobility aids do not hinder motor development, and instead, may enable increased opportunities to practice motor skills while engaging in play-based activities that are critical for development [45].

Use of devices is not the only critical factor to consider, but also where devices are used and how they are accessed. Chapter 3 leveraged data from Project Sidewalk, an open-source accessibility mapping tool, to show that mROCs were used significantly more in areas with accessible sidewalks and that were pedestrian-friendly. These findings demonstrate that the utility of mobility aids, even for young children, is dependent on accessible infrastructure. Through interviews reported on in Chapter 7, caregivers similarly advocated for accessible environments as they considered how they might incorporate mobility aids into their homes and lifestyles. The results from this study showed that the majority of families are open to mobility aids for their child, but need systems that support device access through insurance, loan programs, or community playgroups. These findings point to the need for policy changes that support access to mobility aids for young children with disabilities and accessibility of environments that support safe learning and exploration for new mobility aids users.

This dissertation integrates perspectives from engineering, rehabilitation medicine, and disability studies, with engineering methods serving as a bridge between clinical questions and measurable, real-world outcomes. Through the development and application of wearable, integrated, and geospatial sensing systems, this research demonstrates how engineering approaches can capture not only how much children use mobility aids, but where and what use looks like. One contribution of this work is the introduction of geospatial analysis to the study of young children's mobility aid use (Chapter 3), enabling observation of movement in natural environments. Building on this, Chapter 4 situates emerging quantitative sensing systems within the broader literature by directly comparing integrated loggers, geospatial trackers, and caregiver-reported measures. While the quantitative systems showed strong agreement across objective metrics, caregiver reports offered complementary qualitative insights, such as periods of engagement without active movement, highlighting the value of mixed-methods approaches for understanding how children adapt to and learn to use mobility devices over time. This dissertation also extends prior work by applying wearable sensors to capture young children's posture across different mobility aids (Chapters 5 and 6), a metric that has primarily been measured through behavioral observation in pediatric populations. Finally, to enable consistent measurement of children's

movement across multiple mobility conditions, including unassisted movement, Chapter 6 introduced a machine-learning–based motion capture system that combines object detection and tracking with a minimal camera setup. Designed for flexibility and use across multiple rooms, the system reduces the technical barriers that often limit motion capture in clinical settings, which may make it easier to observe children's device use in rehabilitation research and practice. The methodology employed in this dissertation demonstrates how engineering can be combined with clinical practice to better understand how children are adapting to rehabilitation practices and assistive technology.

8.2 Future Work

This dissertation brings an interdisciplinary lens to the study of how assistive technology can support mobility for young children with developmental disabilities. While this work examines three specific mobility aids in depth, it represents only a small subset of the wide range of devices currently available, with additional technologies continuing to emerge. The following section outlines potential directions for future research that build on the findings from this dissertation and extend them to broader questions of design, access, and everyday use.

8.2.1 Co-Designing next-generation mobility aids with families

Mobility aids for young children have undergone substantial evolution, driven both by commercial innovation and by the creativity of families themselves. Devices such as the Permobil Explorer Mini can be viewed, in part, as a response to longstanding calls in the literature for more developmentally-appropriate mobility options for infants and toddlers with disabilities (e.g.,[11]). At the same time, families have long engaged in adapting, customizing, and inventing mobility solutions themselves, as seen in community-based efforts such as GoBabyGo, the Toddler Mobility Trainer, and semi-commercialized family-led designs like the GoBro. Together, these efforts highlight families as both end users and informal designers of mobility technology for their young children.

Despite this innovation, most research has focused on evaluating how children use existing devices rather than on systematically engaging families in the design of future technologies. Future design research should consider the use of co-design processes that actively involve caregivers and young children in defining mobility aid features, functions, and forms. Through these co-design processes, research could identify families' priorities in devices and how these differ from those emphasized by clinicians or manufacturers. These participatory design practices may also identify unmet needs, such as portability, adaptability across environments, or hybrid functionality. Co-design research has the potential to inform the development of mobility aids that

are more flexible, affordable, and aligned with children's daily routines and family priorities. By explicitly valuing families' lived experience and design expertise, this work could lead to more adoptable technologies and reduce device abandonment.

8.2.2 Impact of access to mobility aids in community settings

Findings from this dissertation suggest that where and how mobility aids are accessed matters for how children use them. Multiple caregivers in Chapter 6 described a desire for mobility opportunities in community settings rather than exclusively at home or in clinical environments. Prior work has begun to explore this possibility, including community-based facilitated play with partial bodyweight support [116] and inclusive playgroups using mROCs [232], demonstrating both feasibility and family interest in these models.

What remains less well understood is how repeated access to mobility aids in community environments influences children's movement behavior, control strategies, and participation over time, both within the community setting and beyond it. Community playgroups may uniquely support motivation, experimentation, and variability in mobility strategies through peer modeling, shared play goals, and exposure to novel environmental challenges. However, existing studies have largely focused on feasibility or immediate engagement, rather than systematic measurement of learning, adaptation, and longer-term change. Future research could address this gap through longitudinal designs that explicitly examine changes in mobility behavior across phases of baseline, community-based intervention, and follow-up. Such designs would allow investigators to quantify not only how children use mobility aids during community play sessions, but also whether and how these experiences carry over to the home environment, such as increased initiation of movement. In addition to measuring overall mobility and participation, future studies could track changes in the quality of movement and control, including emerging control complexity and intentionality. This research could provide evidence as to whether community-based mobility access acts as a transient enrichment activity or as a catalyst for sustained change, which would have important implications for clinical practice and program design.

8.2.3 Measuring multi-modal device use in the home environment

Children's everyday mobility experiences often involve navigating between multiple devices rather than relying on a single mobility aid. While this dissertation examined interactions with multiple devices, these observations were limited to single or short-term exposures and may not capture how children integrate different mobility aids into their daily routines over time. Much of the existing literature has similarly focused on the use of individual devices in isolation [19, 145, 233], providing valuable device-specific insights

but offering a limited view of mobility as it unfolds across a full day at home.

Families' lived experiences suggest a more complex reality, in which different devices serve different functional roles depending on context, activity, or time of day [33, 78]. Future research that explicitly examines multi-device mobility behavior in the home could characterize how children distribute movement across devices, how usage patterns change with experience or development, and how combinations of devices support participation more effectively than any single option alone. Integrating device-mounted sensing with caregiver-reported contextual data would enable researchers to capture both quantitative use patterns and the purposes those patterns serve. This line of work has the potential to inform clinical decision making and strengthen advocacy efforts with insurers by providing empirical evidence that access to multiple mobility aids is functionally important rather than redundant.

8.3 Impact

The overarching goal of this dissertation was to understand how young children use mobility aids to inform future designs and provide quantitative evidence to support advocacy for increased access to mobility aids for young children during this developmentally critical time period. Through the in-depth engineering analysis of how children interact with three different mobility aids, we have been able to demonstrate the importance of combining quantitative and qualitative metrics to understand the uptake and incorporation of mobility aids for young children with developmental disabilities. This research has laid the groundwork for future investigations into how young children with disabilities learn to use a range of assistive technology, including mobility aids.

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