Quantifying Joystick Interactions and Movement Patterns of Toddlers With Disabilities Using Powered Mobility With an Instrumented Explorer Mini

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***Abstract*— Powered mobility technology can be a powerful tool to facilitate self-initiated exploration and play for toddlers with motor disabilities. The joystick-controlled Permobil Explorer Mini is currently the only commercially available powered mobility device for children ages 1-3 years in the United States. However, many open questions persist regarding how joystick-based mobility technologies should be designed to optimally suit the developmental needs of toddlers. The purpose of this study was to quantify how toddlers with motor disabilities use the Explorer Mini during free exploration and play. For this work, we developed a custom-instrumented Explorer Mini with embedded sensors to measure joystick interactions and wheel rotations. Nine children with motor disabilities (ages 12-36 months) participated in 12 in-lab visits, and during each visit they engaged in two 15-20 minute play sessions. For each session, we calculated several quantitative outcome metrics, including the time spent using the joystick, distance traveled, and the number, duration, and complexity of joystick interactions. Every participant independently interacted with the joystick and moved the Explorer Mini during every session. Over 12 visits, participants significantly increased their distance traveled and the time spent with the joystick active. Surprisingly, we found that only 48% of joystick interactions resulted in device movement, which has important implications for learning. These results can serve as a benchmark for caregivers and clinicians to understand early device use patterns. Furthermore, this knowledge can be used to inform the design of new powered mobility technologies for toddlers with disabilities or support the refinement of existing devices.**

***Index Terms*— Children, disability, joystick, mobility, powered wheelchair.**

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I. Introduction

An estimated 4.3% of all children in the United States have disabilities, and this prevalence has continued to rise over the last several years [1]. Children without disabilities typically take steps independently by 12-15 months of age [2], [3]. By contrast, children with motor disabilities who become ambulatory often do not walk independently until they are 3-5 years old—approximately 2-4 years later than nondisabled peers [4], [5]. Similarly, children who go on to be wheelchair users often do not receive access to wheeled mobility until they are 3-5 years old [6], [7], [8]. Thus, no matter a child's future ambulatory status, infants and toddlers with motor disabilities have severely restricted access to self-initiated mobility over the first several years of their lives.

Self-initiated mobility, or the ability to independently explore one's environment (through rolling, crawling, walking, etc.), is important for cognitive, emotional, social, perceptual,

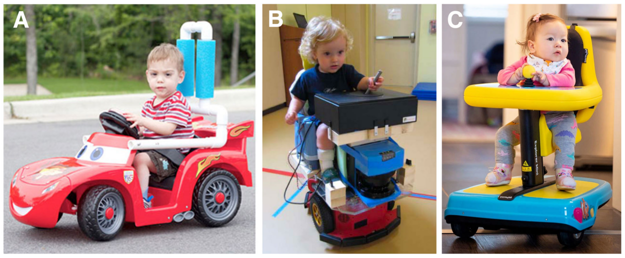

Fig. 1. Powered mobility devices for toddlers. **(A)** A modified ride-on car [14], **(B)** A mobile robot [15], **(C)** The Permobil Explorer Mini [16].

and motor development in infants and toddlers [2], [3], [9], [10]. Experiments with nondisabled infants have established that cascades of developmental changes occur at the onset on independent mobility [2], [3]. Crucially, however, experts argue that these changes do not occur simply *because* a child moves independently, but rather stem from the learning experiences a child can engage in *as a result* of their independent mobility. In fact, Adolph et al. demonstrated that the average nondisabled toddler (ages 12–19 months, including both novice and expert walkers) takes more than 2000 steps, travels 700 meters, and falls 17 times per hour during free play [11]. Accumulated over days, weeks, and months, this process generates thousands of opportunities for learning through independent exploration and engaging with the environment and other people. Therefore, toddlers with disabilities who rely heavily or exclusively on caregivers to move them around their environment may be missing out on important developmental opportunities, including formulating a sense of self-generated actions and a sense of agency, both of which are crucial aspects of early human development [12], [13]. As such, it is imperative that all young children have access to self-initiated exploration at developmentally appropriate stages.

Powered mobility technology may be used during this critical period to facilitate mobility and play. Standard mobile toys, such as off-the-shelf ride-on cars or push walkers, are often inaccessible to children with disabilities, and thus different technology is required to enable self-initiated exploration. The most extensive deployment of powered mobility technology for this population is adapted, pushbutton-operated ride-on toy cars (*i.e.,* GoBabyGo!) (Fig. 1A). Research has shown that using modified ride-on cars can augment a child's movement, cognitive development, communication, social engagement, and participation in home, school, and community environments [17], [18], [19], [20], [21], [22]. However, device-related challenges, including difficult manual steering, the lack of a joystick or alternative driving modalities, low maneuverability, size, and noise have been cited by caregivers as major limitations of modified ride-on cars, which may ultimately lead to device abandonment [23], [24], [25].

Alternatively, joystick-controlled 'mobile robots' have previously been developed as research prototypes (Fig. 1B). Research conducted with these prototype devices has shown that children with and without disabilities can be trained to interact with a joystick and produce exploratory and goal-directed driving behavior as young as 6-8 months old [15], [26], [27], [28]. Although these studies have generated important foundational knowledge regarding how toddlers can operate a joystick-controlled mobile device, the device prototypes are bulky, noisy, and unsuitable for use outside of the laboratory environment. Furthermore, these studies were primarily conducted with nondisabled children, and only a few included a small number (1–2) of children with motor disabilities [15], [27].

A new technological innovation, the Permobil Explorer Mini (Permobil AB, Kista, Sweden) [16] (Fig. 1C), has reduced some device-related barriers to providing powered mobility for young children with disabilities at developmentally appropriate stages. The Explorer Mini was FDA cleared and released in the United States in 2020 as the only commercially available pediatric powered mobility device for children ages 12-36 months. The Explorer Mini can be customized to support children as they learn and grow, and it has joystick-controlled proportional steering, multiple speeds, and the option to use the device in both seated and standing postures. The device is relatively lightweight (24 kg) and comparatively inexpensive (less than \$3000), and accordingly, can be used in home, community, or clinical environments.

The first published studies using Explorer Mini have investigated caregiver perceptions, developmental outcomes, and initial use patterns of the device [18], [29]. One study described toddlers' first experiences with the device, and reported that 94% of the 33 children with disabilities enrolled in the study moved the Explorer Mini during their first exposure [29]. In the first randomized at-home clinical trial with the Explorer Mini, 24 toddlers with cerebral palsy (CP) or suspected CP received a modified ride-on car and the Explorer Mini for eight weeks each. Children who exhibited 'high use' of the Explorer Mini demonstrated significantly greater changes in receptive communication, expressive communication, and gross motor developmental domains (as measured by the Bayley Scales of Infant and Toddler Development, 4th edition) compared to those who exhibited 'low use' of the device [18]. Furthermore, of the ten caregivers interviewed, seven reported that they preferred the Explorer Mini to the modified ride-on car [25]. The researchers posit that, "in combination with high use, the joystick navigation of the Explorer Mini may have resulted in different mobility experiences that can at least partially explain the findings" [18]. These initial results demonstrate that using the Explorer Mini's joystick is intuitive for toddlers and that using the device may offer developmental benefits.

Extensive research has been conducted to measure and understand how nondisabled infants and toddlers acquire motor skills, such as rolling [30], [31], crawling [32], [33], [34], [35], or walking [11], [35], [36]. However, there is a gap in knowledge surrounding how children with motor disabilities learn to use powered mobility. Because the Explorer Mini is the first commercially available device in the US for children under the age of three, there are still many open questions related to how joysticks should be designed and used to control movement for young children. As such, there is a need for studies that quantitatively capture joystick interactions and exploration experiences and evaluate how these quantities change as children learn to use the device.

The purpose of this study was to quantify how toddlers with disabilities (ages 1–3 years) interact with a joystick-controlled

TABLE I
PARTICIPANT DEMOGRAPHICS

ID	Age (mo.)	Sex	Weight (kg)	Disability Type	Mobility at Study Entry
P1	31	F	13.1	Genetic, Neurological	Non-mobile
P2	14	M	9.9	Genetic	Sitting
P3	16	M	10.1	Orthopedic	Cruising
P4	21	M	8.7	Genetic, Neurological	Sitting
P5	28	M	10.7	Cerebral Palsy	Rolling
P6	27	M	13.1	Cerebral Palsy	Non-mobile
P7	16	M	10.3	Neurological	Rolling
P8	18	F	11.3	Cerebral Palsy	Rolling
P9	23	M	11.7	HIE[1]	Rolling

[1]Hypoxic Ischemic Encephalopathy

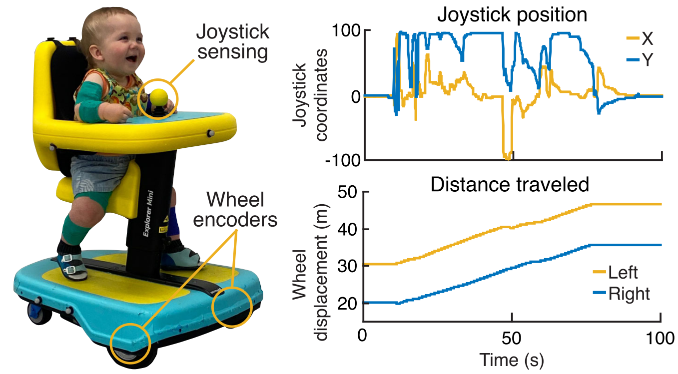

Fig. 2. The instrumented Explorer Mini measures joystick position in (x,y) coordinates and the number of wheel rotations for the left and right wheels at a sampling frequency of 100 Hz. Wheel displacement is calculated by multiplying the number of rotations by the measured wheel circumference. Representative raw data collected from the device are shown here for 100 seconds.

powered mobility device during self-initiated play and exploration. For this work, we developed a one-of-a kind, custom-instrumented Explorer Mini which enabled us to measure joystick interactions and movement patterns during device use. Based on these sensor measurements, we calculated metrics of child-device interaction and exploration, and analyzed how these metrics changed over 12 in-lab visits. The quantitative results derived from this study may be used to develop new theories that govern how young children learn to explore using powered mobility, and how this exploration facilitates their learning and development. Furthermore, this knowledge may be used to inform pediatric rehabilitation practices by establishing benchmark expectations for early device use and providing quantitative metrics by which skill development and progress may be assessed. In the future, these results may be leveraged to refine existing technologies or design new devices that are best suited for the developmental needs of toddlers.

II. METHODS

A. Participants

Nine children with motor disabilities were enrolled in our study, along with at least one adult parent or legal guardian (Table I). Inclusion criteria were that the child must be between 12-36 months old at the time of enrollment, have a disability or developmental delay that impacts their movement, and be able to tolerate sitting upright (with support) while moving through space for up to 15 minutes. The mean (SD) age of children in our study (hereafter referred to as 'participants') was 21.6 (6.1) months. Children had a variety of disabilities and different levels of mobility, as detailed in Table I. All study activities were reviewed and approved by the University of Washington's Institutional Review Board (study number 00014879). Prior to data collection, caregivers gave informed consent for themselves and their child to participate in the study. Caregivers also gave optional informed consent for their child's images to be used in academic publication.

B. Instrumented Explorer Mini

In this study, participants used the Permobil Explorer Mini (Permobil AB, Sweden), the only commercially available, FDA-cleared pediatric powered mobility device in the United States for children ages 12-36 months [16]. The device has adjustable seating and tray height options to accommodate children up to 35 pounds (15.9 kg) and 39 inches (1 m) tall. An 8 cm tall joystick is positioned in the center of the tray, and children interact with the joystick using the large yellow foam ball (4.5 cm in diameter). The joystick provides proportional speed control, and moving the joystick drives the two large front wheels of the device independently, allowing for 360-degree maneuverability. The device features five speed options that control the maximum speed of the device; speed settings 1–5 correspond to maximum speeds of 0.2, 0.3, 0.4, 0.5, and 0.6 m/s, respectively.

For this work, we developed a one-of-a-kind instrumented Explorer Mini in collaboration with LUCI's Sandbox program (LUCI Mobility, Tennessee, USA) [37]. The instrumented Explorer Mini is a novel technology that enables us to measure and record all joystick interactions, wheel rotations, and bodyweight loading through the base during use (Fig. 2). The instrumented Explorer Mini includes custom sensing hardware and software to record joystick position in (x, y) coordinates; joystick neutral corresponds to $(0, 0)$, and each coordinate ranges from -100 to 100 (Fig. 5B). We also added two 12-bit magnetic encoders (AS5600, Teyleten Robot, China)—one on each of the driving wheels—to measure wheel rotations and calculate device velocity and distance traveled. Finally, we built a custom data logger, which comprised a microprocessor (BeagleBone Black, BeagleBoard, Michigan, USA) and custom printed circuit boards for sensor data acquisition, processing, and streaming. Signals from the instrumented Explorer Mini were collected at 100 Hz. All sensors and the data logger were enclosed in the device and the overall footprint and functionality of the device remained the same.

To inform our study results, we performed a preliminary characterization of the Explorer Mini's velocity response to a forward joystick input. In this simple exercise, an experimenter performed eight trials (two at each of the five speed settings) where the joystick of the Explorer Mini was briefly held in the forward direction for 1–2 seconds, with no child in the device. We found that, regardless of the speed setting, there was an average delay of 0.33 seconds from when the joystick was moved forward until the Explorer Mini began

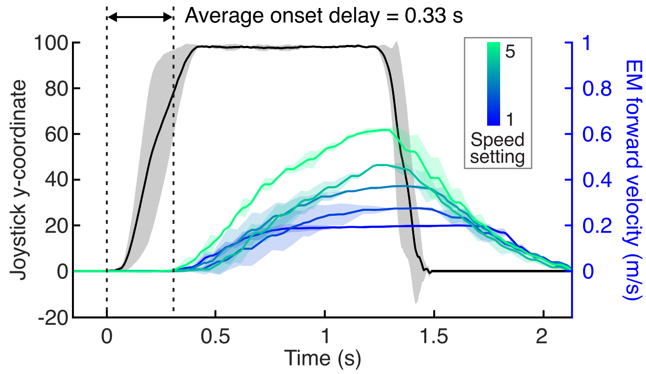

Fig. 3. Dynamic response of the Explorer Mini (EM) velocity to a forward joystick input. The black line shows the y-coordinate of the joystick input, averaged over eight trials and normalized to the average joystick input duration; the gray shaded region shows the standard deviation. Each colored line depicts the EM velocity, averaged over two trials for each speed setting and normalized to average velocity duration; shaded colored regions show the standard deviation.

Fig. 4. Play sessions were held within an enriched environment containing interactive toys arranged at eye-level and within reach.

to move (Fig. 3). Furthermore, the device took approximately one second to reach its peak velocity, and almost one second to return to a stop after the joystick was released. This means that particularly short or high-frequency joystick inputs are unlikely to result in device movement.

C. Experimental Data Collection

Participants attended 12 in-lab visits, during which they used the instrumented Explorer Mini in an enriched play environment. The play environment had a variety of age-appropriate interactive toys (e.g., stacking cups, basketball hoop, music toys, switch-adapted electronic toys) and engaging digital and non-digital visual displays (e.g., disco light, beach balls hung from the ceiling) arranged around the room at the child's eye level and within reach (Fig. 4). Different toys were placed on tables spread throughout the room with plenty of empty space between to encourage exploration [38]. We customized the toys available during a visit for each participant based on caregiver-reported interests and child's demonstrated preferences. Each visit comprised two play sessions separated by a short 5–10 minute break. We targeted about 15–20 minutes per play session for each child, but this duration varied based on the child's engagement with the device and their temperament and tolerance. We consulted with the caregivers to learn their child's cues for when they wanted a break from the device and we did not enforce any time limits for device use.

At the beginning of each play session, the seat and tray height of the Explorer Mini were adjusted so that each participant was in a comfortable position and could access the joystick. We chose the speed setting of the Explorer Mini for each session based on our observations of the child's performance and preferences. We used additional positioning support materials (*e.g.*, towels, foam, pool noodles) for each child as needed. We also used a variety of joystick handle modifications (e.g., foam, PVC T-bar) on a session-by-session basis to maximize joystick access for each participant. During a play session, the participant engaged in child-led, exploratory play in the enriched environment, alongside members of the research team and/or their caregiver(s).

During a play session, caregivers and/or experimenters periodically intervened by operating the joystick themselves. Adult intervention was intermittently used to redirect children toward the center of the play space or to demonstrate joystick use with hand-over-hand guidance. Our interactions with the participant were guided by the Assessment of Learning Powered Mobility (ALP) tool and facilitating strategies [39], [40], and the Guideline for Introducing Powered Mobility to Infants and Toddlers [41].

D. Data Analysis

Each participant completed 12 visits, comprising two play sessions per visit; we analyzed each session individually. Of the 216 total sessions collected, we analyzed 192 play sessions for our nine participants. Our study protocol required three separate computing systems to capture all the necessary data, and there were 24 sessions in which one of these systems did not synchronize properly. We analyzed between 19 and 23 sessions per participant; a detailed list of the excluded sessions are provided in Table SI.

All data labeled as 'adult intervention' were removed from the dataset prior to analysis; all data presented in this manuscript are from periods when only the child was operating the device. We defined several outcome metrics to characterize how participants interacted with the Explorer Mini and explored their environment. Because play session time was variable, we normalized some of these metrics using session time in order to standardize across participants.

1) Active Time: Using the joystick activation and wheel encoder data from the instrumented Explorer Mini, we calculated the time the child spent with the joystick active (*i.e.,* not at neutral) and the time spent in motion. We normalized these metrics by dividing by session time to report the percent of each session spent with the joystick active or in motion.

2) Distance Traveled: We used the encoders on the instrumented Explorer Mini's wheels to calculate total distance traveled. We first calculated wheel displacement by multiplying the number of angular rotations of each wheel by the wheel's measured circumference. We calculated net displacement by averaging the displacement of the left and right wheels and then took the absolute value of the net displacement, such that forward and backward movement contributed to total distance. To calculate total distance traveled, we summed the absolute net wheel displacement over the session.

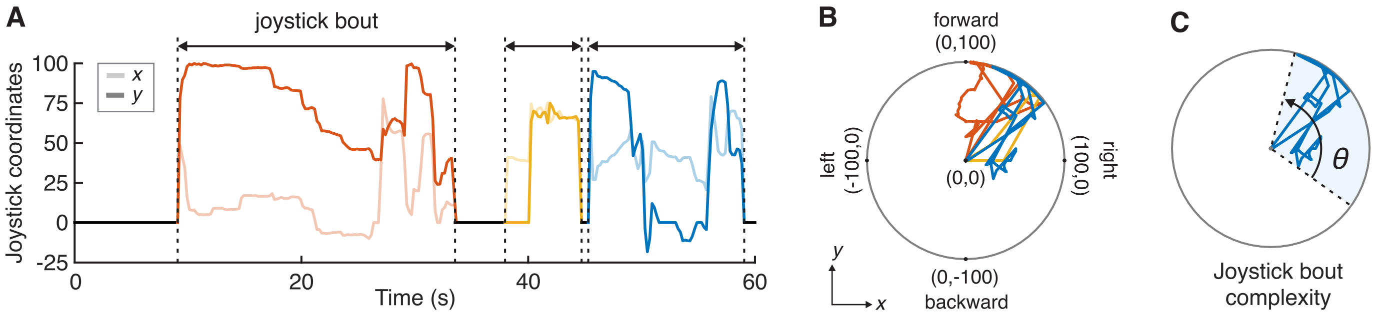

Fig. 5. Defining joystick bouts and joystick bout complexity. **(A)** Three representative consecutive joystick bouts from P2 are shown as a function of time in red, yellow and blue; the lighter color is the joystick *x*-coordinate, the darker color is the *y*-coordinate, and black is when the joystick is at neutral. **(B)** Representation of the three joystick bouts from (A) in joystick coordinate space. Each joystick axis *x* and *y* ranged from −100 to 100, with neutral at (0,0). **(C)** Joystick bout complexity was defined as the angular range θ that encapsulated the entire joystick trajectory for a given bout.

3) Joystick Bouts: Using the joystick activation data from the instrumented Explorer Mini, we segmented the session into 'joystick bouts' (Fig. 5A-B). A joystick bout was defined from when the joystick was moved away from neutral until it was returned to neutral and stayed there for at least 100 ms; we determined this threshold empirically through the examination of joystick bouts resulting from varying thresholds. For each session, we analyzed the number of joystick bouts and the mean and maximum bout duration. We also analyzed the proportion of joystick bouts that resulted in device movement.

4) Joystick Bout Complexity: For a given joystick bout, we analyzed the 'complexity' of the joystick movement. We defined the complexity of the joystick bout as the angular range θ that encapsulated the entire joystick trajectory during the bout (Fig. 5C and Fig. 10A). A smaller angular range indicates less complexity in the joystick movement, while a larger angular range indicates more complexity. We calculated the mean joystick bout complexity across bouts for a given session (hereafter referred to as joystick bout angular range mean). As a measure of variability, we also calculated the standard deviation of joystick bout complexity across bouts for a given session (hereafter referred to as the joystick bout angular range variability).

5) Interaction Efficiency: For each joystick bout, we analyzed the 'efficiency' of the joystick interaction. For a given bout, we first calculated the joystick path length as the sum of all distances between points in (x,y) coordinate space. We then calculated interaction efficiency as the ratio of the output (distance traveled) to the input (joystick path length). Here, a larger ratio indicates that less overall joystick movement was used to move the same unit distance (*i.e.,* increased efficiency). Please note that this metric is relative and enables us to examine changes in interaction efficiency over time, but it does not have a 0-100% absolute scale.

E. Statistical Analysis

We analyzed how each outcome varied over participants' visits using linear mixed effects models (LMEM), which are well suited for repeated measures studies with small sample sizes [42]. For each of our independent outcome variables, we created a LMEM to analyze the effect of visit number (1–12) on the given outcome. All models included participant as a random effect, with both a random intercept and a random slope. For all models, our significance threshold was set at 0.05.

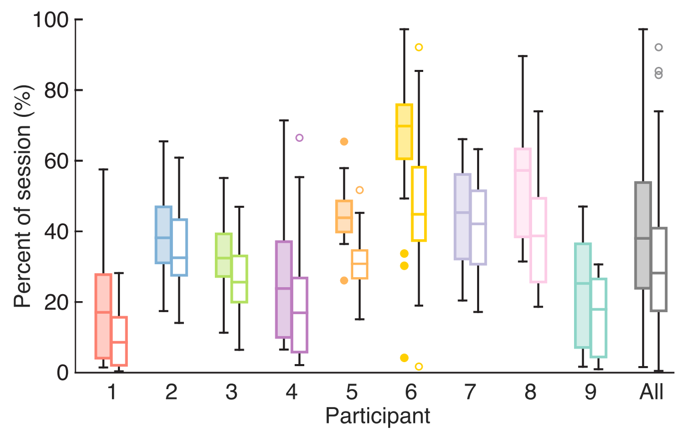

Fig. 6. Percent of session spent with the joystick active (shaded boxes) and in motion (white boxes). Each participant is shown in a different color, and the distribution is calculated over all sessions for that participant. The gray boxes show the distribution over all 192 sessions. The edges of each box depict the 25th and 75th percentiles, and the horizontal line shows the median. Whiskers indicate the minimum and maximum values within the dataset. Circular markers show outliers, defined as a value more than 1.5 times the interquartile range. Outliers were included in the calculation of all outcome metrics.

III. Results

All nine participants interacted with the joystick and drove the Explorer Mini during all sessions. Table II displays the mean, standard deviation, minimum, and maximum of the outcome metrics, calculated across participants. Also shown are the *p*-values for each LMEM with visit number as a fixed effect; a *p*-value less than 0.05 indicates a significant effect of visit number (*i.e.,* time) on the metric. For models with a significant fixed effect, the predicted percent change in that metric over 12 visits is displayed.

Across participants, the mean (SD) session time was 18.2 (1.9) minutes. On average, participants spent 38.8% (15.5%) of the session with the joystick active, while they spent only 29.4% (12.9%) of the session moving (Fig 6). There was a clear discrepancy between the time the joystick was active and the time in motion. We found that, on average across participants, only 48.8% (11.4%) of joystick bouts resulted in device movement.

TABLE II
SUMMARY OF OUTCOME METRICS

	Average	**Lowest**	**Highest**	**LMEM**	**Predicted**
	Mean (SD*)	Mean (SD†) - P#		*p*-value	**Change‡**
Session time (min)	18.2 (1.9)	16.4 (3.1) - P9	22.1 (8.3) - P1	0.50	-
Time with joystick active (min)	7 (2.4)	3.7 (2.9) - P9	11.2 (3.9) - P6	**0.04**	42%
Moving time (min)	5.2 (2.0)	2.2 (2.2) - P1	8.1 (3.5) - P6	**0.01**	54%
Percent of session with joystick active (%)	38.8 (15.5)	18.1 (15.5) - P1	66.4 (21.8) - P6	**0.049**	42%
Percent of session moving (%)	29.4 (12.9)	9.6 (8.4) - P1	48.6 (21.0) - P6	**0.01**	56%
Distance traveled (m)	54.8 (24.4)	14.7 (14.5) - P1	88.3 (31.1) - P7	$<$ **0.001**	133%
Distance traveled (normalized) (m/min)	3.1 (1.4)	0.6 (0.6) - P1	5.2 (1.8) - P7	$<$ **0.001**	134%
Number of joystick bouts	116 (70)	52 (35) - P6	290 (54) - P5	0.74	-
Number of joystick bouts (normalized) (bouts/min)	6 (4)	3 (2) - P6	17 (3) - P5	0.89	-
Joystick bout average duration (s)	5.4 (5.2)	1.7 (0.5) - P5	17.9 (13.5) - P6	0.18	-
Joystick bout maximum duration (s)	67.8 (55.7)	26.5 (24.4) - P1	183.8 (120.9) - P6	0.19	-
Percent of joystick bouts that result in movement (%)	48.8 (11.4)	37.6 (13.3) - P4	73.4 (8.4) - P7	0.15	-
Joystick bout angular range mean (deg)	73.8 (21.6)	39.4 (12.0) - P1	112.2 (20.6) - P5	**0.01**	50%
Joystick bout angular range variability (deg)	68.4 (14.8)	44.7 (13.6) - P1	90.5 (8.70) - P5	**0.02**	30%
Interaction efficiency	0.2 (0.1)	0.1 (0.1) - P1	0.3 (0.1) - P3	**0.001**	79%

**across participants* *†across sessions* *‡over 12 visits*

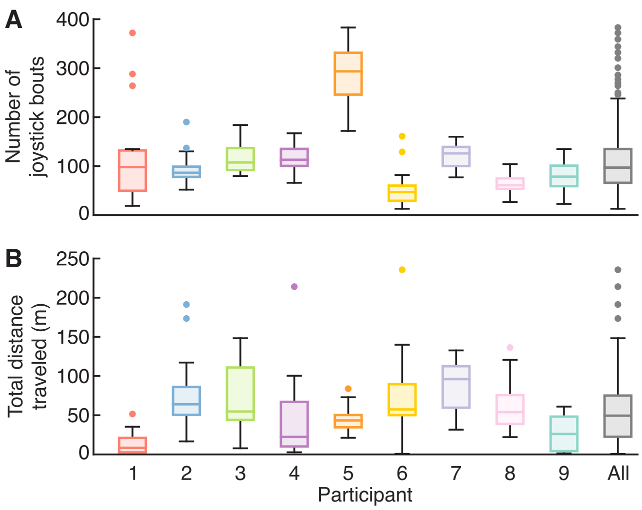

Fig. 7. Distribution of **(A)** the number of joystick bouts and **(B)** total distance traveled calculated across all sessions for each participants. Each participant is shown in a different color. The gray boxes show the distribution pooled over all 192 sessions. Boxplot definitions can be found in the caption of Figure 6.

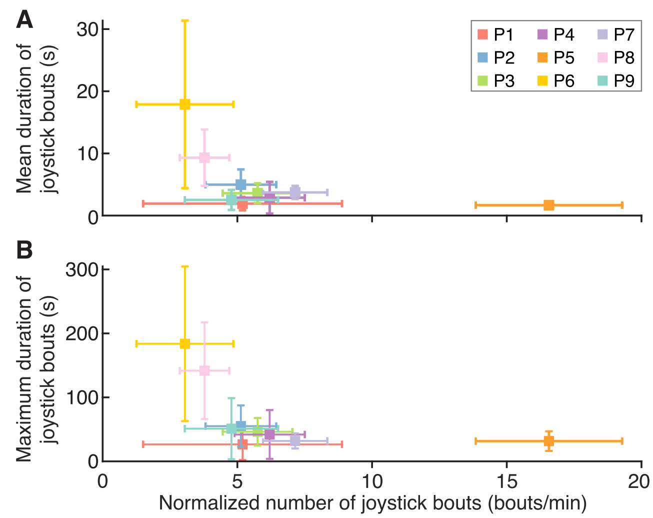

Fig. 8. Analysis of joystick bouts. **(A)** Mean duration of joystick bouts and **(B)** maximum duration of joystick bouts, shown versus the normalized number of joystick bouts (bouts per minute of session time). Each colored square and error bars indicate the mean and standard deviation, calculated across sessions for a given participant.

Participants activated the joystick 116 (70) times per session and traveled 54.8 (24.4) meters (Fig. 7). Across all 192 analyzed sessions, the shortest distance traveled in a session was 0.6 m, and the longest was 232 m. To compare between individuals, we also report the number of joystick bouts and distance traveled normalized by the total session time (Table II).

Across participants, the average duration of a joystick bout was 5.4 (5.2) seconds. While most participants' average joystick bout duration was between 2 and 5 seconds, P6 and P8 had longer average bout durations of 17.9 seconds and 9.3 seconds, respectively (Fig. 8A). P5 had the shortest average bout duration of 1.7 seconds. Similar relationships between participants emerged when analyzing maximum joystick bout duration per session (Fig. 8B).

Participants significantly increased their time spent with the joystick active (p=0.04) and in motion (p=0.01) over their 12 visits (Fig. 9A). The LMEMs predict that, on average, participants would spend 0.22 more minutes (13 seconds) per visit with the joystick active and 0.20 more minutes (12 seconds) in motion, resulting in percent increases of 42% and 54% over 12 visits, respectively. These trends remained significant when normalizing the time with the joystick active or in motion to session time (Table II, Fig. S1).

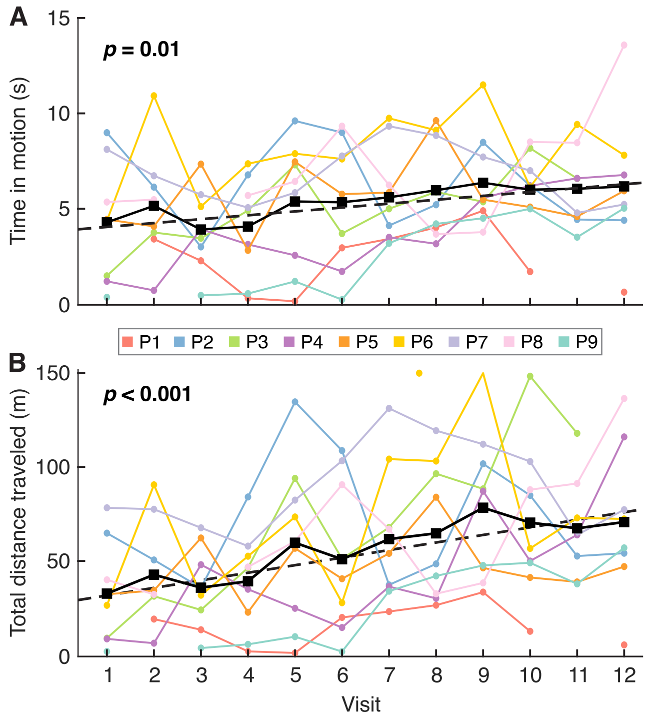

Fig. 9. The time in motion and total distance traveled per session both significantly increased with visit number. Individual colors depict participants and the colored circles show the average of all sessions completed for a given visit. Black squares depict the mean across participants. The black dashed line is the best fit line as determined by the LMEM; the *p*-value for the model slope is shown in the top left corner.

Participants' distance traveled per session also significantly increased over their 12 visits ($p<0.001$) (Fig. 9B), The LMEM predicts that, on average, participants would travel approximately 4 meters more each visit, resulting in a 133% increase over 12 visits. These same trends held when analyzing distance traveled normalized by session time (Table II, Fig. S1).

Across participants, the average joystick bout angular range mean was 73.8 (21.6) degrees, and the average joystick bout angular range variability was 68.4 (14.8) degrees (Fig. 10B). Joystick bout angular range mean significantly increased with visit (p=0.01) (Fig. 10C). The LMEM predicts that, on average, participants would increase their joystick bout angular range mean by 2.7 degrees per session, resulting in a 50% increase over 12 visits. The joystick bout angular range variability also significantly increased as a function of visit (p=0.02) (Fig. 10D). The LMEM predicts that, on average, participants would increase their joystick bout angular range variability by 1.6 degrees per session, resulting in a 30% increase over 12 visits.

Interaction efficiency (*i.e.,* the ratio between distance traveled and joystick path length) significantly increased as a function of visit number (LMEM, p=0.001) (Fig. 11), and the model predicts an expected increase of 79% over 12 visits (Table II).

IV. Discussion

In this study, we quantified how toddlers with disabilities (aged 12-36 months) used a commercially available joystick-controlled powered mobility device (the Explorer Mini) to explore their environment during free play. Every child enrolled in our study independently interacted with the joystick and moved the Explorer Mini during every session. This suggests that the cause-and-effect nature of the Explorer Mini's joystick is relatively intuitive for children this age. Adolph et al. reported that, on average, 12-month-old nondisabled toddlers learning to walk would travel nearly 270 meters per hour during free play [11]; performing this same extrapolation, children in our study would traverse 186 meters per hour. These results are significant because for many children in our study, using the Explorer Mini marks their first exposure to experiencing movement as a result of their own self-initiated actions. These findings add to the growing body of evidence suggesting that children are intrinsically motivated to move and that powered mobility devices like the Explorer Mini can enable new exploration and learning opportunities for children with disabilities [18], [29].

Examining the joystick use patterns in Figure 8, we observed the emergence of different interaction 'strategies' for using the device. Most participants (6 of 9) employed similar strategies, using approximately 5–7 joystick bouts per minute of session time, with an average bout duration of 2–5 seconds. However, we saw that two participants (P6 and P8) used fewer, longer joystick bouts, and one participant (P5) used a higher number of shorter joystick bouts. Beyond individual preferences for joystick interaction, children's motor control abilities may also influence their joystick use. Participants P5, P6, and P8 are the three children enrolled in our study with a diagnosis of cerebral palsy (CP). Anecdotally, both P6 and P8 exhibited low muscle tone and reduced volitional hand and arm movement. Thus, these individual participants initiated joystick activations less often, but when they did, they held the joystick for a longer duration of time. P5 had pronounced spasticity and ataxia, which likely played a role in his more frequent, shorter joystick interactions. These differences between participants raise important considerations for the design and control of powered mobility devices for toddlers. In this study we prioritized joystick access, so we made ad-hoc modifications to the joystick morphology (*e.g.,* added foam to make it bigger) as needed. However, we do not yet know how different joystick morphologies or placements influence use patterns for different children and their unique motor abilities, although some studies have explored this in adult populations [43], [44]. This knowledge could be used in the future to design a suite of interchangeable joystick handles for families to choose from. From a control perspective, these observations suggest that any future assistive driving or steering algorithms will need to be able to adapt or be customized to individual users.

We found that both the mean and variability of joystick bout complexity (*i.e.,* angular range) increased as children gained experience using the device (Fig. 10). This means that participants not only used more complex joystick interactions with experience, they also employed a wider variety of joystick trajectories within a session. To ground these observations in theory, we look to the Assessment for Learning Powered Mobility (ALP) Tool—an instrument that has been previously

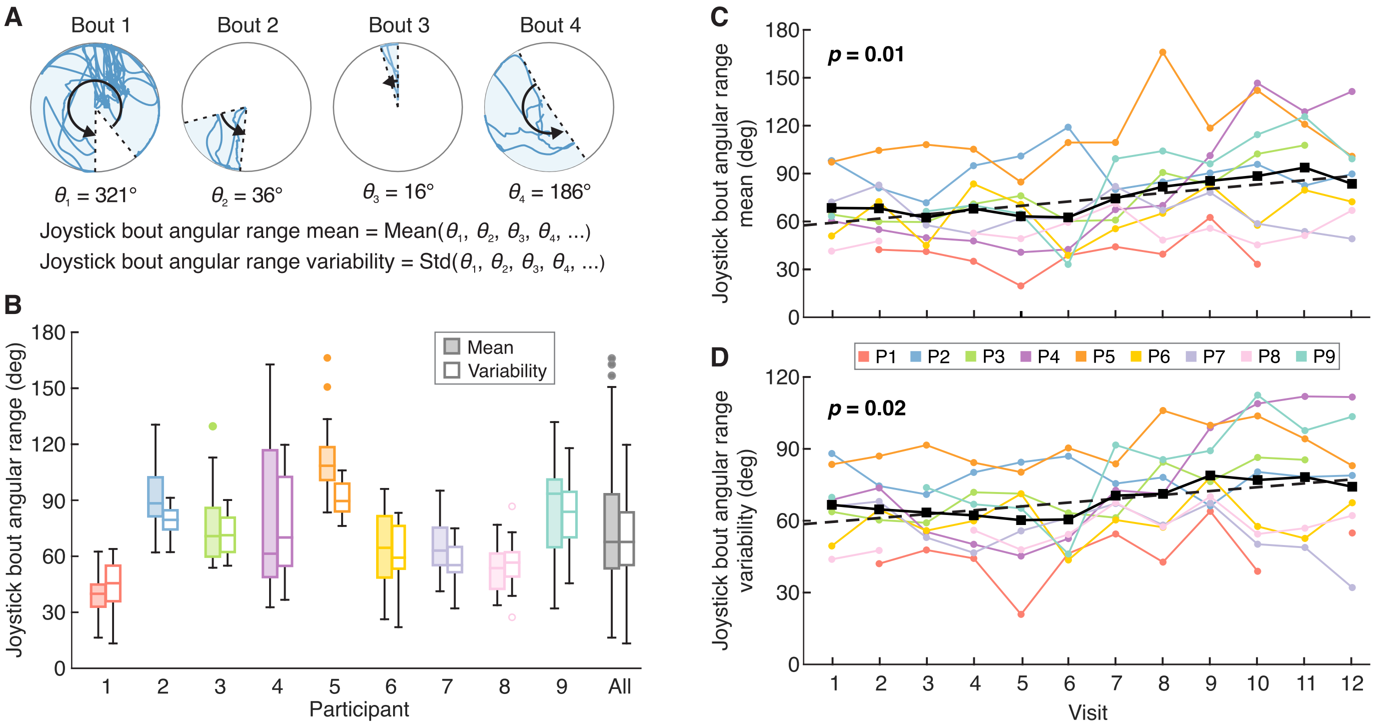

Fig. 10. Analysis of joystick bout complexity. **(A)** Four representative joystick bouts from P2, depicting the joystick bout angular range (*i.e.,* complexity) for each bout. The joystick bout angular range mean and variability were calculated across all bouts within a session. **(B)** Joystick bout angular range mean (shaded boxes) and variability (white boxes). Each participant is shown in a different color. The gray boxes show the distribution pooled over all 192 sessions. Boxplot definitions can be found in the caption of Figure 6. Both the **(C)** joystick bout angular range mean and **(D)** joystick bout angular range variability significantly increased with visit number. Individual colors depict participants and the colored circles show the average of all sessions completed for a given visit. Black squares depict the mean across participants. The black dashed line is the best fit line as determined by the LMEM; the *p*-value for the model slope is shown in the top left corner.

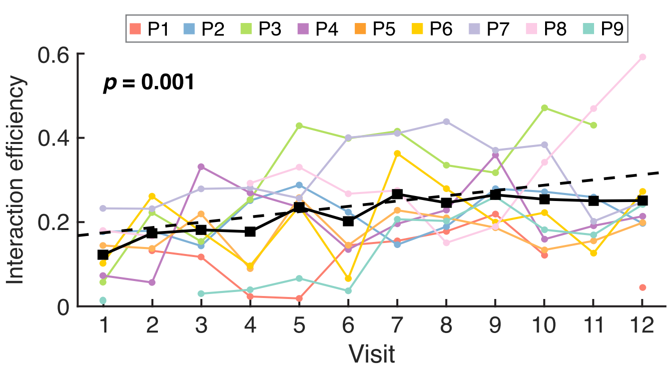

Fig. 11. We defined interaction efficiency as the ratio between distance traveled and joystick path length. A higher ratio indicates increased efficiency. Individual colors depict participants and the colored circles show the average of all sessions completed for a given visit. Black squares depict the mean across participants. The black dashed line is the best fit line as determined by the LMEM; the *p*-value for the model slope is shown in the top left corner.

developed to stage the process of learning to use powered mobility for children and adults [39], [40]. The ALP Tool describes eight learning stages from Novice to Expert (1 to 8), which are assessed through observation of device use. In assessing a learner's stage, one of the categories considered is "activity and movement," which describes how the individual interacts with the joystick and moves about the world. For example, a Stage 3 learner may "activate the joystick to get the effect of motion," and progress to Stage 4 by "exploring different effects—drive, stop." By Stage 5, the ALP Tool predicts individuals will "experiment with steering by composing effects in different patterns" and emerge as Stage 6 when they "steer coarsely in a desired direction, focused on getting from point A to B." Finally, Stage 7 and 8 learners will demonstrate "navigation within a physical space" and "fluid, smooth, and precise movements." In short, the characteristics that describe the process of learning powered mobility from the ALP Tool indicate that changes in joystick interaction patterns and complexity are expected as individuals learn to use powered mobility. Therefore, it is interesting to consider that our observed changes in joystick complexity patterns could reflect fundamental changes in the way that children are synthesizing relationships between self, device, and the environment.

It is important to note that in this study we quantified joystick complexity as a measure of child-device interaction, but this quantitative data alone is insufficient to capture the nuanced ways in which the child may be using the device to achieve their goals. For example, if the child's goal is to move across the room to reach a desired toy, in an open environment this goal may be achieved using a joystick bout with low complexity (*e.g.,* driving in a straight line). In the instance where there are obstacles in the way, this goal would be achieved using a joystick bout with high complexity (*e.g.,* maneuvering and turning). Therefore, future work should seek to contextualize the quantitative child-device interaction metrics by combining them with video data and designing goal-specific experimental protocols to study these relationships. In the future, we hope that quantitative measurements of child-device interaction will be able to supplement observational tools such as the ALP to enhance powered mobility provision and assessment.

The most surprising observation from our study was the notable discrepancy between the time participants spent with the joystick active and the time they spent in motion (Fig 6). This underscores that multi-modal sensing, such as implemented in this study, is needed to capture the full experience of children using powered mobility—relying only on the joystick measurements or the wheel encoders would not have captured this result. In examining this result more thoroughly, we discovered that only 48% of joystick bouts resulted in device movement. We expect that this observation is a direct result of the dynamics of the Explorer Mini's response (Fig. 3). To be clear, there are benefits to this type of smoothed and delayed dynamic response—one certainly would not want to use a device that responded immediately to a change in joystick position because this behavior would likely feel jerky and uncomfortable. However, it is also true that these dynamics can have crucial implications for young children learning to control the Explorer Mini.

The most striking quantitative result from our study is that participants significantly increased their distance traveled per session by 133% over their 12 visits. There are several ways in which an overall increase in distance traveled may be achieved (*e.g.,* increased maximum speed of the device, more joystick bouts, longer joystick bouts, etc.). When we more deeply investigated the patterns of device use that would explain how participants achieved greater distance traveled, we found unexpected results. The most obvious explanation for increased distance traveled is that participants were able to drive faster in later sessions. While it is true that all participants' speed settings (which determined the maximum speed of the device) increased over the 12 visits (Fig. S2), we also found that participants spent significantly more time moving as their experience increased (Fig. 9A), so we do not attribute the change in distance traveled solely to increased device speed. At the group level, we did not identify significant changes in the number or duration of joystick bouts over time, and only some individual participants demonstrated trends in their joystick use patterns over time (Fig. S3). Therefore, if the number and duration of joystick bouts remained constant, but the overall time in motion increased, we conclude that the explanation must lie in the relationship between joystick activation and motion—which we know is highly influenced by the dynamics of the device (Fig. 3).

Given that we did not see a significant increase in the percentage of joystick bouts that resulted in motion, we hypothesized that the increase in distance traveled and overall time in motion could be explained by the *efficiency* of device interaction. That is, the joystick was used more effectively to produce motion. In fact, we did see a significant increase in our measure of interaction efficiency as a function of time (Fig. 11). This result is intriguing because it suggests that children may be learning the dynamics of the device response and adjusting their joystick interactions accordingly. This finding opens up exciting directions for future research examining how the dynamics of device response impact learning in children, which has important implications designing of optimized device control systems [45] and assistive driving algorithms [46], [47].

This study was designed to observe how young children use the Explorer Mini during self-initiated exploration and play and there are inherent limitations associated with working with children under the age of three. We prioritized child comfort, engagement, and fun through the research process. However, this did reduce the total number of trials, repeatability, and standardization that could be integrated into our protocol. The number of participants in this study was small (n=9) and highly heterogeneous in type of disability and current mobility, and thus we did not stratify our results according to these characteristics. Given this heterogeneity, we also did not group participants by chronological age, since each child is on their own unique developmental timeline. In this study, we did not control for additional factors such as at-home device use or frequency or intensity of therapy, and we do not yet know if our observed changes were solely a result of device training or if a child's natural development also played a role. Future randomized controlled trials should be specifically designed to examine these effects. Our goal was to observe participants' device interaction patterns when they had the best possible access to using the Explorer Mini. Therefore, we attempted to maximize joystick access for each child, subject to their unique abilities, by introducing a variety of low-cost modifications to the joystick handle, including using foam to make it bigger, or adding a PVC T-bar or ring attachment. We also added padding and additional postural support materials as needed, and adjusted the participant's speed setting at our team's discretion. These modifications varied between participants and between sessions for an individual participant, which introduces an unmodeled source of variability into the dataset. Although we tried to standardize our verbal interactions with the child using established facilitation guidelines [39], [40], [41], we acknowledge that there are always variations in verbal coaching that are highly dependent on child temperament and child-experimenter and child-caregiver interactions.

V. Conclusion

Our novel experimental platform, the instrumented Explorer Mini, enabled us to quantify the joystick interactions and movement patterns of toddlers with motor disabilities learning to use using powered mobility. The quantitative results presented here can serve as a benchmark for caregivers and clinicians to understand early device use and may assist in staging the learning process. The results from our study reveal surprising relationships between joystick interactions and device movement, which have important implications for learning. The knowledge generated from this study can be used to inform the design and control of new powered mobility technologies for young children with disabilities or support the refinement of existing devices.

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