Look at Them Go! Using an Autonomous Assistive GoBot to Encourage Movement Practice by Two Children with Motor Disabilities

Ameer Helmi[1], Tze-Hsuan Wang[2], Samuel W. Logan[2], and Naomi T. Fitter[1]

Abstract—**Young children with motor disabilities face barriers and delays to learning motor skills such as walking. Pediatric body-weight support harness systems (BWSHes) are a newer technology for helping young children to practice supported motor skills. Incorporating an assistive robot to mediate BWSH interventions can support further child motion and engagement, but almost no work to date has studied autonomous robot-mediated BWSH use. We conducted a six-month-long single-case study series with two participants to evaluate the effectiveness of an autonomous assistive robot in motivating the children to move and stay engaged while in the BWSH. We collected and analyzed objective movement data and self-reported parent survey data to determine how much the child moved and stayed engaged during sessions. Our results showed that both children displayed more movement while the assistive robot was active (relative to in prior no-robot periods). Parents also rated their children as more engaged while the assistive robot was present. An autonomous assistive robot may provide motivation for a child to move and stay engaged while using a pediatric rehabilitation aid such as a BWSH. The products of this work can benefit roboticists who work with children with disabilities and researchers who use pediatric rehabilitation technologies.**

Index Terms—**List of keywords (from the RA Letters keyword list)**

I. Introduction

YOUNG children with motor disabilities are typically late to major motor milestones [1]. Pediatric rehabilitation technologies such as treadmill trainers can help improve long-term motor skill development by offering supported walking practice [2], but these systems typically do not allow for two-dimensional overground motion with the ability to freely interact with toys and other elements in the environment. This gap led us to focus on pediatric body-weight support harness systems (BWSHes) as the central mobility aid in the presented work; these systems enable users to traverse the ground under a given system footprint and access toys, robots, and other items in the surroundings.

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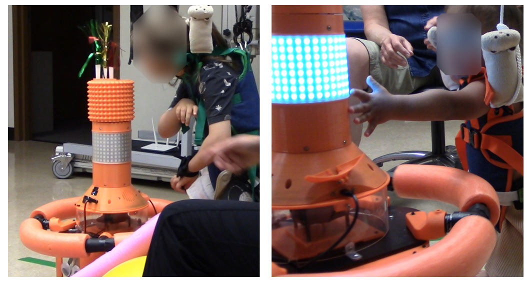

Figure 1: Images of our study participants interacting with the assistive robot while using a BWSH.

Further, assistive robots have shown recent promise as an engaging mediating component of a pediatric intervention [3], [4]. Embodied assistive robots with age-appropriate stimuli can help promote the interrelated skills of social and object interaction in addition to motor skill practice [5]. Accordingly, we were interested in studying the pairing of a BWSH with an engaging assistive robot (GoBot, a pre-existing custom autonomous system shown in Fig. 1) to study if the assistive robot could promote more movement by two children with different motor disabilities. We used a single-case study design for our work, as single-case work can reveal the unique benefits of the assistive robot intervention for each child [6]–[8].

Overall, our main research goal for this work was to *understand if an autonomous assistive robot could motivate child motion and engagement during a physical therapy intervention with a BWSH.* We conducted a six-month-long single-case series deployment with GoBot and two children with motor disabilities, shown in Fig. 1, both of whom were unable to independently walk at the beginning of the study. We cover related work in the fields of pediatric rehabilitation technologies and assistive robotics in Section II. We describe the robot and harness hardware that we used for the study and the single-case series study design in Section III. Our results, as reported for each participant in Section IV, showed that both children in the BWSH tended to improve their amount of movement and engagement over the study and while interacting with the assistive robot. Finally, we discuss of our results, their design implications, and the strengths and limitations of the work in Section V, and end with conclusions in Section VI. The main contribution of this work is evidence that incorporating a mobile autonomous assistive robot as part of a relatively long-term physical therapy intervention can help keep a child with a motor disability moving and engaged.

II. Related Work

We reviewed works in the pediatric physical therapy domain to inform the design of our intervention. We focused on pediatric rehabilitation technologies, including both robotic and non-robotic mobility aids that are sometimes used in conjunction with other types of assistive robots.

The treadmill trainer is the most commonly utilized pediatric rehabilitation technology for developing the physical skills associated with independent walking. Studies have shown that children with Down syndrome that use a treadmill trainer achieved earlier walking milestones compared to a control group without intervention [9], while children with cerebral palsy demonstrated overall gross motor improvements with a treadmill trainer [2]. However, treadmill training systems often prove monotonous; users are restricted to only moving on the treadmill and are unable to interact with their surroundings. To address this limitation, researchers are integrating technologies such as VR and biofeedback to make use of social and cognitive benefits associated with environmental interaction, thereby enhancing motor gains. Several studies have successfully incorporated VR games or environments (e.g., a VR soccer game [10]) to elicit more engagement during treadmill training with children [11], [12]. Similarly, researchers have created biofeedback tools that present motivating visual or audio cues to the user as a result of changes in biosignals such as heart rate [13], [14]. However, other types of assistive devices could offer more motivating affordances, such as physical environment exploration and interaction [4].

Gait trainers, exoskeletons, and BWSHes are other types of rehabilitation technologies that have successfully provided supported motor skill practice for adults and are now being researched for use with children with motor disabilities. Gait trainers, also known as overground supported-stepping devices, allow a child or adult to engage in social interaction while walking with support [15]. Results from a literature review showed that gait trainers can provide benefits in mobility levels and participation [16]. However, this type of device still limits the person's ability to reach and use their hands to interact with items of interest; an exoskeleton or BWSH may enable similar mobility practice and affords a child the use of their hands. Researchers have developed a wide array of rehabilitation exoskeleton technologies for adults, focusing on both upper and lower limb support [17], [18]. Research into pediatric exoskeletons, robotic or non-robotic, is a newer topic that requires further study [19], [20], but these devices are expensive and difficult to acquire [21]. Researchers are also investigating the effects of BWSHes for children with motor disabilities as a result of the success of these systems in adult rehabilitation [22], [23]. Portable BWSHes, such as the Andago system [24] or the Portable Mobility Aid for Children (PUMA) [25] (as used in our work), provide motor support to allow a child to freely move in an open space and use their hands to interact with objects [3], [4], [8], [26]. However, further long-term research is still needed to understand the gross motor benefits for children with motor disabilities and appropriate external motivators like an assistive robot are still needed to keep a child engaged while in the BWSH.

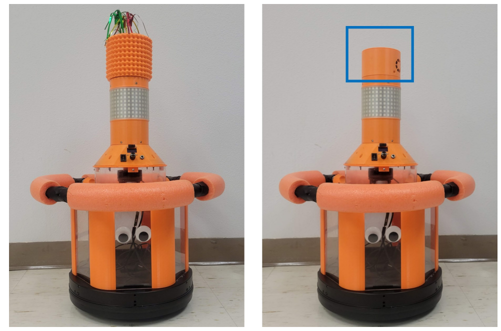

Figure 2: *Left:* Version of assistive robot used with our first participant, including light, streamer, and music reward modules. *Right:* Version of assistive robot used with our second participant. Light and music reward modules were the same, and a bubble reward module (indicated by the rectangle) was used in place of the streamer reward module.

We wondered if incorporating an autonomous assistive robot as part of the intervention would provide the necessary motivation for a child to move and stay engaged over time. We expected that an embodied robot could boost a child's amount of movement and engagement with motor skill practice since people (including children) prefer physically embodied robots to virtual agents in many cases [27]; it follows that having an assistive robot in the loop may provide higher levels of engagement during an intervention. Assistive robots are used across domains such as education [28], social skill development [29], and exercise [30], but little work has evaluated using an assistive robot in conjunction with a BWSH. Two studies, including one from our own similar past work, used robots to encourage a child in a BWSH to move [3], [4]. Both studies demonstrated preliminary evidence that the robots may be able to encourage a child to move and engage while using a BWSH, but partial-to-no robot autonomy was used, and the studies did not follow the type of single-case study design that is often used in clinical trials. In this paper, we build upon previous related work by using a fully autonomous robot with personalized features for each participant and a single-case study design.

III. Study Methods

We conducted a multi-month single-case series study with two participants to understand the impact of the assistive robot on motivating children with motor disabilities to move while using a BWSH, as further described below. We first elaborate on the study hardware used with both participants and then describe the methods for the study. Our university ethics board approved the study under #IRB-2020-0723.

A. Study Hardware

For the study, we used our custom assistive robot, GoBot, and a commercial BWSH, as further detailed below.

1) Assistive Robot: GoBot appears in Fig. 2. The robot was custom-built with a TurtleBot2 base running ROS Noetic on a Raspberry Pi 4. The robot included our previously designed light, bubble, and music modular reward hardware to encourage

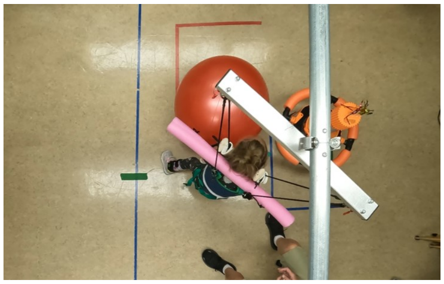

Figure 3: Overhead view of body-weight support harness (BWSH), assistive robot, participant, clinician, and toys.

child movement and engagement [30]. The robot's modularity encouraged a child-centric design by allowing the changing of reward hardware for individual users. Due to our first participant having a partial vision impairment, we used a high-contrast streamers reward, as shown at the left of Fig. 2, in place of the bubble reward. We used the light, bubble, and music hardware rewards for our second participant, as shown at the right of Fig. 2.

To enable autonomy, the robot was equipped with an RPLIDAR-A1 LiDAR sensor, a custom pre-existing overhead camera tracking system [31], and custom behavior tree software [32]. For the current effort, we designed manual behavior trees to personalize to each child. The behavior tree software allowed us to update manual trees between sessions based on feedback from parents and clinicians. During operation, the behavior tree autonomously chose movement and reward actions based on sensor data from the overhead camera tracking system and the LiDAR to encourage the child to move towards the robot. Movement actions included moving slowly towards or away from the child while reward actions included using the light, bubble, music, or a combination of rewards.

2) Body-Weight Support Harness: The harness system we used for our study was a portable Enliten PUMA support harness system [25]. Figure 3 shows the BWSH in the study space with one of our participants and the assistive robot. The BWSH is rated for users up to 60 lbs (27.2 kg). While secured in the harness, child users are able to freely move within a 9ft×9ft (2.7m×2.7m) floor area and interact with the environment (with unobstructed hands).

B. Study Design

We conducted 12 sessions during this study using a single-case ABAB withdrawal study design [33]. In a single-case withdrawal design, the study includes two phases: a baseline phase (labeled as "A") in which the intervention (i.e., the assistive robot) is not present and an intervention phase (labeled as "B") in which the assistive robot is added. The most common single-case study designs within the field of rehabilitation use the ABAB withdrawal pattern, where the baseline phase occurs for a number of sessions (i.e., 3 sessions for this study), then the intervention follows for the same number of sessions (3 sessions), and this pattern is then repeated for a second time [33]. This study design allows for repeated evidence of the impact of the intervention on each participant. As young children with motor disabilities will have unique needs and goals, we used the ABAB withdrawal design with each child serving as their own baseline and the assistive robot serving as the intervention. We used the BWSH across every session (as a base element), as both participants required the harness to be able to traverse the environment at the beginning of the study. The study phases were designed as follows:

- *First Baseline - A1* (3 sessions): The child used the BWSH with no assistive robot.
- *First Intervention - B1* (3 sessions): The child used the BWSH, and the autonomous assistive robot moved around the play space and used its features to encourage the child to move and stay engaged.
- *Second Baseline - A2* (3 sessions): The child used the BWSH with no assistive robot.
- *Second Intervention - B2* (3 sessions): The child used the BWSH with the assistive robot.

We conducted 12 sessions following this procedure, with the overall AAA-BBB-AAA-BBB withdrawal design. Each session lasted up to 30 minutes and occurred approximately every two weeks over a six-month period. These sessions took place between the participant's usual physical therapy sessions, which occurred approximately once every other week throughout the study for the first participant and once a week for the second participant.

C. Participants

Prior to the study, our clinical collaborators provided recommendations of prospective participants who would benefit from the use of the assistive robot and BWSH. Both participants who completed the study were unable to independently walk at the beginning of the study, making them suitable candidates to participate.

The first participant (P1) was female (4.1 years old) and has a diagnosis of pontocerebellar hypoplasia and cerebral palsy. At the beginning of the study, she was rated a GMFCS Level IV [34] and was unable to independently sit, crawl, or walk. The second participant (P2) was male (1.2 years old) and has a diagnosis of Trisomy-21 (Down syndrome). At the beginning of the study, he was able to sit and crawl, but was unable to walk independently. Both participants had experience interacting with the BWSH and the assistive robot in pilot sessions before the study.

D. Procedure

At the beginning of the study, parents signed an informed consent form and completed demographics questions and a pre-study survey. During each session, at least one clinician, the parents of the participant, and two research assistants were present. After the child was secured in the harness and cameras and sensors were set up to record the session, we began each session by first conducting a 2-minute walk test in the BWSH. This test has been used in pediatric rehabilitation studies to track long-term changes in walking ability for young children [35]. The participant was placed on a designated starting mark and was allowed to move freely around the play space. During the test, the clinician could provide verbal encouragement for the child to move but was not allowed to provide direct physical assistance. The robot was also active during the walk test for intervention sessions.

During the main part of the session, the clinician and parents could use any motivational tool, including toys, verbal encouragement, and direct physical assistance, to encourage the participant to move in the BWSH. During intervention phases (B1 and B2), the autonomous assistive robot moved around the play space and used used its features as an additional motivating tool. We administered a one-question engagement survey during every session to the parents every five minutes, as further described below. The participant remained in the BWSH until either 30 minutes passed or the child was unwilling or unable to continue and the clinician or parents recommended that the session end. We then removed the sensors from the child and the child was helped out of the BWSH. At the close of each session, parents completed the post-session survey and received \$15 in compensation. At the end of the study, parents completed the post-study survey.

E. Hypothesis

Our main hypothesis for the study was:

H1: Both participants will have a larger amount of overground movement and stepping and be more engaged during sessions with the assistive robot. This hypothesis is based on past work showing that using a mobile assistive robot can encourage children to move [30].

F. Measurements

We collected *behavioral* and *survey* data to understand how child movement and engagement changed over the study. Our *behavioral* measurements included overhead video tracking, processed ActiGraph sensor data, 2-minute walk test results, and BWSH duration. We measured the duration of active BWSH use during each session, with a maximum of up to 30 minutes. Our *survey* data included pre- and post-study surveys, intermittent parent ratings of child engagement throughout each session, and a post-session survey.

1) Overhead Video Tracking: We recorded overhead video during each session with a GoPro Hero Black 10 camera and then used OverTrack, our previously validated custom region-of-interest (ROI) tracker, to provide a post-hoc estimate of per-session overground movement by each child [31]. For each video, a researcher used OverTrack to extract the centroid location of the child in the environment in each frame. We then calculated the change in the child's centroid location between subsequent frames as a sum to estimate the total overground movement of each participant. Based on our standard tool operation protocol from the past work, we scaled the change in centroid location using the 2ft×2ft (0.61m×0.61m) right-angle tape mark seen in Fig. 3. We excluded position changes larger than 0.5ft (0.2m; unlikely based on maximum child ambulation speed [36]) and smaller than 0.06ft (0.02m; likely to be noise).

2) ActiGraph Sensor: We placed four ActiGraph GT9X Link sensors across the right and left ankles, dominant wrist, and hip of the child, to record changes in the child's movement throughout the study. For this analysis, we primarily focused on the right and left ankle sensor data, as we were most interested in the participants' walking movements. We used ActiLife v6.13.4 software and an algorithm from prior related work [37] to compute a count of the child's ankle movements during each session from the sensor data. We used the algorithm to calculate participant-specific thresholds for movement from the sensor data, and then the algorithm counted instances when both the acceleration and angular velocity readings exceeded the thresholds (start of movement) and subsequently when the angular velocity dropped below its respective threshold (end of movement). For this work, we did not use the smoothing step of the original algorithm based on input from our collaborators; they indicated that this smoothing (combined with the participants' initial irregular gait patterns) could lead to missed movements.

3) 2-Minute Walk Test Performance: We conducted the 2-minute walk test at the beginning of each session to track changes in the child's stepping ability over the study. A trained annotator video-coded each session to count instances of right and left footsteps during the 2-minute test. A second trained annotator video-coded a randomly selected 33% of the session videos to establish inter-rater reliability. The intraclass correlation coefficient (ICC) for the coding, as commonly used for continuous quantitative data [38], was 0.92 between the two coders. A value of 0.85 or higher is considered acceptable in observational studies of children [39].

4) Intermittent Engagement Survey: We asked parents to rate their child's level of engagement every five minutes during the session with the following custom Likert-type question: "My child was engaged during the past 5 minutes:" from Strongly Disagree (1) to Strongly Agree (7). Single-question surveys are a common way to measure young children with disabilities engagement with mobility technologies [40].

5) Pre- and Post-Study Surveys: At the beginning of the study, parents shared demographic information and completed a pre-study survey. Demographic questions collected child age, gender, diagnoses, and if the child was able to walk or crawl. The pre-study survey included 7-pt Likert scales of the three components of the Negative Attitudes towards Robots Scale (NARS) [41], the Trust Perception Scale-HRI (TPS-HRI) subscale items [42] (rated as a percentage from 0 to 100), and free-response questions asking about the parents' prior experiences with robots. We administered these surveys to parents to understand their perceptions and trust levels of a robot being used as a component of their child's clinical care, but also to potentially use the same robot in the parents' homes. At the end of the study, parents completed the same survey with additional free-response questions asking about their perceptions of the assistive robot and BWSH.

6) Post-Session Survey: Parents answered the following 7-point Likert-type question at the end of sessions during intervention phases: "Do you think your child was engaged with the robot throughout the session?" from Strongly Disagree (1) to Strongly Agree (7). We also asked parents to expand upon their answer in a free-text response.

G. Analysis

When analyzing our data, we considered trends between phases and across sessions.

1) Behavioral Data: For each behavioral measurement, we evaluated trends between phases of the study using the log response ratio (LRR). Commonly used in single-case work across domains such as ecology [43], special education [44], and behavioral psychology [45], LRR represents the natural log ratio of the mean values of a behavioral measurement (e.g., overhead video tracking). It compares the intervention phase (M_t) to its preceding baseline phase (M_b) using the following equation:

$$LRR = ln(\frac{M_t}{M_b}) \tag{1}$$

A positive LRR value indicates a benefit of the intervention, while a negative LRR value indicates the opposite. An LRR value of zero marks no change. Larger LRR values represents a larger change between phases. For all of our behavioral measurements, we calculated the LRR value for the first intervention phase against the first baseline phase (i.e., B1 to A1; identified as LRR_1) and the second intervention phase against the second baseline phase (i.e., B2 to A2; LRR_2) for each participant. We report each individual LRR value, as well as the per-user mean LRR (LRR_M).

2) Survey Data: We report phase-wise and participant-wise descriptive statistics for each survey. We used observations from the free-text responses to help explain the quantitative data.

IV. Results

We present the behavioral results for P1 and P2 first, followed by the survey results. Figure 4 shows the overhead tracking, ActiGraph sensor, 2-minute walk test, and intermittent engagement rating results for each participant, while Table I specifies the LRR values when comparing intervention phases with preceding baseline phases.

A. Behavioral Results

P1: Our first participant completed all 12 sessions in the BWSH and the assistive robot was autonomous and fully functional for every intervention session. The LRR results indicated a positive change during intervention sessions in all behavioral measurements. This participant tended to move more in sessions with the assistive robot and showed the highest amount of movement during sessions with the robot. We observed differences in the child's amount of right and left ankle movements, but they tended to display closer symmetry towards the end of the study. The 2-minute walk test results showed variability for both right and left feet, but the child's amount of stepping tended to improve throughout the study. P1 tended to use the BWSH for at least 20 minutes during most sessions, including all sessions with the assistive robot. Three baseline sessions (3, 7, 9) lasted less than 20 minutes.

P2: Our second participant completed all 12 sessions in the BWSH. The assistive robot was autonomous for every intervention session with the exception of session 10, when it was teleoperated by a research assistant due to an error in the overhead camera system. The LRR results showed a positive change for all behavioral measurements, with the exception of duration in the BWSH for the second intervention phase (LRR_2). The behavioral results show that the participant tended to move more over the course of the study with the exception of the final two sessions. An important note for interpreting this data is that the participant started to independently walk prior to the 11th session. We observed the highest amount of overground movement in the final session with the assistive robot and the highest count of ankle movements in session 10 (also with the assistive robot). The child also tended to show some variability in right and left ankle counts of ankle movements, which may have been a result of the child using one foot more than the other while learning to kick a toy ball over the course of the study. P2 generally showed an increase in the amount of steps taken during the 2-minute walk test throughout the study. The participant used the BWSH for at least 25 minutes in every session and for the full 30 minutes in 7 of the 12 sessions, possibly saturating this measurement. P2 used the harness less in sessions 11 and 12, which may have been due to the child learning how to independently walk.

Video clips from each user near the beginning and end of the study appear in the paper's supplementary material.

B. Survey Results

P1: Results of the intermittent engagement survey, as displayed in Fig. 4, showed that parents generally rated their child as more engaged during intervention sessions, matching the behavioral measurements. For the NARS questionnaire, there tended to be an increase in ratings between the start and end of the study for the interaction ($M = 2.0$, $SD = 0.0$ before; $M = 3.2$, $SD = 0.4$ after) and social ($M = 2.0$, $SD = 0.0$ before; $M = 3.2$, $SD = 1.2$ after) components. The emotional component showed a decrease in ratings ($M = 5.7$, $SD = 0.6$ before; $M = 4.7$, $SD = 0.6$ after). A decrease in ratings for each component of the NARS would indicate that the parent tended towards a lower negative attitude towards robots for that component. TPS-HRI ratings of trust increased between the start and end of the study ($M = 76.0$, $SD = 23.7$ before; $M = 80.0$, $SD = 24.9$ after). Figures for these survey results appear in the paper's supplementary material. Results of the post-session survey found that parents tended to rate their child as engaged with the robot ($M = 5.8$, $SD = 0.4$).

P2: As shown in Fig. 4, the parents tended to rate their child as very engaged throughout most sessions. For the interaction component of the NARS questionnaire, there was no change in ratings between the start and end of the study ($M = 4.0$, $SD = 1.2$ before; $M = 4.0$, $SD = 1.2$ after). The social component showed a decrease in ratings between the start and end of the study: social ($M = 2.7$, $SD = 1.0$ before; $M = 2.5$, $SD = 1.2$ after), while the emotional component showed a small increase in ratings ($M = 4.0$, $SD = 1.0$ before; $M = 4.7$, $SD = 0.6$ after). Trust ratings tended to increase between the start and end of the study ($M = 67.0$,

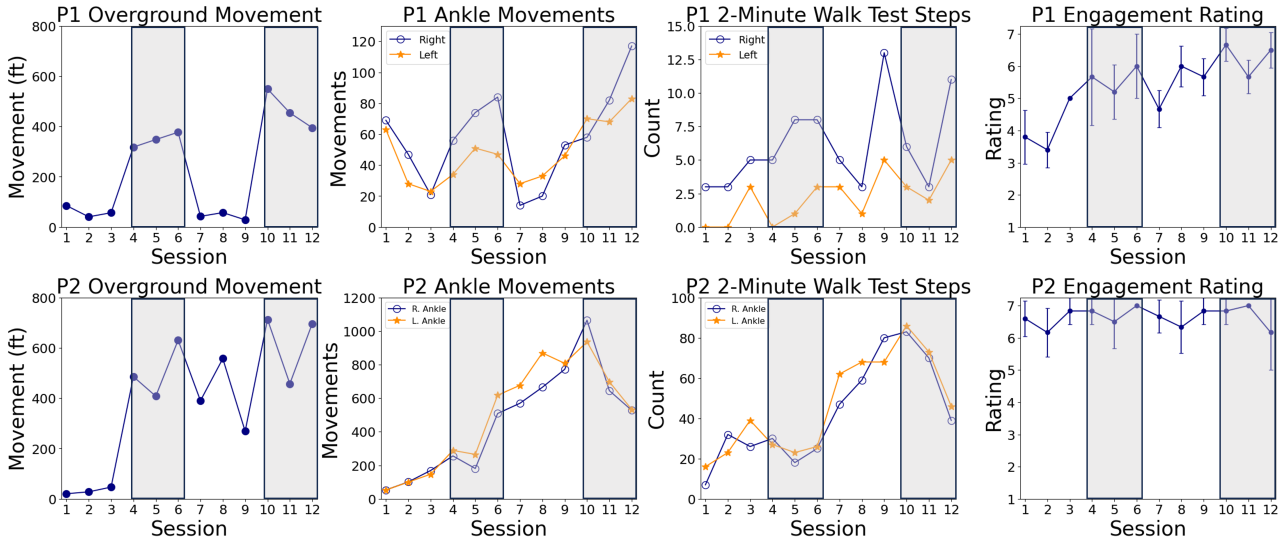

Figure 4: Behavioral and selected survey results by session for P1 (top) and P2 (bottom). We note that the results for P1 and P2 used the same measurements, but showed different scales of movement. Results include overhead-video-based tracking, ActiGraph-based count of ankle movements, 2-minute walk test performance, and intermittent engagement ratings. The shaded area highlights the intervention phases of the study (i.e., sessions with an active robot).

Table I: Log response ratio (LRR) results for P1 (left) and P2 (right). We computed the LRR of each intervention phase with its preceding baseline phase and the overall mean LRR. LRR_1 compares the first intervention phase with the first baseline phase while LRR_2 compares the second intervention phase with the second baseline phase. A positive LRR value indicates a positive trend for the intervention phase when compared to the preceding baseline phase. Shaded values specify large increases in child movement when comparing an intervention phase to the preceding baseline phase (i.e., LRR > 1).

Measurement	P1 LRR_1	P1 LRR_2	P1 LRR_M
Overground Movement	1.74	2.39	2.06
Ankle Movements	0.32	0.90	0.61
2-minute Walk Test	0.57	0	0.29
BWSH Duration	0.01	0.32	0.21

Measurement	P2 LRR_1	P2 LRR_2	P2 LRR_M
Overground Movement	2.77	0.43	1.60
Ankle Movements	1.22	0.01	0.62
2-minute Walk Test	0.04	0.03	0.04
BWSH Duration	0.07	-0.06	0.01

$SD = 31.6$ before; $M = 75.0$, $SD = 38.1$ after). The parents tended to rate their child as overall engaged with the robot in intervention sessions ($M = 6.8$, $SD = 0.4$).

V. Discussion

In this work, we evaluated how an autonomous assistive robot and BWSH could be leveraged to provide motor skill practice for two children with different motor disabilities. This section covers our hypothesis testing, key design implications from the work, and important strengths and limitations of the work.

A. Hypothesis Testing

Our main hypothesis was largely supported by the study results. We found that for both participants, sessions with the autonomous assistive robot had positive LRR values for overhead tracking, ActiGraph sensor, and 2-minute walk test results (with the exception of sessions 11 and 12 for P2), indicating more movement while the robot was active. Previous work has shown that assistive robots can promote children to move [3], [30], and our results add further evidence in early pediatric contexts. Both participants also used the BWSH for over 20 minutes in every intervention session with the assistive robot, supporting the notion that the robot could potentially motivate children to obtain a higher dosage of physical therapy interventions. These results align with parent free-response feedback, which included notes such "[P1] followed [the robot] and listened to the music" and that "[the robot] was good." Similarly, the parents of P2 said that "the robot was a great experience with movement, bubbles, and music" and that "my child liked the bubbles and to chase and push the robot."

B. Design Implications

Our study displayed the value that single-case series studies can provide in learning about child-robot interactions during pediatric rehabilitation. We evaluated each child's results independently against their own baseline, which gave us valuable insights into how the assistive robot was encouraging motion and engagement. We observed each child increase their amount of movement over the course of the study, but with unique changes in motor ability, including the development of independent walking by our second participant (P2). Additionally, with this child-centric study design, we were able to focus on each child's preferences for the robot and use appropriate stimuli. As the field of assistive robotics progresses, we believe it is important to include single-case series studies in more work when considering assistive robots for pediatric rehabilitation. We recognize the necessity of studies with large groups of participants to generalize results, but single-case study designs reduce the chance of missing important details and outcomes from an individual child's progress. These types of studies allow researchers to emphasize personalized capabilities of robots and accommodate the unique needs of each child.

While we were successful in utilizing full autonomy for the robot throughout nearly every session of the study, we also informally observed the clinician ask for specific actions from the robot. It follows that although an autonomous robot can help extend clinician effort, allowing clinicians easy access to override the autonomy may be most appropriate for clinical pediatric interventions. We found that participant 2's session 10 (with the robot being teleoperated) yielded the highest amount of movement, although sessions with the autonomous robot generally tended to show high amounts of movement as well. Generally, we found preliminary evidence that BWSHes may be an effective rehabilitation tool for children who need to practice motor skills with assistance, although further study is still needed with a more diverse group of children with motor disabilities. Both participants tended to increase their amount of overground movement and 2-minute walk test results over the course of the study. P2 also learned the ability to independently walk just before our 11th session. With the BSWH, each child was able to explore the environment and could interact with the assistive robot, toys, clinicians, and parents while practicing important motor skills for standing and walking independently. Robot-mediated pediatric interventions with a BWSH show potential for being a successful pairing to increase dosage of BWSH use, warranting further study with larger groups of participants and comparing the BWSH to more common mobility technologies. The parents of P2 mentioned in free-response feedback that "[the BWSH] was great. It worked well and got [the child] walking a lot faster."

C. Key Strengths and Limitations

Our work has several strengths. We conducted a successful and relatively long-term intervention, measuring changes in gross motor benefits for children with disabilities over multiple months. Both participants displayed important gains in levels of movement and motor skill practice, and our second participant even learned the ability to independently walk during the course of the study. The robot was successfully autonomous for every session but one, and both children tended to move more with the robot active, demonstrating the potential effectiveness of a robot-mediated intervention.

One limitation of this work is the small number of participants and the uncertain impact of the participant's regular physical therapy sessions. Single-case study designs provide valuable evidence of an intervention's success even with small sample sizes, but further clinical trials with larger sample sizes would be necessary to speak to the broader potential of the assistive robot and BWSH. In future work, we aim to conduct a more controlled study with more participants and with a wider range of feedback collected from the participants, clinicians, and parents. A second limitation is that while our multi-month study is relatively long-term for child-robot interaction studies, the lengths of studies for rehabilitation technologies can involve more regular interaction and longer timeframes in addition to more conditions. For example, we were unable to assess if the children's motor skills gains were maintained after the study was completed and the BWSH was removed. In future studies, we aim to complete more sessions over a longer period of time with the presence of the BWSH (vs. other mobility aids) also serving as a condition.

VI. Conclusion

In this work, we set out to understand whether an autonomous assistive robot and BWSH pairing could promote movement and engagement for children with motor disabilities. We conducted a successful single-case series study with two participants that were able to practice motor skills and interact with the environment. Our results included some evidence that the robot could keep both children moving and engaged while in the BWSH for the typical length of a physical therapy session. Our single-case series study demonstrated the capabilities of a mobile assistive robot in physical therapy domains, as well as evidence that using a BWSH with an assistive robot can perhaps maximize movement and engagement. As one parent observed during a session: "Wow! Look at [my child] go!"

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