Harnessing the Power of Movement: A Body-Weight Support System & Assistive Robot Case Study

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***Abstract*— Young children with motor disabilities face extra obstacles to engaging in movement and initiating social interaction. A body-weight support harness system (BWSS) allows a child to take steps, explore the environment, and interact with people and objects, but further research is needed to understand how this type of system can help children with motor disabilities. Assistive robots have the potential to keep a child engaged and motivated during physical therapy sessions with a BWSS. We conducted a case study over three and a half months to understand if the BWSS alone and if the BWSS with an assistive robot could promote child movement and engagement. Our results show that the child tended to increase their amount of movement over each session with the BWSS. The assistive robots used in this study also tended to keep the child engaged. The products of this work can benefit clinicians and researchers interested in early mobility intervention technologies, as well as roboticists working in the child mobility domain.**

I. Introduction

For young children with motor disabilities, learning movement skills and engaging in physical activity are important to physical, cognitive, and social development [1], [2]. Assistive mobility devices and technologies, such as partial body-weight support treadmill training and gait support walkers, are widely used in pediatric rehabilitation to facilitate active walking experiences, increase physical activity, and promote daily life participation [3], [4]; however, these systems focus mainly on the singular skill of walking [5] and can limit the child's social and object interaction during physical therapy sessions. For children with motor disabilities (such as Down syndrome or cerebral palsy), using a body-weight support harness system (BWSS) has shown feasibility in providing social interaction and gross motor skill benefits [5], [6]. A BWSS provides a large open area for a child to explore and has the potential to assist children with motor disabilities to develop self-initiated mobility skills while encouraging exploration of and interaction with people and objects in the environment [7]. However, there is little work on the use of BWSSes for children with motor disabilities classified as level IV or V on the Gross Motor Function Classification System (GMFCS) [8], despite the strong potential for this type of intervention to support these children's holistic development. Hence, we are investigating the potential and effects of BWSSes for non-ambulatory children in clinical settings.

It can be difficult to keep a child engaged and calm during a physical therapy session [9]. Technology-based solutions such as virtual reality (VR) have shown promise for encouraging motivation and engagement during physical therapy sessions [10], but robots can offer more flexible, motivational, and social abilities than other types of technology [11], [12]. Accordingly, assistive robots, which can help a child achieve goals over the course of therapy, are a newer resource for encouraging child mobility that combine fun toy-like stimuli with long-term adaptability. Pairing a BWSS with a mobile assistive robot is therefore a promising fit for supporting engaging motor practice in long-term interventions for children with motor disabilities. In this work, we evaluated the efficacy of a BWSS with and without assistive robots designed to encourage child movement and engagement.

Fig. 1: *Left:* Shelbytron, a custom mobile assistive robot with light, joke, encouraging phrase, and music stimuli. *Right:* GoBot, a custom mobile assistive robot with light, music, and air dancer stimuli.

Our central research goal in the presented work is to begin to understand *whether a BWSS and a BWSS coupled with an assistive robot could encourage movement and engagement during physical therapy interventions for children with GMFCS Level IV or V motor disabilities*. We conducted a case study with a child who has a GMFCS Level IV motor disability. This user experienced sessions with both a BWSS alone and a coupled BWSS and assistive robot to help us understand how the harness and the assistive robot impact movement and engagement during sessions. We used two pre-existing custom research robots, Shelbytron and GoBot (shown in Fig. 1), to support the robot-mediated sessions. In this paper, we first cover related work in physical therapy technologies and assistive robotics in Section II and then elaborate on our study and assistive robot designs in Section III. As conveyed in Section IV, our case study results showed that the child tended to improve their self-initiated

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Fig. 2: *Left:* Close-up camera view of the child in the BWSS while interacting with GoBot. *Right:* Overhead camera view of the child interacting with Shelbytron.

step-taking while in the BWSS and the assistive robots tended to encourage the child to follow the robot. Finally, we draw conclusions in Section V. The contributions of this work are early evidence that 1) the BWSS can allow a child with a motor disabilities to practice overground movement when they otherwise would not be able to and 2) an assistive robot can help keep a child with a motor disability engaged and encourage them to move towards the robot while they are using a BWSS.

II. Related Work

Related work on early mobility intervention tools and assistive robots informed our intervention and study design. Across physical therapy interventions, tools such as treadmill trainers and support walkers have been deployed successfully in interventions. Studies with treadmill trainers have been conducted for children with motor impairments originating from cerebral palsy (CP) or Down syndrome with resulting evidence of positive benefits for gait function, walking speed, and gross motor performance [13]–[16]. While treadmill training provides clear benefits, drawbacks such as restricting a user from exploring the environment and inhibiting manipulation of objects limits the overall impact of this intervention.

Gait trainers are typically used when a child is unable to fully bear their weight [17]. Outcomes of gait training have shown positive qualitative impacts on movement and social interaction for children with CP [18]. A gait trainer provides a child needed trunk support to move more freely around the environment, but this type of aid still limits the child's ability to reach and interact with items of interest.

A BWSS can provide appropriate support for children with motor disabilities and can enable them to explore the environment, interact with people, and manipulate objects; however, only a small amount of research has involved children's use of these types of systems. Portable BWSSes have been successfully deployed for children with CP, spina bifida, and Down syndrome, yielding preliminary positive evidence for supporting movement practice [5], [6], [19]. The Andago gait training system is portable, similar to the Portable Mobility Aid for Children (PUMA) system we used in this study, and allows a user to move safely in the environment but initial studies with children have been short-term [20]. Further work with BWSSes are needed to better understand their feasibility; this work aims to provide further evidence of system viability with children with motor disabilities classified as GMFCS level IV.

Assistive robot technologies have seen a recent surge in use with children with disabilities. Assistive robots can offer more motivation than similar types of technologies which are not embodied in the physical world [11], and have achieved preliminary success in mobility encouragement. In past studies of robot-assisted treadmill trainers, such as Lokomat [21], these systems improved walking performance [22], [23], but faced similar limitations as those of treadmill training generally. Newer research into exoskeleton-assisted gait training shows promise [24], [25] but may not be appropriate for very young children.

Within the research area of socially assistive robotics, NAO and Dash robots provided motivation for a child with Down syndrome to move while in a BWSS [7]. The study showed that the robots could encourage the child to complete motor tasks such as climbing while in the BWSS but further validation with more participants is needed. In our own previous work, we deployed a version of GoBot with a bubble module in a playgroups with children with typical development; these participants stood and engaged with the robot more while it was active [26]. These initial results encouraged us to deploy robots alongside the BWSS in the current study. Our goal for this work was to examine initial benefits of the BWSS and consider if the assistive robots could encourage a child with a motor disability to keep moving and stay engaged while in the BWSS.

III. Methods

We conducted a case study over the course of 3.5 months, as further described below. The study was approved by our university ethics board under protocol #IRB-2020-0723.

A. Study Design

Our case study followed an ABA single-subject-style design with three phases: baseline, treatment, and retention. The seven sessions of the study each lasted up to 30 minutes and occurred roughly biweekly (every two weeks) between normally occurring physical therapy sessions. The phases were designed as follows:

- *Baseline* (2 sessions): The child used the BWSS, and no robot was present.
- *Treatment* (3 sessions): The child used the BWSS, and one of the assistive robots was also present and active. The parents and clinician decided which robot to use prior to the start of each session.
- *Retention* (2 sessions): The child used the BWSS, and no robot was present.

B. Study Hardware

Key hardware to our study design included the BWSS and assistive robots, as further described below.

1) Body-Weight Support Harness System (BWSS): Our BWSS was a portable PUMA support harness system [27]. The BWSS is rated for users up to 60 lbs (27.2 kg) and allows a child to move within a 9ft×9ft (2.7m×2.7m) floor area. Figure 2 shows the BWSS and study space.

2) Robotic Systems: In the study, we used Shelbytron in session 3 and GoBot in sessions 4 and 5. Each robot offered different reward features for encouraging child movement and engagement.

Shelbytron, as shown in Fig. 1, is a wheelchair dog-like robot designed in collaboration with physical therapy experts at the Oregon Health & Science University (OHSU) Doernbecher Child Development and Rehabilitation Center (CDRC) in Eugene, Oregon. The robot runs on a Teensy 3.6 microcontroller. Included features such as lights, jokes, encouraging phrases, and music were designed to motivate child movement. Shelbytron was teleoperated in this study.

GoBot, as shown in Fig. 1, was designed in collaboration with kinesiology experts in the Oregon State University Disability and Mobility Do-It-Yourself Cooperative. In prior work, we designed and conducted an exploratory study with GoBot and our custom modular reward stack [26], [28]. The robot uses a TurtleBot2 base which is running ROS Noetic in Ubuntu 20.04 on a Raspberry Pi 4. For this study, the robot used light, music, and inflatable air dancer stimuli on the reward stack and was teleoperated.

C. Participants

One participant (female, 4.1 years old) completed the study. The participant has a diagnosis of pontocerebellar hypoplasia and cerebral palsy. At the start of the study, she was rated a GMFCS Level IV [8] and was unable to independently sit, crawl, or walk, or verbalize. The child had experience interacting with the BWSS and both assistive robots during exploratory sessions prior to the study.

D. Procedure

Each study session was administered by one clinician and two research assistants. At the start of the study, the parents reviewed and signed an informed consent form and completed the demographics and pre-study surveys. Before the start of a session, a GoPro Hero Black 10 camera recording at 30 Hz was placed overhead and the child was secured into the BWSS. ActiGraph GT9X Link sensors, which recorded at 100 Hz, were placed on the right ankle and hip of the child and then the session timer and 30-second walk test would begin. During sessions, we used a Canon camera recording at 30 Hz to record the child's leg movements and affect. During the baseline and retention phases, the clinician and parents could use any motivational tool to encourage the participant to move in the BWSS during and following the 30-second walk test. During the treatment phase, the robot chosen by the clinician and parents was teleoperated by a researcher and could use any of its features to motivate the child to move in the BWSS. The clinician and parents were also allowed to encourage the child to move, during all phases. After completion of the 30-second walk test, the participant would remain in the BWSS until either 30 minutes pass or the clinician or parents deem that the session should end. At the end of a session, the sensors were removed from the child and the child would be taken out of BWSS. Parents completed the post-session surveys and were compensated $15 for the session. At the end of the study, parents completed the post-study survey.

E. Measures and Analysis

We collected data which focused on two measures: child *movement* and *engagement*. Movement-based measures included video coding of steps, ActiGraph sensor data, overhead video data, and 30-second walk test results. Engagement-based measures included video coding of child-robot interaction, mean child-robot distance, BWSS use duration, and self-report surveys. For each metric, we analyzed how the data trended over each session and between each phase. For ease of matching the framing information about these measures with later results and interpretation of data, the order of measure explanations here matches the later order of the results presentation.

Step video coding: We used the up-close view provided by the Canon camera to annotate visible, in-frame child steps, including self-initiated and assisted steps. A trained rater completed coding of all data, and a second trained coder repeated this process with 15% of the videos to establish an inter-rater reliability (IRR). Our Cohen's Kappa value of 0.87 shows a strong degree of reliability; 0.85 or higher is considered acceptable in observational studies of children [1].

ActiGraph sensor data processing: We first transferred the recorded sensor data using the ActiLife v6.13.4 software. We fed the root mean square (RMS) values of the tri-axial acceleration and angular velocity data into an algorithm described further in [29], which determined a count of events that were likely to be ankle movements. For this work, we focused on the ankle sensor recordings, which provide results most closely corresponding with overground walking movement. Note that we skipped the smoothing step of the algorithm upon the advice of our kinesiology collaborators. Otherwise, the algorithm calculates a threshold and uses it to determine when a movement begins and ends, i.e., beginning when both the acceleration and gyroscope RMS exceed the thresholds and ending when the gyroscope data drops below its threshold. The data for sessions 1 and 4 were lost due to recording errors.

Overhead video tracking: Using the overhead video recorded with the GoPro, we ran a custom region-of-interest (ROI) tracker to estimate the total overground movement of the child during each session. For each video, a researcher initially drew bounding boxes over the child (for all sessions) and robot (for treatment sessions), and they re-drew boxes if the tracker failed. The ROI tracker outputted the centroid location of each bounding box for every video frame. We calculated the total amount of child movement during each session by summing the change in the child's centroid location between subsequent frames after excluding position changes larger than 0.5ft (0.2m; unlikely based on maximum child ambulation speed [30]) and smaller than 0.06ft (0.02m; likely to be noise). The change in the centroids was scaled using the 2ft$\times$2ft (0.61m$\times$0.61m) right-angle tape mark shown in the overhead view of Fig. 2.

30-second walk test performance: At the start of each session, we conducted a 30-second walk test with the participant in the BWSS to track changes in baseline stepping ability over the study. The participant was placed on a designated starting mark, and we measured their total amount of forward movement during a 30-second period. This process was recommended by our clinician collaborators for tracking gross changes in walking ability.

Child-robot interaction video coding: To help us understand the influence of the robot on the child's movement, a trained rater annotated child-robot interactions using the overhead video from treatment sessions. This coder counted instances of successful encouragement (i.e., the child came within 3ft (1m) of the robot while it was active) and failed interactions (i.e., the robot moved again before the child approached the robot). Interactions of this kind were labeled as robot-initiated if the robot moved immediately prior to the child's approach or as child-initiated if the child moved toward the robot first. A second trained coder video coded the same treatment session videos to establish our IRR. Between these two coders, we established a Cohen's Kappa of 0.88 on the counts of successful and failed interactions.

Overhead video-based child-robot spacing: Using the outputted centroid locations from the ROI tracker described above, we computed the mean and standard deviation of child-robot Euclidean distance for each treatment session.

BWSS use duration: We measured the duration of active BWSS use during the study session. The maximum time allowed was 30 minutes, due to limitations on study length and recommendations from our clinical collaborators.

Self-report surveys: At the beginning of the study, parents filled out demographics and pre-study surveys. Demographic questions collected child age, gender, and diagnoses. In the pre-study survey, we used the Likert-type standard questions of the NARS (Negative Attitudes towards Robots Scale) [31] and the Trust Perception Scale-HRI [32] to gauge parents' pre-existing perceptions of robots. The pre-study survey also contained free-response survey questions regarding parents' experiences with BWSSes, experiences with robots, and thoughts on the usefulness of both BWSSes and robots.

At the end of each session, parents were given a BWSS perception survey, which asked questions on a 7-pt Likert type scale relating to the child's engagement while they were in the harness. The survey asked the parents to rate the child's:

- Excitement (Very Calm (1) - Very Excited (7))
- Enjoyment (Very Unhappy (1) - Very Happy (7))
- Interaction level (Very Poor (1) - Very Well (7))
- Safety (Very Poor (1) - Very Good (7))

A researcher also took notes on direct clinician and parent insights during sessions. During the treatment sessions, parents also completed a survey with Likert-type and free-text questions asking about robot engagement. The Likert-type questions touched on three topics: general perception of child engagement with the robot of choice, belief in robot usefulness for child well-being, and interest in participating in future studies, each on a scale of Strongly Disagree (1) to Strongly Agree (7). Finally, we asked parents the following

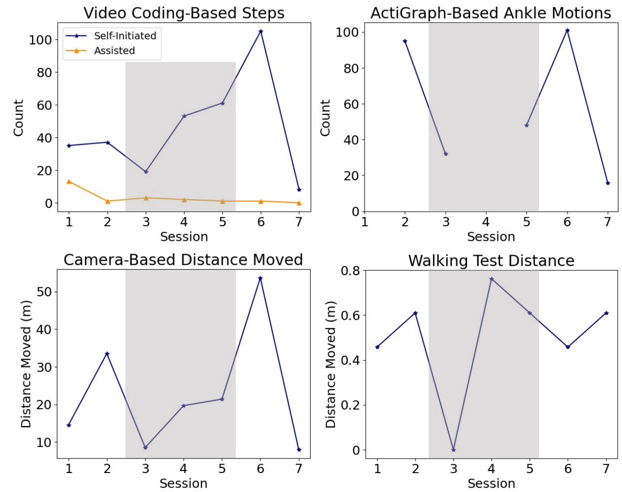

Fig. 3: Movement-related results by session for video coding of steps, ActiGraph-based count of ankle movements, overhead video-based movement tracking, and 30-second walk test distance. The shaded area highlights the treatment phase of the study (i.e., sessions with an active robot).

free-response questions: 1) How do you think robots can be useful to improve the well-being of children?, 2) In general, how did your child interact with the robot throughout the session?, and 3) In general, what is your perception of the robot used in this session?

At the end of the study, parents completed the post-study survey which asked the same NARS and trust perception questions as the pre-study survey. The post-study survey contained similar free-response questions as the pre-study survey for parents to answer regarding their perceptions of the BWSS, assistive robots, and the usefulness of both systems.

IV. Results and Discussion

Below, we report our study results in terms of our two main measures: child *movement* and *engagement*. We compare treatment phase results with baseline and retention phase results, in addition to looking at trends across all sessions.

A. Movement-related Results

Our movement results showed how the child's ability to move while in the harness trended both with and without an assistive robot. Figure 3 shows the per session results for each movement measure, including video coding of child steps, ActiGraph sensor, overhead video tracking, and 30-second walk test results. Our video coding of child steps revealed that for each session, the child took at least 10 self-initiated steps while in the BWSS for 6 of the 7 sessions and the child tended to increase the number of self-initiated steps for 4 of the 7 sessions. We observed that the highest self-initiated step count was over 100 in session 6 and that assisted steps remained low for each session.

Similar to our video coding results, the highest values of ankle movement counts and total overhead camera-based movement calculated by the ROI tracker was in session 6. Counts of ankle movements and total overhead camera-based

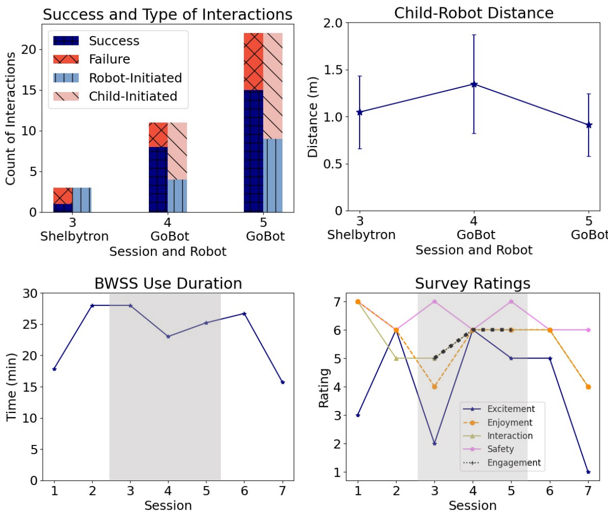

Fig. 4: Engagement-related results by session for video coding of child-robot interactions, mean and standard deviation of Euclidean child-robot distance, duration of BWSS use, and survey results. In the lower plots, the shaded area denotes the treatment phase.

movement were higher in the final treatment session when compared with the first. The 30-second walk test conducted at the beginning of each session showed movement of at least 1.5ft (0.46m) or more in 6 of the 7 sessions. The participant traveled the most distance during the 30-second walk test in session 5 with GoBot.

B. *Discussion of Movement Findings*

The result of our movement-related measures support that the BWSS enabled the child, who was unable to independently step or crawl at the beginning of the study, to successfully practice taking steps during every session. The child's movement showed a tendency to increase when comparing the first and second-to-last sessions. The final session showed a reduction in movement, which may have been due to the child being sick prior to the session. Overall, the BWSS shows promise for potentially improving child mobility during physical therapy interventions.

The robot's ability to motivate child motion was less clear. We observed that the final treatment session with an active robot showed higher movement-related results when compared with the first baseline session, although the largest amount of total movement occurred in session 6, during the retention phase. The amount of movement tended to rise during the treatment phase, and the highest observed 30-second walk test results occurred during a treatment session with GoBot. The results showed that an assistive robot with engaging stimuli can encourage a child in a BWSS to move, although further work is needed to determine the effects over a longitudinal study.

C. *Engagement Results*

Our engagement results, with per session results shown in Fig. 4, indicate trends in overall endurance and enjoyment of the child while in the BWSS and with an active robot. Our engagement measures included video coding of child-robot interactions, child-robot spacing, duration of BWSS use, and survey results. While video coding each child-robot interaction, we observed instances of both robot- and child-initiated interactions. Successful interactions with an assistive robot tended to rise during the treatment phase, and both child- and robot-initiated interactions tended to rise as well. The mean child-robot spacing across treatment sessions was lowest in session 5 with GoBot, followed by session 3 with Shelbytron. The child remained in the BWSS for at least 20 minutes in 5 of the 7 sessions and spent the longest time (28 minutes) in the harness during session 3 with Shelbytron.

Our survey results show that the parents rated the child's excitement, enjoyment, interaction and safety in the harness as high over most sessions. During the treatment phase, parents rated child engagement as higher in the final treatment session when compared with the first.

D. *Discussion of Engagement Findings*

Engagement during each phase showed some variability but tended to remain high. The child spent at least 20 minutes in the BWSS for 5 of the 7 sessions, and the parents rated the child's interaction and enjoyment as high for each session, with the exception of the final session. The clinician observed during a session that "[the child] approached [the parents] more than once" and "she took great steps today."

Engagement results during the treatment phase showed a tendency for the assistive robots to keep the child motivated and engaged, as supported by interaction, spacing, BWSS duration and survey results. During each session of the treatment phase, we observed that the child initiated interactions and approached the robot more often. A lower mean spacing between the child and robot during a treatment session could also indicate more potential engagement and interaction. We observed the lowest distance between the child and robot in the final session, which aligns with the highest count of successful interactions. The child spent more time in the BWSS across the treatment phase with an active robot when compared with the initial baseline session. Parent free-text responses noted that "[GoBot] was great" and "[the child] really interacted at the end [of session 4]."

V. Conclusions

In this work, we conducted a 3.5 month case study to investigate the viability of both a BWSS alone and the combination of a BWSS system with an assistive robot for motivating children with motor disabilities movement and engagement. We showed preliminary evidence that the BWSS can enable a child with no prior ability to independently step to take supported self-initiated steps and initiate interactions with people and an assistive robot. While a strength of this work is early insights on a population that has not been engaged much previously in the BWSS research literature, a limitation of the study was that we had a small sample size and a low number of data collection sessions. In future work, we plan to use the early insights from this case study to conduct a long-term study with more participants.

Another limitation was that we used two different robots across treatment sessions. We empowered the clinician and parents to make a child-centric robot selection, but this design choice reduced our ability to understand the influence of each specific robot during the intervention. In future studies, we will aim to choose just one assistive robot, if possible. A third limitation is that the assistive robots were teleoperated, which is not a scalable solution for clinical interventions. Our future work will incorporate a fully autonomous robot. Overall, we show that a BWSS can allow a child with a motor disability to *harness* the power of movement, and that having an assistive robot as a component of interventions may support child movement and engagement.

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