Green Means Go(Bot): Using an Assistive Robot to Encourage Independent Walking Practice by a Child with Motor Disabilities

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Abstract— **For children with motor disabilities, a wide range of assistive technologies (such as exoskeletons, treadmill trainers, and body-weight support harnesses) exist to support learning to walk. However, after the onset of independent walking, few technologies are geared toward helping children with motor disabilities to practice walking and improve walking control. In this paper, we assess the ability of GoBot, a custom assistive robot with multiple game modes, to encourage one child with a motor disability to improve their amount, speed, and control of independent walking. We conducted a 12-session single-subject study and found that the child walked more and faster while engaging in lightly competitive races against a directly teleoperated GoBot, compared to during experiences in a standard of care condition. As a second and more exploratory element of our work, we equipped GoBot to autonomously play the common children's game red light, green light (RLGL) with the user as an entertaining way to motivate balance practice. Anecdotally, this RLGL activity led to some of the highest levels of child engagement. The preliminary findings of our single-subject study can benefit researchers working with assistive robots and physical therapists working with children with independent walking practice goals.**

I. Introduction

Children with motor disabilities typically experience delays in major motor milestones such as walking [1]. Research into improving children's ability to walk has primarily focused on helping children develop the skill of walking through physical therapy interventions with devices such as a treadmill trainer [2]. However, outside of adaptive physical education programs [3], few works have evaluated assistive-technology-mediated methods to support the continual improvement of children's amount and speed of overground walking after they develop the ability to independently walk. This gap is important; children with enhanced walking stamina and control are able to better participate in activities of daily living [4] and accomplish higher levels of physical activity [5]. In this work, we designed a proof-of-concept intervention with a custom assistive robot to help augment the methods available for encouraging a child with a motor disability to walk more, faster, and with more control.

Our custom assistive robot, GoBot, uses gamification in the presented interactions with the end user. Gamification of physical therapy interventions (e.g., with virtual reality [6]) is a common strategy for improving child engagement, but gamified motor interventions for children have primarily centered on treadmill training for children who are still learning to walk. One novel emergent method to motivate the practice of walking is the use of assistive robots; a robot's embodiment allows it to facilitate compelling gamified interactions in the physical world to keep children engaged during interventions. Two past efforts have shown the benefits of using peer-like assistive robots to improve motor practice by children with motor disabilities who are still using mobility aids [7], [8]. This promising initial work motivated us to research a robot-mediated intervention for a child who was beginning to walk independently, but required motivation to continue practicing aspects of walking such as stamina, speed, and control.

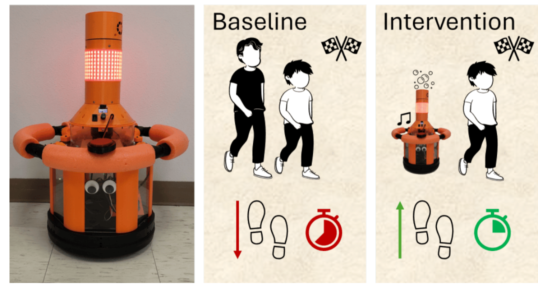

Fig. 1: *Left*: GoBot, our custom assistive robot with light, sound, and bubble rewards. *Center and Right*: Depiction of the key methods and results for our study phases.

Our main research goal in the presented work was to *evaluate if an assistive robot could motivate a child with a motor disability to improve their amount and speed of independent walking*. We used a GoBot robot [9], as shown in Fig. 1, that was equipped with racing and red light, green light (RLGL) game modes to conduct a 12-session single-subject study with a child who was focused on improving their independent walking. In this paper, Section II covers related work on the improvement of children's walking skills, gamification, and assistive robotics. Then, we elaborate on the robot design and the methods of the multi-month single-subject study in Section III. As conveyed in Section IV, our study results showed that the child tended to improve their amount and speed of walking while racing against the robot when compared with the baseline (i.e., standard of care) condition. Additionally, the child was able to successfully understand and play the RLGL game independently. Finally, we discuss the implications, strengths, and limitations of this work in Section VI. The main contribution of this work is early evidence that an assistive robot could help improve a child's amount, speed, and control of independent walking.

II. Related Work

Related work on improving children's walking skills, gamification strategies in pediatric interventions, and assistive robot design helped to inform the presented work.

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When forming the presented work, we learned from our clinical collaborators that for some children with disabilities who are beginning to walk independently, physical therapy goals range from increasing the amount of walking to increasing speed and balance. Increasing levels of physical activity for young children is vital for health and carries benefits such as improving bone density and cardiometabolic health [10], [11]. Children typically perform the most physical activity in physical education (PE) programs at school, but adaptive physical education programs for children with disabilities continue to lag behind PE programs for children without motor disabilities [3], [12]. Outside of school programs, children with motor disabilities will engage in physical therapy interventions using rehabilitation technologies such as the previously mentioned treadmill trainer to improve motor skills [2]. Exoskeletons are another technology that could help young children (before and after the onset of walking) via different levels of support for walking more and faster, but these devices are cost-prohibitive and primarily tailored towards children still learning to walk [13], [14]. This leaves a gap for children with motor disabilities who need to improve their walking functions; they still need engaging interventions designed to help encourage the further improvement of walking. In our study design, we focused on improving our child end user's amount and speed of walking through lightly competitive races with an assistive robot and enhancing their walking control via playing RLGL with an assistive robot.

Keeping children engaged in any pediatric intervention is a key component of further enhancing motor gains. Researchers have focused on using gamification strategies with technologies such as virtual reality (VR) or biofeedback to encourage social and cognitive interaction during an intervention, but have primarily incorporated these technologies into assistive devices such as treadmill trainers. One team designed a VR soccer game to allow children on a treadmill trainer to walk and kick a virtual soccer ball [6] while another team designed a VR world for a child to experience while walking on a treadmill trainer [15]. Researchers have also developed biofeedback tools as another method for increasing engagement during treadmill training interventions. While the child is walking on the treadmill, changes in heart rate or breathing rate prompts visual or audio cues on a tablet or larger screen that are designed to celebrate walking more or faster and continue to encourage movement [16], [17]. While these tools could be used for a child walking with or without assistance on a treadmill, there are benefits to children walking overground, such as social and cognitive benefits that complement the motor gains [8]. This idea encouraged us to use assistive robots, a newer tool in pediatric interventions, as the external motivating factor to encourage child motor practice during overground walking.

Assistive robots can offer more motivation than similar types of technologies which are not embodied in the physical world [18], and have achieved preliminary success in child mobility encouragement. Assistive robots encouraging physical activity are often studied with older adult populations [19], but fewer works have investigated using robots to encourage physical activity for young children without motor disabilities [9], [20]. For children with motor disabilities, robotic treadmill trainers such as the Lokomat have shown success in providing direct support to a child's gait during treadmill training interventions [21], but these tools are focused on children still learning to walk. In our own related work, we found preliminary evidence that GoBot could encourage a child with a motor disability using a body-weight support harness (BWSH) to take more supported steps in the environment [7], while a different research team using a BWSH found promising results using NAO and Dash robots [8]. These benefits of using robots for motivation during physical activity interventions encouraged us to develop multiple game modes for GoBot and conduct a multi-month single-subject intervention designed to encourage a child with a motor disability to independently walk more and faster.

III. Single-Subject Study Methods

We conducted a single-subject study to evaluate if the presence of an assistive robot could motivate a child to independently walk more and faster during a physical therapy intervention, compared to experiences in the standard of care. The study was approved by the university ethics board under protocol #IRB-2020-0723.

A. Study Design

The study lasted for 12 sessions using a single-case ABAB withdrawal study design [22]. With this design, the study was divided into 4 phases: two 3-session baseline phases (labeled as "A1 and A2") in which the assistive robot was not present and two 3-session intervention phases (labeled as "B1 and B2") in which the assistive robot encouraged the child to walk. We alternated the baseline and intervention phases in an AAA-BBB-AAA-BBB pattern as further described below:

- *First Baseline - A1* (3 sessions): The child independently walked during races with a clinician or research staff, but no assistive robot.
- *First Intervention - B1* (3 sessions): The child independently walking during races with a teleoperated GoBot, which used its reward features (as further explained in Section III-B) to encourage the child to stay moving and engaged.
- *Second Baseline - A2* (3 sessions): As in the first baseline phase, the child independently walked during races with a clinician or research assistant (but no assistive robot).
- *Second Intervention - B2* (3 sessions): As in the first intervention phase, the child independently walked during races with the assistive robot.

In alignment with the single-subject style of this work, the participant served as their own baseline, allowing us to observe the impact of introducing the assistive robot on the child's amount and speed of walking.

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 every other week physical therapy sessions.

B. Robotic System

We used a teleoperated GoBot (see Fig. 2) with flashing lights, bubble-blowing, and a library of sounds as motivating stimuli to encourage the child to walk during the robot races. Further detail on the early design of GoBot and its reward features is available in our past work, e.g., [23]. Briefly, this robot has a custom reward hardware stack on top of a TurtleBot2 robot. It is capable of two-dimensional overground motion as well as the aforementioned reward features. The robot is orange to match Oregon State University colors while also providing high-contrast and easy visibility.

C. Participant

Our participant was male and 7.1 years old. The participant has a diagnosis of multiple malformation syndromes with global developmental delay. At the start of the study, the participant primarily used wall walking and bottom scooting at home and was able to walk independently, but frequently required assistance. He communicated with single words, as well as through signs and gestures. The clinicians' goal was to improve his walking balance, endurance, and speed.

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 a demographics survey and a pre-study survey, as further explained in Section III-E. Before the start of a session, cones were laid out in a straight line at 5ft (1.5m) intervals to the side of the participant's walking course, ending at 50ft (15.2m) away. During intervention phases (B1 and B2), GoBot was placed alongside the child prior to beginning the session. A Canon camera recorded a front view while a GoPro Hero Black 7 recorded a side view. Four ActiGraph GT9X Link sensors were placed on the right and left ankle, right wrist, and hip of the child.

During the session, the child was tasked to race alongside either a clinician or research assistant (in baseline sessions) or GoBot (in intervention sessions) to the end of the cones. Each time the child reached the end of the cones, we noted a completed lap. At the end of each lap, we asked the child if they wanted to immediately turn around and start a new lap or take a break. During each lap, the child could request direct physical assistance from the clinician or parent in the form of holding one hand. A researcher noted the duration of each lap using a stopwatch. The researcher also recorded if the lap was completed independently or was assisted at any point by a clinician/parent. During the intervention phases, a researcher teleoperated GoBot to race alongside the child and used its features to encourage them to walk faster than the robot. Figure 2 shows a schematic of the study setup. Each session lasted 30 minutes.

At the end of a session, the sensors were removed from the child. Parents completed the post-session survey and were compensated $15 for each session. At the end of the study, parents completed the post-study survey. (These surveys are further explained in Section III-E.)

E. Measurements and Analysis

Measurements collected included *movement* data and *self-report* data. For each movement-based measurement, the data was analyzed for trends between baseline and intervention phases and the log response ratio (LRR) was calculated to compare each baseline and intervention phase. The LRR compares the intervention phase mean (M_t) to its preceding baseline phase mean (M_b) using the following equation:

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

LRR is commonly used in single-case work across domains such as ecology [24], special education [25], and behavioral psychology [26] to show changes in a measurement between the baseline and intervention. A positive LRR value indicates an upward trend for the measurement, an LRR value of zero marks no change, and a negative LRR value indicates a decline in the trend for the measurement. Larger LRR values represents a larger change between phases. For each of the movement-based 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). We report each individual LRR value, as well as the overall mean LRR (LRR_M).

1) Movement-Based Measurements: This data included a count of ankle movements (calculated from the ActiGraph data recordings), the total distance of independent walking (transcribed during study sessions and later checked), the number of completed independent laps (live transcribed and checked), and the average duration of independent laps from each session (live transcribed and checked), as further elaborated below.

Ankle Movement Counts came from ActiGraph sensor data that was processed through an algorithm in related work [27] to compute a count of events that were likely be *ankle movements*. We first used ActiLife v6.13.4 software to extract the recorded accelerometer and gyroscope data from the ActiGraph sensors. In this work, we focused on analyzing only the ankle sensor recordings since we were most interested in walking movement. The algorithm operates by first calculating the root mean square (RMS) acceleration and angular velocity from the raw ankle sensor recordings and then filtering the output by rejection ranges clarified in the related work [27]. After incorporating a 0.5-second window moving average filter, the algorithm identified an ankle movement starting when both the acceleration and gyroscope thresholds were exceeded and ending when the gyroscope data dropped below the associated threshold. We used the algorithm to calculate the total count of ankle movements for each session, including movement during both independent and assisted laps.

Independent Walking Metrics (i.e., total amount of independent walking, number of completed independent laps, and average duration of independent laps) came from live transcription during the study sessions by a researcher who actively monitored each lap. This live transcription data was

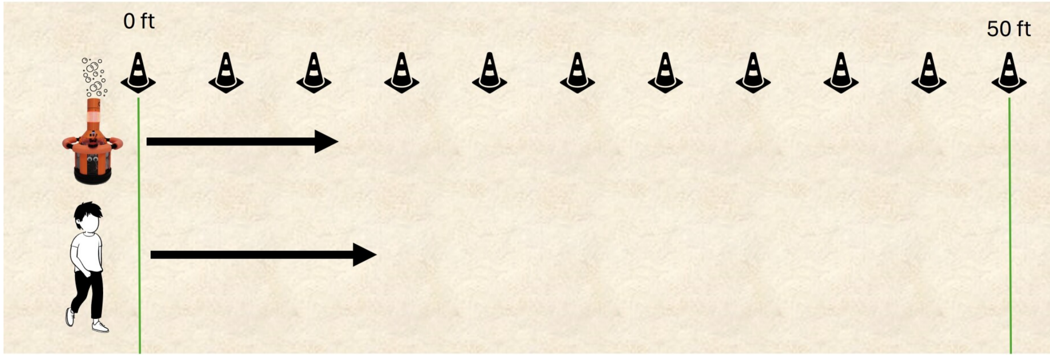

Fig. 2: Schematic of the robot races setup, including the child participant, robot, and cones for easily tracking distance walked. A complete “lap” was marked each time the child reached one extreme end of the cones.

then reviewed post hoc using video recordings; a video coder work with the original note-taker to ensure a 100% match rate in the coding. For both coding rounds, each lap was marked as completed fully independently (i.e., no physical assistance while walking) or assisted (i.e., holding one or both of the clinician’s hands while walking). We only considered laps that were completed fully independently by the participant in the coding, as the the child’s goals centered on amount and speed of independent walking specifically. We calculated the total amount of independent walking (in ft) by multiplying the number of laps completed fully independently by the length of the walking course (50ft). We also tallied the total number of fully completed independent laps for each session and calculated the mean duration of the fully independent laps during each session (in seconds).

2) Self-Reports: These inventories included demographic questions, pre-/post-study surveys, and a post-session survey.

Demographic questions collected child age, gender, diagnoses, and if the child was able to walk or crawl.

The pre-study survey included the following:

- All three components of the Negative Attitudes towards Robots Scale (NARS) [28], which the parents responded to using Likert-type scales from Strongly Disagree (1) to Strongly Agree (7).
- Trust Perception Scale-HRI (TPS-HRI) subscale items [29] rated as a percentage from 0 to 100. We used the 14-item abridged version.
- Free-response questions asking about the parents’ prior experiences with robots.

At the end of each session, parents completed a survey which included Likert-type questions relating to the child’s experience during each session. Specifically, parents answered the following custom Likert-type questions after every session:

- “How excited was your child today?” from Very Calm (1) to Very Excited (7)
- “What was the enjoyment level for your child?” from Very Unhappy (1) to Very Happy (7)
- “How well do you think your child interacted with others?” from Very Poor (1) to Very Well (7)

For intervention sessions with the robot, parents also answered the following Likert-type and free response post-session questions about their perception of the robot:

- “Do you think your child was engaged with the robot throughout the session?” from Strongly Disagree (1) to Strongly Agree (7)
- “Do you think robots can be useful to improve the well-being of children?” from Strongly Disagree (1) to Strongly Agree (7)
- “How do you think robots can be used to improve the well-being of children?”
- “In general, how did your child interact with the robot throughout the session?”
- “In general, what was your perception of the robot used in this session?”

At the end of the study, parents completed the same NARS and TPS-HRI survey items with additional questions asking about their final perceptions of the assistive robot.

IV. Single-Subject Study Results

The participant completed all 12 sessions and the assistive robot was fully functional for every intervention session. In this section, movement-based results are presented first, followed by self-report results. ActiGraph sensor results for session 8 were lost due to a recording error.

A. Movement-Based Results

The results of the study show that the child tended to increase their amount of independent walking throughout the study. Figure 3 shows the results for each measurement while Table I shows the LRR outcomes for each baseline and intervention phase combination. The participant completed at least one independent lap in every session. Although ankle count (including independent and assisted steps) results showed a decrease during the first intervention phase with the robot, independent walking distance generally increased during the first intervention phase’s sessions. Step counts were generally high during the second half of the study, and LRR results showed a repeated increase in independent walking distance for the second intervention phase (when compared with the second baseline phase), although the second LRR value was not as high. The independent lap results closely mirrored the independent walking distance results. The highest number of completed laps occured during session 10 (a robot intervention session). Results also

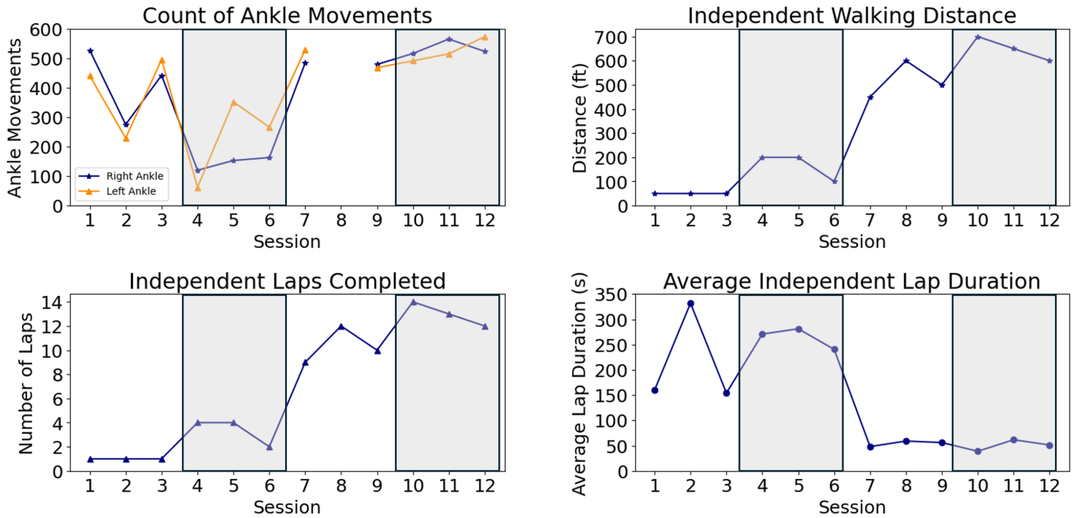

Fig. 3: Movement results by session, including the count of ankle movements, distance of independent walking, completed independent laps, and average duration of completed independent laps. The participant completed at least one independent lap in every session. The shaded area denotes the intervention phases.

TABLE I: Log response ratio (LRR) results. Shaded values specify large increases in child movement when comparing an intervention phase to the preceding baseline phase (i.e., LRR > 1).

Measurement	LRR_1	LRR_2	LRR_M
Ankle Movements	-0.77	0.08	-0.20
Independent Walking	1.20	0.23	0.36
Independent Laps	1.20	0.23	0.36
Fastest Lap	0.2	-0.07	0.15

elucidated that the participant sped up their average duration of independent laps in the second half of the study. The child's fastest independent laps occurred during session 10, with the robot.

B. Self-Report Results

Self-report results for the per-session surveys are shown in Fig. 4. The parents tended to rate the child's excitement, enjoyment, and interaction level as above average for most sessions, with the exception of session 3. Overall, the parents rated the child as being very engaged during intervention sessions with the robot ($M = 6.7$, $SD = 0.5$). For the NARS questionnaire, there was no change in the average ratings between the start and end of the study for the interaction component ($M = 3.6$, $SD = 0.9$ before; $M = 3.6$, $SD = 1.1$ after). There tended to be a decrease in ratings for the social component ($M = 3.3$, $SD = 1.1$ before; $M = 3$, $SD = 0$ after) and an increase in the emotional component ($M = 2.3$, $SD = 0.8$ before; $M = 3.3$, $SD = 0.8$ after). A decrease in ratings for each component of the NARS would indicate that the parent tended towards a more positive attitude towards robots for that component. Trust ratings tended to stay the same between the start and end of the study ($M = 78.0$, $SD = 11.4$ before; $M = 77.0$, $SD = 9.5$ after). Free-text responses from the parents offer insights into interactions with the robot. The parents noted that "[he] seemed more interactive with [GoBot] and I understand why because of mobility" and "[GoBot's] movement, lights, and bubbles kept him more engaged." For the final session, the parents responded that "he appeared to be competitive during racing and attentive during interactions."

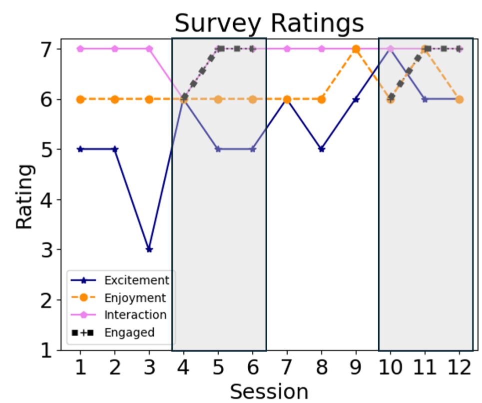

Fig. 4: Self-report results by session. Results include parent ratings of excitement, enjoyment, interaction, and engagement with the robot. Engagement questions were only distributed during intervention sessions.

V. Exploratory RLGL Interaction

Although we were able to evaluate walking amount and speed using the single-subject-style study, this interaction did not provide much of an ability to study motion control, another important part of motor development and practice. Accordingly, we added a brief (exploratory) RLGL interaction to the close of intervention sessions as a way to begin to assess this interaction's viability for motor control practice. We chose to use RLGL for this child based on a collaborative discussion between the researchers, clinicians, parents, and child. The game includes a high stimulus-response agreement between green means "go" and red means "stop while also encouraging starting and stopping movement control.

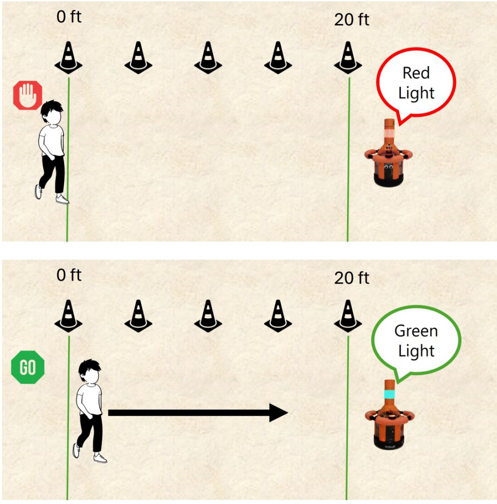

Fig. 5: Schematic of the exploratory RLGL setup.

A. RLGL Interaction Methods

At the close of the intervention sessions, we presented the participant with the opportunity to play RLGL with the robot.

Gameplay Procedure: The participant could play RLGL with GoBot for up to five minutes (i.e., one or two games' duration). We placed GoBot 20ft (6.1m) from the starting mark and a researcher started the autonomous game mode, as further described in the next paragraph. Figure 5 demonstrates the setup for the game.

GoBot's RLGL game mode involved three states: *green light*, *red light*, and *game win*. Typically, the green light and red light states alternated until the child reached the robot and pressed the robot's big red button, which activated the game win state. The green light state involved the robot turning away from the participant (i.e., the googly eyes looked away) while flashing the green lights, and saying "green light" out loud. In the red light state, the robot turned to face the participant, flashed the red lights, and said "red light" out loud. Based on the typical rules of the game, the child needed to move toward the robot during the green light state and to stop moving during the red light state. Both states alternated with a random duration in the range of 3-5 seconds. The game ended when the child pressed the robot's onboard button during a green light state. At that point, the robot indicated that the game was complete by flashing the green lights, blowing bubbles, and playing a cheering sound. The leftmost panel of Fig. 1 shows the robot in the red light state.

Measurement: During the RLGL game, a researcher took field notes which included observations, the number of times the game was played, and the percentage of games in which the child walked independently.

B. RLGL Interaction Results

Results from playing RLGL are shown in Table II. The child completed the game at least once every intervention session and displayed an understanding of the game by stopping and starting during the correct game states. In session 10, the child asked to play the game a second time before the session ended and walked independently during all time spent playing the game. The parents noted "his best interaction was during red light/green light" in session 10. Anecdotally, we also observed that the child would make a "stop" gesture with his hand during the red light phase and would point forward during the green light phase while making a train engine sound.

TABLE II: RLGL results from intervention sessions. The RLGL game was played at least once during each intervention session. For each session, the number of games played and the percentage of independent walking during the game was noted. Shaded cells denote sessions where the child played RLGL independently at least once.

Session	Games Played	% Independent
4	1	0
5	1	0
6	1	0
10	2	100
11	2	50
12	1	0

VI. Discussion

In this work, we evaluated how GoBot could motivate a child with a motor disability to independently walk more and faster by engaging in lightly competitive races. We found that the robot tended to encourage the child to independently walk more and faster, especially during the second half of the study. The largest change in independent movement was between sessions 6 and 7 which may have been due to additional family members being present for session 7. However, the child continued to improve their levels of independent movement for the rest of the study and the highest amount of independent movement and the fastest independent lap occurred during session 10 with GoBot. The parents observed that their child was more engaged during intervention sessions and seemed motivated by the robot's reward features and mobility.

The RLGL game offered a different interaction premise to continue encouraging independent walking and balance. The child demonstrated an understanding of the game and asked to play a second time in sessions 10-11. The nature of RLGL encourages stopping and starting, which helped the child to practice balancing and starting to walk again. The presence of the button on the robot provided a clear goal for the child and facilitated celebration through bubbles and lights once the game was won. The majority of games played involved assisted movement, which may have been a result of the child being tired at the end of a session. There was no baseline comparison made against RLGL so further study is warranted to understand how the robot-mediated RLGL experience compares to other analogous experiences. The flexibility of GoBot to incorporate novel reward modules and different types of gameplay enables a plethora of interaction paradigms for children with unique needs.

A key *strength* of this work is its multi-month duration and preliminary demonstration that an assistive robot could motivate a child with a motor disability to independently walk more and faster. The robot races seemed to offer light competitiveness and encourage the child to move faster through the robot's mobility and rewards. A second strength is that the RLGL mode demonstrated that different robot paradigms can potentially motivate a child to work towards different goals, such as improving balance. A *limitation* of this study was the small sample size. The single-case design provided unique insights into this specific child's progress throughout the study, but further study with larger samples is needed to generalize the results. A second limitation is that we did not use any assessments such as the GMFCS [30] or collect self-report results from the child beyond their approval to play RLGL. Future work with this robot may include a focus on children with cerebral palsy, a more common developmental disability, and in game-play sessions with multiple children (i.e., group play).

We set out to understand whether an autonomous assistive robot could promote more independent walking for a child with a motor disability who was already walking. We conducted a longer-term successful single-case study and showed that the robot tended to motivate more and faster movement from the child during robot races. Additionally, we found that the child understood and enjoyed playing the RLGL game with the robot during exploratory interactions, demonstrating potential for a future study focused on improving the child's balance, cognitive, and social abilities with RLGL. We encourage others in the assistive robotics space to consider ways that robots can help children to "start their engines" and play.

Acknowledgments

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