Improving Foot Rocker via Robot-Resisted Gait Training With Self-Awareness Biofeedback in Adults With Cerebral Palsy

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***Abstract*—Cerebral palsy (CP) is a non-progressive neurological disorder that impairs motor control and coordination due to brain injury or abnormalities before, during, or shortly after birth. Although robotic gait training can improve overall gait patterns in CP, interventions targeting the 'foot rockers' motion, essential for stable weight transfer and effective push-off, have received limited attention. In this study, five adults with CP were recruited to train on a robotic treadmill system in which controlled downward forces were applied to the pelvis during walking, promoting implicit motor learning to develop an improved foot rockers strategy. Following this, during overground walking, participants received distinct real-time auditory cues at heel strike and push-off, providing self-awareness feedback to reinforce and maintain the foot rockers pattern acquired during treadmill training. Post-training analyses reported increased Tibialis Anterior activation during early stance, enhancing dorsiflexion and heel strike, and greater Soleus and Gastrocnemius engagement in late stance for stronger push-offs ($p < 0.05$). These functional gains were reflected in key spatiotemporal metrics: longer step length, greater toe clearance, a reduced stance percentage, and a shorter double stance time ($p < 0.05$). Participants also exhibited increased range of motion of the foot and increased knee and hip extension throughout stance, reflecting a more upright lower limb ($p < 0.05$). Survey responses confirmed that participants acknowledged the resistive treadmill training for strengthening their muscles and influencing their walking patterns, and reported that the auditory biofeedback enhanced their awareness of heel-to-toe contact. Participants emphasized the necessity of incorporating both interventions, highlighting its potential as a promising approach to improving foot rockers and overall gait pattern in adults with CP.**

***Index Terms*—Robotic gait training, cerebral palsy gait, foot rockers, biofeedback.**

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I. INTRODUCTION

CEREBRAL Palsy (CP) is caused by a brain injury before, during, or shortly after birth, resulting in impaired control of peripheral muscles, affecting hand and foot control [1]. The resulting neuromuscular deficits include restricted range of motion (ROM), spastic muscle tone, and insufficient muscle activation [2]. Specifically, it leads to impaired coordination of muscle activation timing, which is essential for generating proper gait patterns [3]. Due to high spasticity in the flexor muscles of the limb, individuals with CP typically develop a toe-walking pattern, and they undergo surgery to reduce excessive muscle activations. This does not, however, resolve the issue of insufficient control of extensor muscles, which causes them to walk with excessive lower limb flexion during stance, commonly referred to as crouch gait [4].

Individuals with crouch gait often experience impaired ground contact, which is a fundamental component of healthy gait. A good ground contact enables balance and provides the necessary propulsion to move the body forward [5]. In healthy individuals, ground contact begins with a heel strike (HS), creating a stable base for weight transfer and shock absorption, known as the heel rocker [6]. This is followed by tibial advancement over the foot during midstance (ankle rocker) and then a transition to the forefoot during the stance phase (forefoot rocker), resulting in a powerful push-off that propels the body forward [6]. Due to spasticity in the flexor and extensor muscles of the lower limb, individuals with CP frequently lack proper HS, leading to midfoot, flat foot, or forefoot ground contact instead [7]. With the toe contact at initial loading instead of HS, this gait pattern frequently fails to stabilize the foot during the stance phase and generates insufficient body propulsion [8]. It contributes to smaller steps, reduced toe clearance, and slower walking speed [9]. Achieving proper ground contact through heel-to-toe progression facilitated by the foot rockers (heel, ankle, and forefoot), is fundamental for stable and efficient bipedal locomotion.

Robot-based gait training has been shown to improve motor function in individuals with CP [10]. Broadly, robotic gait trainers can be grouped into assistive, resistive, and adaptive depending on their control strategy. Assistive robots such as HAL [11], [12], CPWalker [13], Lokomat [14], MIT Skywalker [15], and ankle exoskeletons [16], [17] provide external assistive torque, trajectory guidance, or partial body weight support. Resistive approaches apply phase-specific loads that oppose motion to increase effort, recruit underactive muscles, and refine the timing of activation. For example, a cable-actuated pelvic robot is used to apply downward resistance at the pelvis [18]. Several ankle exoskeleton studies have delivered stance phase plantarflexion resistance, including sensorimotor feedback variants [19], [20], [21]. Adaptive systems, on the other hand, scale ankle assistance or resistance torque in proportion to the user's real-time biological demand [22], [23], [24], [25], [26].

Although robotic interventions can improve gait in controlled settings, their benefits often fail to generalize to walking outside the training context, as evidenced by a limited number of case studies [12], [23]. To date, only a few studies have demonstrated carryover improvements. For example, Patritti et al. [14] reported spatiotemporal and kinematics improvements in a 52-year-old following Lokomat training. Susko et al. [15] reported increased walking speed and balance in two adults (aged 24 and 56) after one month of MIT-Skywalker training. Hybrid Assistive Limb (HAL) studies have demonstrated immediate changes in hip and knee motion, however, spatiotemporal parameters remained similar [11]. Ueno et al. reported significant improvements in walking speed, step length, and cadence, while Gross Motor Function Classification System levels (GMFCS) did not change, and other parameters weren't assessed [27]. Moll et al. [12] found only non-significant trends toward improved walking speed, six-minute walk distance, and Gross Motor Function Measure (GMFM) scores. Several adaptive ankle exoskeleton studies have also reported improvements in unassisted overground walking. Fang et al. [24] demonstrated faster gait and longer stride length together with improved Soleus (SOL) activation patterns, although, cadence did not change significantly, and Tagoe et al. [25] observed faster gait and longer stride length, but ankle co-contraction of Tibialis Anterior (TA) remained unchanged. While these studies present some degree of overground transfer, reported outcomes remain concentrated in a narrow set of spatiotemporal measures, and improvements have not been consistent across parameters, making the evaluation of transfer of training effects limited. Additionally, some of these studies relied on very small participant samples, restricting generalizability, and several others did not assess joint-level kinematics or muscle activity. Furthermore, ground contact measures such as reaction forces have not been evaluated, and no study to date has explicitly targeted improvements in foot rockers function or foot-ground contact.

The limited carry-over effect observed in prior studies may stem from a predominant reliance on external forces to drive movement rather than actively involving participants in the learning process. To ensure the effective transfer of robotic training benefits to daily life, a more engaging approach is required that enables users to assess their current gait pattern and provides clear targets or guidance for maintaining the training effect. This would encourage individuals to take active control of their movement patterns and make conscious adjustments to their foot placement, leading to a longer carry-over effect of the robotic training.

Biofeedback has been proposed as an engaging, goal-directed strategy to enhance gait pattern in individuals with CP [28]. Prior work has transformed gait measures such as step length, surface electromyography (EMG), joint kinematics, and plantar-pressure into visual or audio-visual representations to effectively engage participants in the gait training procedure [29], [30], [31]. For instance, Flux et al. used EMG-driven gaming to increase calf activation in late stance [29]. Van Gelder et al. provided real-time visual feedback on hip and knee kinematics during treadmill walking in a virtual reality environment, and reported significant improvements in peak hip and knee extension as well as spatiotemporal parameters [31]. Booth et al. employed immersive virtual reality feedback on step length, knee extension, and ankle power, reporting immediate improvements in these parameters [30]. Conner et al. [32] validated a plantar-pressure audio-visual biofeedback system that produced comparable increases in SOL and GA activation to an EMG-based system.

Motivated by these findings, several groups combined biofeedback with resistive ankle exoskeletons to create multimodal training [20], [21], [22], [26], [32], [33]. Such approaches are motivated by evidence that training across separate sensory pathways can lead to more effective learning, often more than unisensory training [34]. These studies paired EMG-based audio-visual cues, plantar-pressure-based audio, machine-learning-based audio-visual cues, or step length-based visual cues with resistive or assistive loading through exoskeletons. However, most of these studies did not evaluate transfer to unassisted or overground walking [20], [26], [32], [33], [35], while those that did, reported only modest or non-significant improvements [21]. Across all these studies, feedback primarily targeted the late stance, thus, participants were cued to emphasize propulsion rather than focusing on the initial heel rocker that impacts the rest of the stance. To date, feedback targeting the HS to engage the initial rocker has remained unexplored, and the transfer of training effects from multimodal systems to unassisted or overground walking has rarely been reported. A further limitation is the limited inclusion of adults with CP. Most multimodal or robot-based training studies have enrolled children or young adults, with adult representation often limited to isolated case studies. For example, Lokomat, MIT-Skywalker, HAL, and

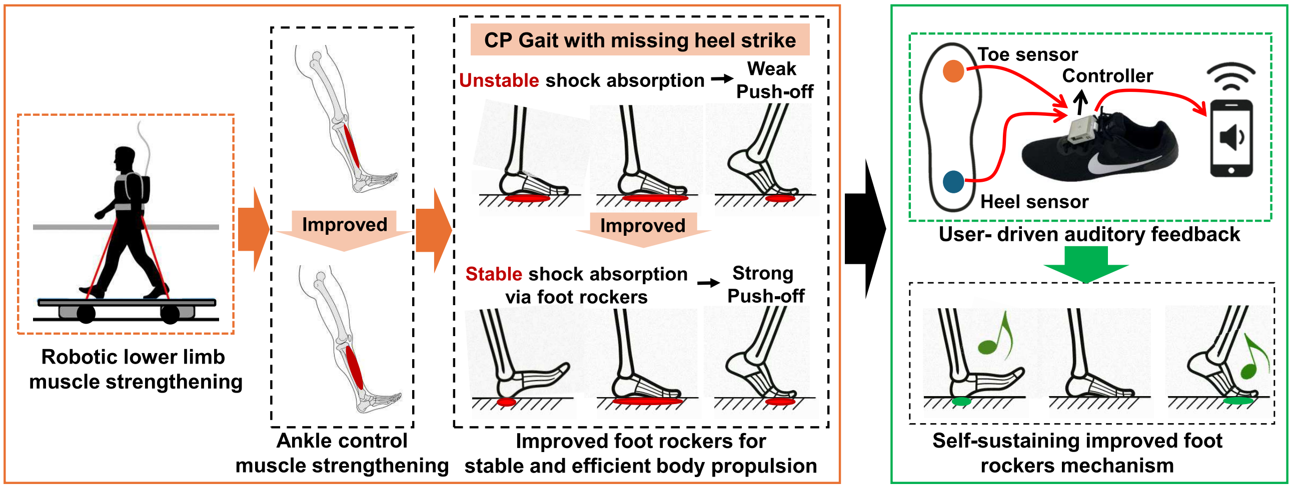

Fig. 1. Depiction of the training intervention using the Robotic Trainer (left) and Biofeedback-assisted walking (right). The Robotic Trainer's applied resistive forces effectively recruit the lower-limb muscles, leading to muscle strengthening and improved control at the ankle joint, which facilitates improved foot rockers motion through implicit motor learning. This yields a more effective shock-absorption phase at heel strike and greater propulsion during push-off. Biofeedback walking with the smart insole increases awareness of heel-to-toe ground contact by delivering distinct auditory cues at both heel strike and push-off. These cues reinforce the improved foot rockers developed on the treadmill with the robotic trainer as participants transition to overground walking.

ankle exoskeleton studies typically reported just one or two adult participants, generally in their 30s–50s [16], [17], [22], [23], [24], [26], [33], [35].

This research addresses three critical gaps discussed above: (i) lack of work targeting the heel rocker at initial contact, and, (ii) limited evidence for transfer of robotic training benefits to overground walking in multimodal systems with explicit evaluation of the foot rockers (heel, ankle, forefoot), and, (iii) the under-representation of adults with CP. In this study, we investigated the effectiveness of resistive robotic training in promoting the execution of HS and push-off, the two crucial components of foot rockers, through implicit motor learning. We hypothesized that walking under resistive forces would enhance lower limb muscle strength and control, facilitate a more distinct heel-to-toe transition, and thereby establish a more effective foot rockers motion. Following the robotic training, participants received self-awareness auditory biofeedback, delivered as distinct cues at HS and push-off. These auditory cues were intended to reinforce the improved foot rockers pattern acquired during treadmill training and support its transfer to overground walking, ultimately promoting gait patterns comparable to those achieved on the treadmill through explicit motor learning.

Unlike prior multimodal systems that deliver biofeedback concurrently with robotic training, our approach applies biofeedback sequentially after robotic training, which has been shown to improve learning retention and may facilitate better transfer to overground walking [36] (Fig. 1). The main contributions of this study are i) Exploring the resistive robotic intervention in the adult CP population, ii) Implementing auditory biofeedback to enhance self-awareness of heel-to-toe patterns after the robotic training, iii) Investigating the changes in foot rockers, gait parameters, lower limb kinematics, and walking abilities as a result of the training intervention during treadmill walking and while transitioning to overground walking, iv) Surveying to assess participants' perceptions of the training and its impact on gait patterns, and v) Analyzing the mechanisms underlying these gait adaptations and their relation to the mindfulness of the participants.

II. Experimental Set-up

A. System

The resistive treadmill training was provided by a cable-actuated robot used in [18]. The robot consists of motors, tension sensors, a pelvic belt, and a controller box (Fig. 2a). The cables were actuated by i-max motors (Maxon Inc., Switzerland) and controlled by tension sensors (LSB 200, Transducer Technique, LA). Utilizing four motors, a constant downward resistive force was provided on the pelvis of the participant, which was 10% of his/her body weight. This resistance level has been shown to elicit meaningful changes in gait parameters for children with CP [18]. The control was achieved using a feedforward-PID scheme: the feedforward voltage was set proportional to the target force (10% of body weight), while the PID feedback term regulated the motor output to maintain that force. The robotic system provided resistive force while participants walked on the treadmill to strengthen their muscles.

After the treadmill training, an auditory biofeedback system was used in the experiment (Electroskip, NY, USA) (Fig. 2b). This user-driven biofeedback system consists of a total of four Force Sensitive Resistors (FSRs) embedded below the shoe insoles. The pressure pad signal was transferred to an Electroskip (E-Skip) controller, which communicated wirelessly through a tablet via the E-Skip trainer application. Each insole was equipped with two pressure pads situated on the heel and toe areas of the foot. These pressure pads emitted distinct tones that, when synchronized by hitting all four pressure pads in succession, produced a straightforward rhythmic song aligned with the walking pattern. The location of the FSR sensors was adjusted based on the size of each participant's shoe insole

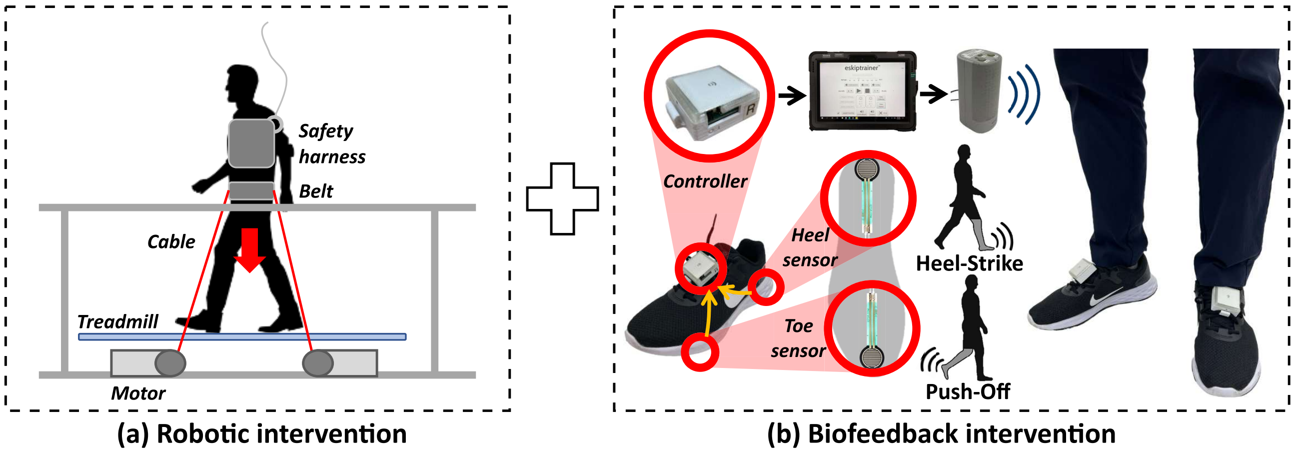

Fig. 2. Cable-Driven Robotic System (Left) and Smart Insole System (Right). The robotic system features four treadmill-mounted motors that apply downward resistive forces to the pelvis via cables, with the total force estimated at 10% of the participant's body weight. The smart insole is equipped with two force-sensitive resistors (FSRs) positioned at the heel and toe. A proper HS and push-off trigger pressure changes, which are transmitted to an E-skip controller. This controller wirelessly communicates with the E-skip trainer app installed on a tablet, converting the signals into distinct auditory cues via a speaker.

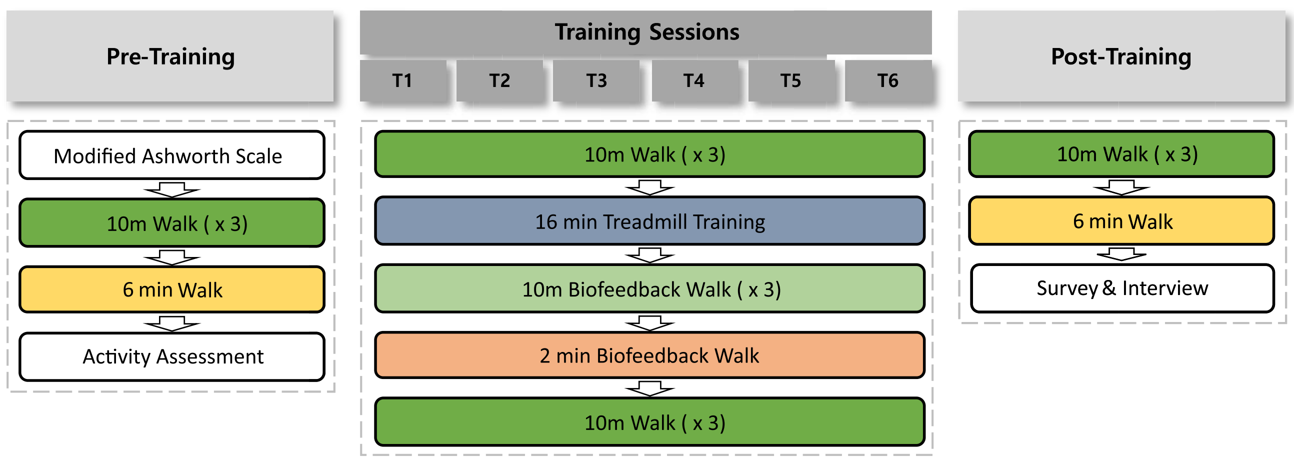

Fig. 3. The overall experiment consisted of a Pre-training session, followed by six training sessions, and concluded with a Post-training session. The Pre-training session was conducted to establish baseline data, during which participants completed a 10-meter overground walking test and a 6-minute overground walking test. Six training sessions include 10-meter baseline overground walking, walking on the treadmill with robotic therapeutic forces, and training to walk with biofeedback overground. The post-training session involved the same 10-meter walking and 6-minute overground walking tests to assess the effects of the intervention.

until the participants were able to reliably trigger the cues at their own HS and push-off events during the pre-training session.

B. Experimental Protocol

The experimental protocol is outlined in Fig. 3. For each participant, the experiment consisted of one pre-training session, six training sessions, and one post-training session. During the pre-training session, participants were familiarized with the experimental setup, including the robotic gait training system. They were introduced to resisted treadmill walking. Their comfortable walking speed on the treadmill without resistance was determined. Participants were also acquainted with the smart insole and the auditory feedback associated with HS and push-off. The auditory cues included two distinct auditory tunes on the occurrence of HS and push-off events in an attempt to make the participants aware of their foot contact. Following the introductory session, muscle spasticity was assessed using the Modified Ashworth Scale (MAS) [37]. Subsequently, baseline data for each participant were gathered through a 10-meter walk (3 laps) and a 6-minute walk [38], [39]. The session concluded with a physical activity assessment, during which participants provided an ad hoc self-report of their general level of physical activity in their day-to-day lives. This was categorized as low, medium, and high levels.

The training session spanned six sessions, covering Training 1 through Training 6, with an average of two sessions per week. The session began with a 10-meter overground walk (comprising three laps) to establish the participant's baseline data for that specific session. Following this, participants completed two minutes of treadmill walking without resistance or biofeedback, which served as both a warm-up and a baseline measurement for treadmill walking. The training started with eight minutes of treadmill walking against resistive forces, conducted twice with suitable rest in between. This was followed by biofeedback walking sessions. Under biofeedback walking, initially, there was a one-minute session of walking on the treadmill with biofeedback but no resistive forces. After this, the participant engaged in a 10-meter overground walk with biofeedback (three laps). The biofeedback walking concluded with an additional two-minute overground walk with biofeedback [40]. Post-training, a final 10-meter overground walk without biofeedback (three laps) was performed.

Following the six training sessions, a post-training evaluation was carried out. This involved the participants completing a 10-meter walk followed by a 6-minute walk. The post-training session concluded with a questionnaire and an exit interview, during which participants were asked additional questions related to their responses. The questionnaire was an ad hoc self-report consisting of 12 questions about participation in the training, with responses primarily structured using a Likert scale to assess participant perceptions and satisfaction levels quantitatively.

III. Data Analysis

Motion capture data (Vicon, UK) from the 10-meter walks of all participants was collected at 100 Hz and segmented into individual gait cycles. The marker placement was followed as per [18]. The gait cycles were computed from the foot and sacrum markers and were separated by the consecutive occurrence of HS of the right and left leg [41]. Only complete gait cycles were included in the analysis. Gait parameters, foot trajectories, lower limb kinematics, and EMG data (Delsys Inc., MA) were obtained and averaged over six gait cycles. All values were taken as the mean between the left and right legs to derive a representative gait profile for each participant and highlight overall intervention effects. The Wilcoxon signed rank test was used to compare the parameters, with a significance level set at ($\alpha = 0.05$) [42].

Measurements were taken to determine the temporal and spatial parameters of individual participants' gait. The spatial parameters included step length and toe clearance. Step length was computed as the anterior-posterior difference between the right and left heel marker coordinates when both feet were on the ground. Toe clearance was measured as the minimum vertical distance between the toe and the ground during the swing phase. Temporal parameters included stance percentage, stance time, stride time, single stance time, double stance time, and walking speed. Stance time refers to the duration of the foot contact with the ground while walking, from initial contact, HS to toe-off. Stance percentage was the proportion of the gait cycle that stance time occupied. Stance time was further divided into Single Stance, defined as the duration from the toe-off of one leg to the HS of the other leg, and Double Stance, defined as the period from the HS of one leg to the toe-off of the other leg. Walking speed was determined by averaging the speeds recorded during the 10-meter overground walking test across three trials.

Foot angle trajectories were calculated to understand the change in mobility of the foot due to training and also to determine the foot rockers angle. The foot angle was determined by calculating a vector from coordinates of the heel and toe markers in the sagittal plane. ROM symmetry of foot angle was computed to assess the balance between the right and left legs as follows.

$$ROM\ Symmetry = abs\left(\frac{R}{L} - 1\right) \tag{1}$$

Additionally, the joint angles of the hip, knee, and ankle were computed. These angles were determined by computing 3D vectors for the respective limb segments and calculating the angles following a procedure similar to that described in [43]. To account for variations in gait cycle duration among participants, joint angle trajectories were time-normalized to 0–100% of the gait cycle starting with HS. To detect muscle activation, EMG data were obtained at 2000 Hz. A fourth-order band-pass (40 to 450 Hz) Butterworth filter was used, followed by rectification and further filtering with a fourth-order low-pass Butterworth filter (6 Hz) [18], [44]. The EMG data were calculated during the time interval when the highest activation should be observed. In this study, three muscle groups are considered, namely SOL (Soleus), GA (Gastrocnemius), and TA (Tibialis Anterior). For SOL and GA, the EMG data were obtained during 40-60% of the gait cycle (push-off phase). For the TA, the EMG data were obtained during 0-10% of the gait cycle (HS phase). The muscle activation is taken as the Area Under the Curve (AUC) of the mean EMG data [45]. During treadmill walking, the force plate data or the Vertical Ground Reaction Force (vGRF) from the treadmill were obtained at 1000 Hz. Spearman's Correlation Coefficient (SCC) and Euclidean Distance (ED) were calculated to compare the vGRF data with that of healthy participants. The vGRF data of healthy participants were obtained from our previous study [46]. The vGRF data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 20 Hz.

IV. Participant Information

The experiment was approved by the University at Buffalo IRB, and participants provided written informed consent before participation (IRB STUDY00005147, Approval date: 4/5/2021; NCT05335798 Reinforcing CP Robotic Training With Auditory Feedback). Five adults with diplegic CP participated in the experiment. The inclusion criteria were adults with CP (18-65 years old), who were capable of ambulating at least 100 feet with or without assistive devices and without requiring physical assistance. The exclusion criterion was a MAS score greater than 3, assessed in the quadriceps, hamstrings, ankle dorsiflexors, and plantarflexors. Participants were excluded if they had severe Equinovarus foot or Genu recurvatum of the knee. Participants who had undergone surgery within the previous 6 months were excluded. Individuals were also excluded if they were pregnant or had lower limb prostheses, severe respiratory problems such as chronic obstructive pulmonary disease, heart disease, a loss of sensation, uncontrolled blood pressure, a seizure disorder, or severe arthritis. For detailed participant information, please refer to Table I.

TABLE I
PARTICIPANT INFORMATION

ID	Weight (kg)	Height (cm)	Gender	Age (years)	Paralysis	10 m (sec)*	Modified Ashworth Scale (MAS)				Functional Level
							Quad	Ham	DF	PF	
1	84	180	M	41	Diplegic	9.68	2/1	1/1	1/1	1/1	Medium functional
2	59	169	F	31	Diplegic	7.53	0/1	1/1	0/1	0/1	Medium functional
3	52	157	F	33	Diplegic	9.22	1/1	0/0	2/2	2/2	Low function (use cane)
4	82	173	M	28	Diplegic	10	1/1	0/0	0/0	0/0	Highly functional
5	76.4	171	M	52	Diplegic	7.97	0/0	0/0	1/1	1/1	Highly functional

MAS: Quad = Quadriceps, Ham = Hamstrings, DF = Ankle dorsiflexors, PF = Ankle plantarflexors. *10-meter walk collected during pre-evaluation

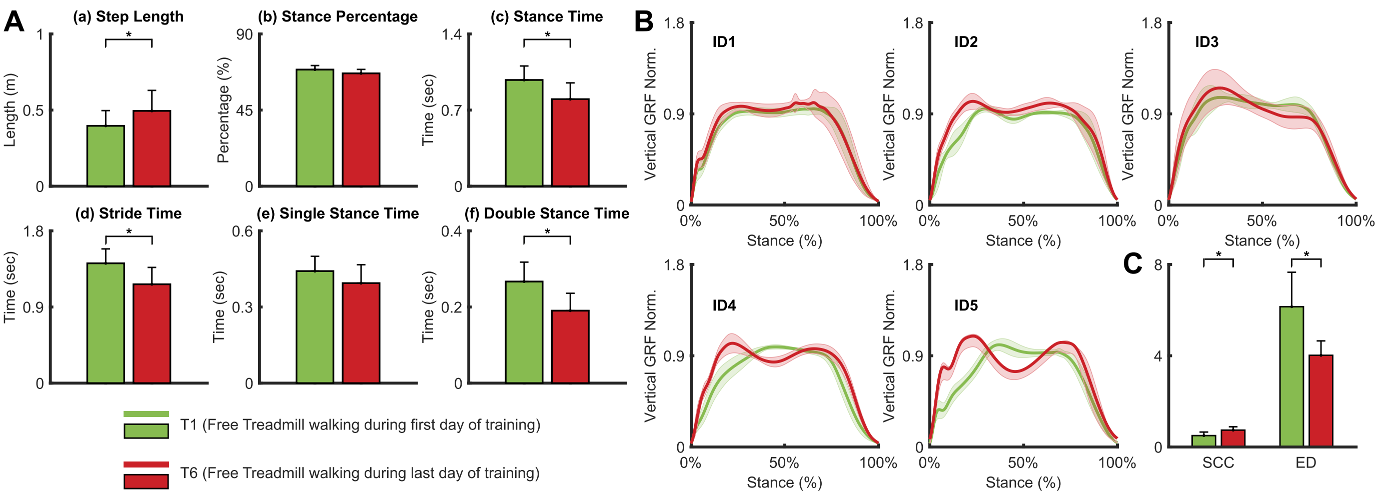

Fig. 4. Treadmill walking results of five participants: A. Spatiotemporal Gait Parameters, B. Normalized vGRF profiles of all five individuals with cerebral palsy, C. Spearman's Correlation Coefficient (SCC) and Euclidean Distance (ED) between individuals with CP vs. healthy participants. The asterisk indicates p <0.05.

V. RESULTS

A. Treadmill Training Results

The gait parameters and ground reaction forces when walking on the treadmill are presented in Fig. 4. The temporal and spatial gait parameters were computed during T1 and T6 before they participated in the resistive robotic intervention to observe the longitudinal training effect (Fig. 4A). Participants showed a significant increase in the step length when training proceeded from T1 to T6 ($p < 0.05$). Significant improvements were also observed in temporal parameters for decreased stride time and double stance time ($p < 0.05$). This indicates that participants were confident in their gait, which reduced the overall stance time ($p < 0.05$). Furthermore, the comfortable walking speed on the treadmill increased from 0.55 ± 0.088 m/s at T1 to 0.86 ± 0.278 m/s at T6.

Fig. 4 B depicts the changes in the weight-normalized vGRF patterns for all participants during the T1 (green line) and T6 (red line) sessions. In healthy individuals, the vGRF profile is typically characterized by two distinct peaks: the first corresponding to HS and the second to push-off. As shown in the figure, the vGRF curves during the T1 session lacked the two distinct peaks that are indicators of missing distinct HS and push-off. As the training progressed, the vGRF patterns at T6 exhibited clearer dual peaks for most of the participants, with faster self-selected walking speeds. In particular, ID1 and ID4 show a flat top of the graph, which indicates insufficient HS and push-off at T1. It improved over time at T6. ID2 shows a somewhat delayed shock absorption phase at T1, which instead happens faster at T6. ID3 used a walking aid (cane) and did not exhibit distinct dual peaks, however, it should be noted that a faster weight acceptance was observed during T6. ID5 also transitioned from a single peak to dual peaks in vGRF over time.

To quantitatively assess group-level changes in vGRF, comparisons between the vGRF patterns of individuals with CP and those of healthy individuals were conducted using both SCC and ED, as illustrated in Fig. 4C. The SCC was used to evaluate the rank-based correlation between individuals with CP and healthy participants. Fig. 4C shows that the SCC increased from 0.50 ± 0.16 at T1 to 0.74 ± 0.15 at T6 ($p < 0.05$). In addition, the ED directly quantifies the magnitude-based differences across the time axis. The ED of all vGRF data decreased from 6.15 ± 1.51 at T1 to 4.02 ± 0.63 at T6 ($p < 0.05$). The increased SCC reflects stronger monotonic relationships, and the decreased ED indicates a decrease in magnitude-based deviations from weight-normalized healthy vGRF profiles in individuals with CP over time.

B. Overground Walking Results

This section presents the effects of the six- session training program on participants' overall gait performance. Data from pre- and post-training sessions are compared, with a focus on changes in gait parameters, foot angle trajectories, and lower limb muscle activity (Fig. 5).

The gait parameters of pre-training and post-training sessions are depicted in Fig. 5A. Spatial parameters, including

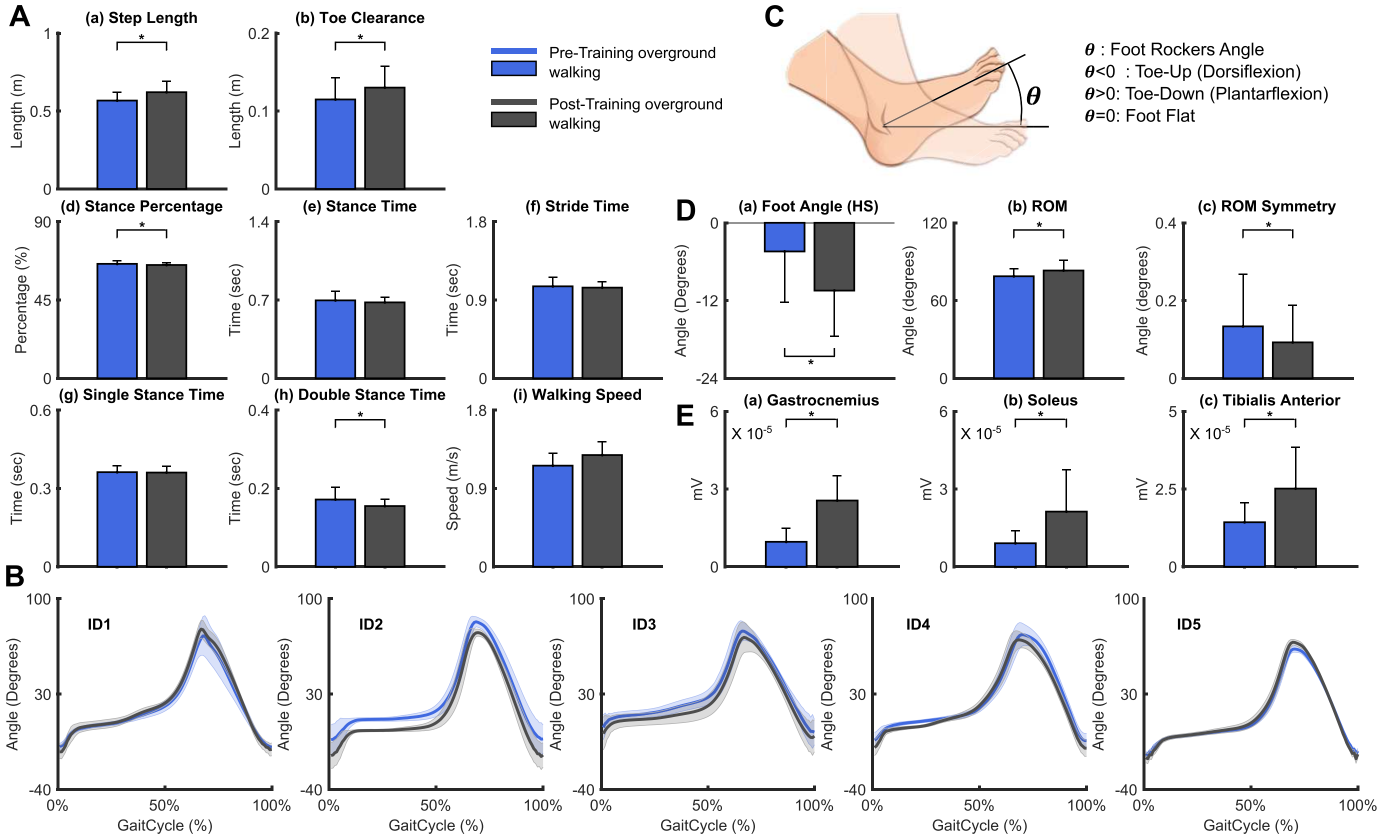

Fig. 5. Overground walking results of five participants during pre-training and post-training sessions: A. Spatiotemporal Gait Parameters, B. Foot Rockers Angle profile of five participants, C. Schematic of the foot rockers angle, D. Foot angle trajectory parameters, E. Average EMG of Gastrocnemius, Soleus, Tibialis Anterior muscles. The asterisk indicates p <0.05.

step length and toe clearance, showed significant increases following training ($p < 0.05$). Temporal parameters such as stance percentage and double stance time showed a significant decrease ($p < 0.05$). Furthermore, participants demonstrated an increasing trend in walking speed. Other temporal parameters did not show any significant result.

In addition to gait parameters, the foot angle trajectory was computed for both pre- and post-training, with particular attention to the contact angle relative to the ground (Fig. 5B). The foot angle provides critical insight into which part of the foot makes contact with the ground during different phases of the gait pattern. This information is, therefore, pivotal in understanding the foot rockers mechanism. A negative foot angle trajectory indicates a toe-up directional movement of the foot, whereas a positive trajectory corresponds to a toe-down directional movement of the foot. The schematic of the foot rockers angle is shown in Fig. 5C. Different features of the foot trajectories were extracted, such as foot angle maxima, the foot angle at HS, foot ROM, and the symmetry associated with the ROM (Fig. 5D). The ROM was computed as the difference between the foot angle at its maximum plantarflexion and HS. All participants exhibited improved foot posture at HS during the post-training session ($p < 0.05$). At post-training, the foot angle at HS shifted toward a more negative value, indicating a more appropriate toe-up posture upon ground contact in all five participants. Furthermore, a significant increase in foot angle ROM ($p < 0.05$) was observed. Additionally, symmetry associated with foot angle ROM showed a significant improvement ($p < 0.05$).

TABLE II
Lower Limb Joint Angle Parameters

	Maximum Extension (degrees)					
	Hip*		Knee*		Ankle	
	Pre-Training	Post-Training	Pre-Training	Post-Training	Pre-Training	Post-Training
AVG	-6.65	-11.83	28.81	23.68	-16.04	-13.63
STD(±)	4.69	5.54	10.24	11.17	10.78	3.74
	Maximum Extension Timing (%)					
	Hip*		Knee		Ankle*	
	Pre-Training	Post-Training	Pre-Training	Post-Training	Pre-Training	Post-Training
AVG	56.93	58.51	39.12	39.74	67.89	67.02
STD(±)	1.71	2.18	4.79	5.51	1.09	0.95

*Asterisk indicates $p < 0.05$. Negative value indicates extension.

The changes in lower limb maximum extension of hip, knee, and ankle joints and their time of occurrence in the gait cycle are shown in Table II. A higher positive value indicates flexion, while a more negative value represents increased extension of the respective joints. The table shows that the participants significantly increased hip and knee extension during the stance phase (30%~60% of the gait cycle) ($p < 0.05$). This suggests a more extended lower limb posture. This is

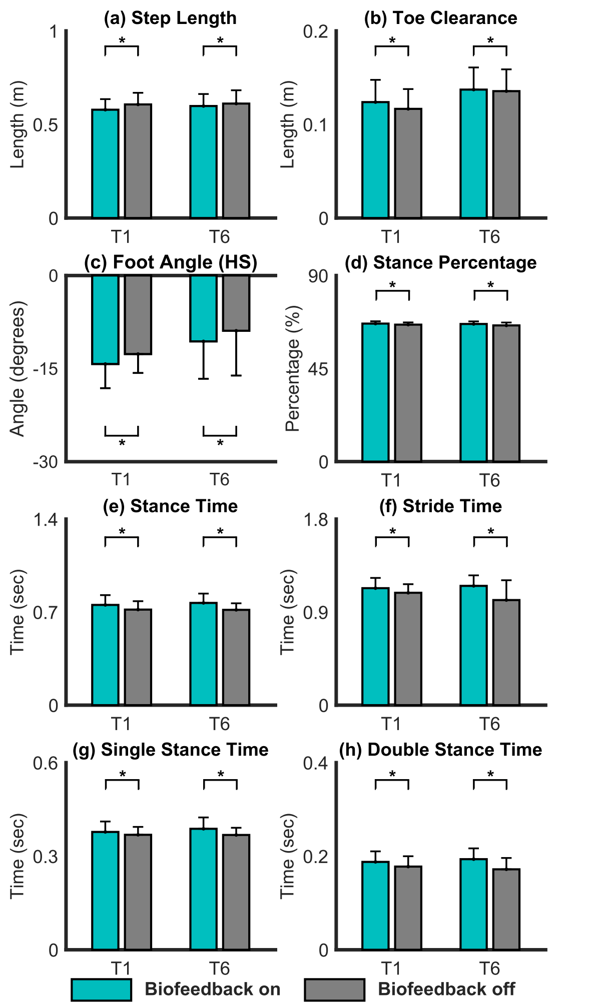

Fig. 6. Spatiotemporal gait parameters with and without biofeedback. Asterisk indicates p <0.05.

considered an important improvement, as individuals with CP typically exhibit excessive flexion during the stance phase. No significant change was observed in ankle joint plantarflexion. Additionally, the timing of maximum hip extension during terminal stance showed a significant shift to a later time of the gait cycle after training, from 56.93% to 58.51% ($p < 0.05$), whereas, the timing of maximum ankle extension during pre-swing shifted earlier, from 67.89% to 67.02% ($p < 0.05$).

The changes in muscle activity of the SOL, GA, and TA muscles were measured before and after the training (see Fig. 5E). The activation of TA shows a significant increase during the HS phase ($p < 0.05$). Furthermore, the activation of GA and SOL shows a significant increase during the push-off phase ($p < 0.05$).

C. Biofeedback Walking Results

In this section, the effect of biofeedback cues on the participants' gait patterns is presented. The changes in gait parameters due to biofeedback during T1 and T6 are shown in Fig. 6. Participants significantly reduced their step length in response to biofeedback ($p < 0.05$). Increased dorsiflexion at HS, greater toe clearance, and a more negative foot angle at contact were observed ($p < 0.05$). The temporal parameters, such as stance percentage, stance time, stride time, single stance time, and double stance time, increased when biofeedback cues were applied (all $p < 0.05$).

As the training progresses to T6, the spatial gait parameter values, including step length and toe clearance, during biofeedback walking, began to align more closely with the magnitudes of these parameters recorded without biofeedback (see Fig. 6a-b). This alignment suggests that, as training sessions progressed, participants adapted to the biofeedback walking and incorporated the learned patterns into their natural gait. However, a different trend was observed for the temporal parameters (see Fig. 6d-h), where the gap between the biofeedback and no-biofeedback conditions increased at T6, suggesting the need for extended sessions to fully naturalize walking with biofeedback.

D. Participant Perception of Their Gait

Table III presents the post-survey questionnaire and responses, including the corresponding Likert scale ratings for each question. Participants shared similar and positive reviews about the treadmill training. Three participants "agreed" and two "strongly agreed" that the level of resistance on the treadmill was appropriate. All five participants perceived changes in their walking after the resistance was removed, with ID1 and ID5 expressing stronger confidence in their responses. One participant remarked feeling *"more confident in my walking...my heel-strike was there."*

Participants' perceptions of the auditory biofeedback were predominantly favorable. Four participants agreed or strongly agreed that the auditory cues enhanced walking quality, whereas one participant reported remaining neutral due to difficulty interpreting the tones. Increased awareness of heel–toe strike and step length was repeatedly reported when walking with auditory cues. Notably, gait analysis revealed a decrease in step length during walking with biofeedback (Fig. 5), yet four participants perceived taking longer steps. This apparent discrepancy is likely attributable to increased attentional focus on foot placement and temporal rhythm rather than true spatial alterations. As one participant stated, *"I was more conscious of how the foot was doing and...the quality of walking was better."* Furthermore, all participants agreed that auditory cues supported continuity between treadmill and overground walking, with one participant explicitly referring to a carryover effect. Collectively, participants strongly recommended coupling treadmill training with overground practice incorporating smart insole feedback to reinforce and generalize gait improvements. Additional representative quotations are provided in the Supplementary Material.

VI. Discussion

This study highlights the potential of resistive treadmill training combined with self-awareness biofeedback to improve foot rockers motion in adults with CP by promoting proper HS and push-off phases. To our knowledge, this is the first attempt

TABLE III
SURVEY RESULTS

#	Question	ID 1	ID 2	ID 3	ID 4	ID 5	LC
1	During treadmill training, the amount of resistance was appropriate (Q1)	Agree	Strongly Agree	Agree	Strongly Agree	Agree	4.4±0.5
2	When the resistance was removed on the treadmill, my walking changed when compared to walking pre-training (Q3)	Strongly Agree	Agree	Agree	Agree	Strongly Agree	4.4±0.5
3	Quality of walking with the sounds from the smart insole was different than when I walked without the sounds (Q4)	Agree	Agree	Agree	Strongly Agree	Neutral	4.0±0.7
4	The smart insole consisting of a cue and feedback was easy to understand what information the sound provided (Q5)	Agree	Agree	Agree	Agree	Strongly Disagree	3.4±1.3
5	Using the sounds from the smart insole reminded me to walk in a way similar to walking on a treadmill (Without resistance) (Q6)	Agree	Agree	Agree	Agree	Agree	4.0±0
6	The smart insole sound consisting of a cue and feedback should be altered in the future (Q7)	Disagree	Neutral	Neutral	Agree	Strongly Agree	3.4±1.1
7	Should quantitative information be provided after each session using the smart insole (Q9)	Strongly Agree	Agree	Agree	Neutral	Neutral	3.8±0.8
8	Would you like to use smart insole at home (Q10)	Agree	Strongly Agree	Strongly Agree	Strongly Agree	Neutral	4.4±0.9
9	Would you recommend combining the treadmill training with over ground practice using sounds from the smart insole (Q11)	Strongly Agree	Strongly Agree	Strongly Agree	Strongly Agree	Strongly Agree	5.0±0
10	What amount of time would you recommend using the smart insole after training (Q8)	<5min	10min	10min	10min	<5min	
11	I took longer steps with the sound from the insole [yes, no, same] (Q4a)	Same	Yes	Yes	Yes	Yes	
12	I walked faster with sound from the insole (Q4b)	Yes	Same	No	No	Yes	

Questions #1–9 were designed using a Likert scale. 5: Strongly Agree; 4: Agree; 3: Neutral; 2: Disagree; 1: Strongly Disagree

LC: Likert scale mean ± standard deviation

to integrate resistive treadmill training with real-time auditory cues aimed explicitly at enhancing foot rockers function in the adult CP population. The resistive treadmill is designed to induce internal motor learning by encouraging the formation of a proper foot rockers motion without requiring conscious awareness. Once this motion is established, the self-awareness biofeedback provides real-time information and guidance on how to recognize and maintain the improved gait pattern. We propose a novel strategy that integrates implicit (non-aware) and explicit (aware) learning mechanisms to generate a synergistic effect, improving foot rockers motion and enhancing the overall gait performance of adults with CP.

Walking against resistive forces on the treadmill effectively facilitated the emergence of distinct heel and toe peaks in the vGRF patterns across all participants, consistent with prior observations in children with CP [18]. We interpret these changes as evidence of enhanced ankle muscle control, reflected in more organized foot rockers pattern as previously reported [18], and accompanied by presumably faster self-selected walking speeds. For instance, the improved activation of the TA during the early stance phase likely contributed to the improvement in dorsiflexion during HS, accompanied by greater toe clearance, ensuring better foot placement at initial contact. A well-executed HS is essential for establishing proper plantar contact, which in turn facilitates a stronger push-off. This push-off is further reinforced by the heightened activation of the GA and SOL during the late stance phase, which likely led to the significant increases observed in step length. With an enhanced toe clearance and increased step length, the legs swing further, which would result in an effective HS and faster self-selected walking speed.

In addition, the improved activation of the SOL led to greater knee extension during stance by controlling the tibial rotation while allowing the center of mass to move forward [47]. While hip extension may involve other muscles, previous research suggests SOL activation can indirectly facilitate it [48]. Additionally, an extended knee posture may further promote hip extension. Together, an extended hip and knee create a more stable stance, which can reinforce HS and push-off. The delayed hip extension observed during post-training likely resulted from improved push-off. As push-off became more effective, it allowed the participants to extend their hip further before initiating the swing phase. The stronger push-off also led to an earlier shift in maximum ankle plantarflexion, aligning with reductions in temporal parameters.

It should be noted that treadmill-based gait training in individuals with CP has often struggled with limited transfer to overground walking [49], [50]. These limitations may stem from biomechanical discrepancies between treadmill and overground walking [51], [52]. In contrast to these prior studies, when transitioning to overground walking, participants in the present study retained foot rockers motion and its related improvements over time. The biofeedback after resistive treadmill training provided awareness of their improved gait pattern when transitioning overground through auditory feedback. It helped participants understand and maintain their foot rockers motion after treadmill training during overground walking. The biofeedback prompted the participants to become more aware of their heel-to-toe pattern and make necessary adjustments to their gait to have better contact with the ground. This was reflected in changes to the temporal parameters while walking with the auditory cues, as participants spent more time transitioning through stance, single stance, double stance, and stride phases of the gait cycle, indicating conscious adjustments in foot placement and timing. From survey responses, participants reported that the addition of biofeedback increased their awareness of foot-ground contact throughout the gait cycle. They also noted being more mindful of their heel-to-toe pattern, more conscious of their foot movement, and prioritizing their heel-to-toe pattern. This is supported by the outcomes during the initial training with biofeedback (T1) when participants showed improved foot rockers by improved foot angle at HS and toe clearance while spending more time during the stance phase and walking slower. Due to the training intervention, the participants showed consistent improvements in dorsiflexor and plantarflexor activation. Such improvements in muscle activation were also observed in prior studies during multimodal intervention. Conner and Lerner reported increased SOL activation when plantar-pressure biofeedback combined with resistance walking [19], and Fang and Lerner demonstrated increases in biological ankle and knee power along with higher GA and Vastus Lateralis activity using biofeedback coupled with assistance during incline walking [26]. Spomer et al. also reported that audio-visual feedback and resistance walking together increased SOL activation to achieve the target EMG level [20]. In a subsequent study, they found no overground transfer of these gains as participants likely adopted compensatory strategies in response to the biofeedback [21]. While these studies show improvements during intervention, most emphasized plantarflexor recruitment and late-stance propulsion, and rarely evaluated the effect without intervention. In contrast, by targeting both HS and push-off, we demonstrated transfer to unassisted overground walking, as shown by improvements across a broader set of outcome measures encompassing spatiotemporal gait metrics, EMG activation of the dorsiflexors and plantarflexors, joint kinematics, and vGRF profiles.

While the training showed improvements in the gait pattern among individuals with CP, there are a few limitations to acknowledge in this study. The first constraint pertains to a limited number of training sessions. For some gait parameters, we observed an overall improved trend, but the improvements were not significant. We believe more sessions are necessary to capture significant changes. Second, the downward pull of the treadmill training was provided as a fixed percentage of the body weight without accounting for the severity of each individual's CP condition. Developing a model to characterize the pulling force based on severity level could improve the training effect. Third, several adjustments could be implemented in the physical smart insole for tailored training. For this study, the positioning of heel and toe sensors was manually adjusted to fit the dimensions of each participant's foot ROM. Future versions will automate this by integrating a sensor array with an algorithm that identifies personalized HS and push-off locations, eliminating need of manual placement. Fourth, the type of biofeedback could be enhanced to train the participants effectively. Some participants suggested modifications for future versions of the smart insole, such as integrating customizable audio cues, that allow them to select their preferred tune. Fifth, alternative feedback modalities could be explored, such as incorporating haptic feedback in the form of vibrating pulses. This tailored biofeedback can facilitate better comprehension and differentiation between HS and push-off. Sixth, it should be noted that participant ID3's use of a cane may have influenced their gait adaptation, as assistive device use can alter spatiotemporal parameters and muscle activation patterns. Finally, this study was designed as a pilot trial to examine the feasibility and potential our training intervention in adults with CP. While the number of participants was limited to five, the analysis across multiple gait and neuromuscular outcomes provides meaningful preliminary insights into the effects of the intervention, and future work will expand this investigation into a larger clinical trial with increased enrollment and focused outcome measures.

VII. Conclusion

This study showed evidence that resistive robotic training can successfully facilitate an effective foot rockers in adults with CP. When supplemented with self-awareness auditory biofeedback, these improvements were maintained during overground walking. The training increased muscle activation of the Tibialis Anterior during the early stance and of the Soleus and Gastrocnemius during the late stance. The improved neuromuscular activation and control created an effective weight transfer and push-off, the two key components of foot rockers motion. Consequently, lower limb posture, foot mobility, and key spatiotemporal measures improved. Participants reported high satisfaction, emphasizing the importance of both treadmill and biofeedback training to improve their foot rockers motion and overall gait pattern. These findings fill the research gap in exploring robotic interventions among adults with CP, demonstrating improvements not only during treadmill training but also in overground walking. From quantitative metrics and participant feedback, this intervention shows promise for enhancing foot rockers and overall gait patterns in individuals with CP.

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