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Improving Ankle Muscle Recruitment via Plantar Pressure Biofeedback during Robot Resisted Gait Training in Cerebral Palsy

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Abstract— **Neurological impairment from stroke or cerebral palsy often presents with diminished ankle plantar flexor function during the propulsive phase of gait. This deficit often results in slow, energy-expensive walking patterns that limit community mobility. Robotic gait training interventions may prove effective in improving functional outcomes, including exoskeleton resistance used to provide targeted neuromuscular recruitment. However, these interventions to date have required regular verbal cues and coaching for proper plantar flexor engagement with resistance, particularly for pediatric applications. In this validation study, we sought to address the need for automating and improving the effectiveness of facilitating user engagement with robotic resistance. Specifically, our main goal was to compare changes in plantar flexor activity between walking with plantar flexor resistance alone vs plantar flexor resistance combined with plantar pressure biofeedback in individuals with cerebral palsy. We recruited 8 ambulatory adolescents with cerebral palsy between the ages of 11-18 years old to participate in this cross-sectional feasibility study. Supporting our hypothesis, we observed a 36 ± 36% and 46 ± 39% increase in mean and peak soleus activity, respectively, between resistance plus biofeedback vs resistance alone (both $p < 0.05$). Compared to other biofeedback sensing modalities like assessment of muscle activity via surface electrodes, integrating the plantar pressure-based system within the wearable robotic devices minimizes barriers to clinical implementation by reducing cost, complexity, and setup time. With these positive feasibility results, our future work will explore longer-term training effects of ankle resistance combined with plantar pressure biofeedback.**

I. Introduction

Proper timing and activation of lower-limb muscles, particularly the ankle plantar flexor muscles, is key to efficient walking [1], [2]. Many individuals with injury to the motor cortex and other parts of the central nervous system, including people with cerebral palsy (CP) [3] and stroke survivors [4], experience deficits in ankle plantar flexor function. Inadequate ankle push-off power often results in slow and inefficient walking patterns that can lead to impaired mobility and reduced quality of life [5].

Functional gait training is often used in rehabilitation therapy for treating ankle plantar flexor deficits in individuals with physical disabilities [6]. Long-term gains can be elusive with traditional physical therapy, in part because training typically takes place relatively infrequently (e.g., 1x per week) and can lack muscle-level specificity. As a result, research groups, including our own, have recently developed robotic interventions providing targeted resistance for improving the efficacy of neuromuscular gait training [7]–[12]. In theory, these robotic systems may one day provide reliable targeted muscle recruitment and enable daily at-home training. Training with adaptive ankle resistive facilitated improved clinical measures of mobility, and gait mechanics and energetics in children and young adults with CP. However, prior work has highlighted the need for almost near constant coaching to ensure proper engagement with the resistive device so that users do not adopt compensatory strategies that mitigate the effectiveness of targeted muscle recruitment [13]–[15]; the need for continued coaching from a therapist severely limits the utility of resistive technologies for use outside the laboratory. Real-time biofeedback, either alone or implemented in a video game [16], may improve user-interaction with robotic therapy, particularly for children.

Our overarching objective was to address the need for automating and improving the effectiveness of facilitating user engagement with robotic resistance for gait rehabilitation. In this validation study, we sought to determine if combining plantar pressure-based biofeedback with a robotic ankle exoskeleton used for functional ankle resistance gait training in cerebral palsy [17] could increase engagement with the device in the absence of coaching. Therefore, our specific objectives were to compare changes in plantar flexor activity between walking with plantar flexor resistance alone and when combined with plantar pressure biofeedback in adolescents with CP. We hypothesized that the addition of plantar pressure biofeedback would increase activation of the plantar flexors when walking with ankle exoskeleton resistance, supporting the use of this biofeedback modality to increase engagement during functional gait training. The primary contributions of this work include (1) the first report of an integrated plantar pressure biofeedback system for improving user interaction with robotic ankle plantar flexor resistance and (2) pilot clinical validation of biofeedback system effectiveness in 8 individuals with CP.

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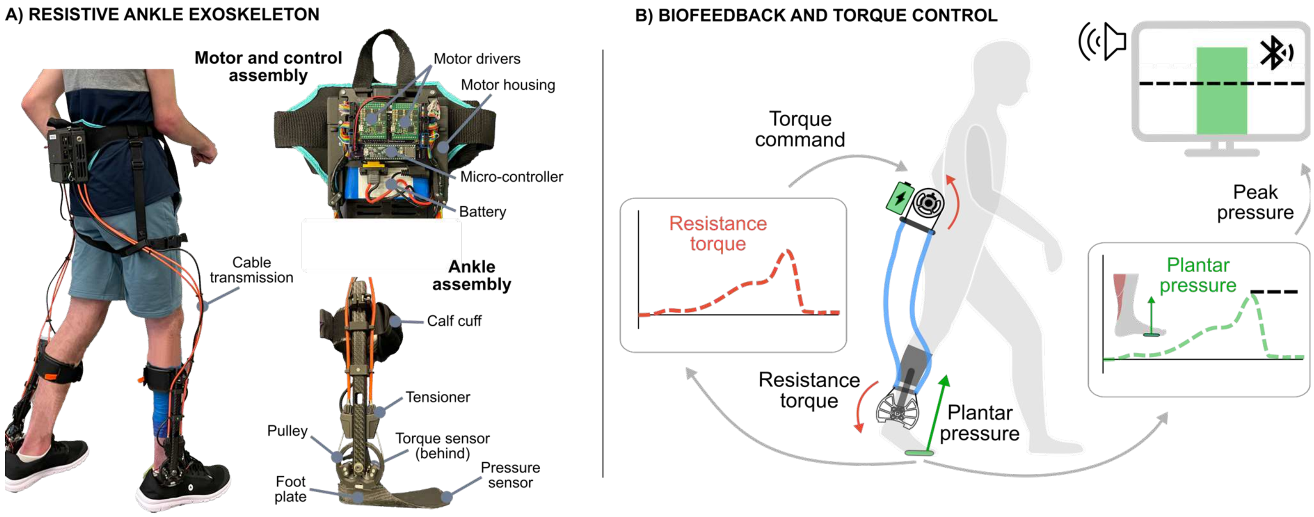

Figure 1. A) Pictures of the ankle exoskeleton and components. B) Schematic of the real-time ankle-moment-adaptive resistance and biofeedback

II. Methods

A. Ankle Exoskeleton

Pictured in Fig. 1, we developed a custom robotic exoskeleton used to deliver targeted ankle resistance and real-time biofeedback. The device had lightweight carbon fiber ankle assemblies (0.50-0.70 kg/leg) and a 1.36 kg waist-mounted control unit comprised of motors (Maxon EC-4pole), an electronics module (custom printed circuit board with Teensy 3.8 microcontroller and Maxon 50/8 motor drivers), and a battery. The device was powered by a 24 V, 2 Ah battery and communicated with control software via Bluetooth, rendering it completely untethered.

The device functioned by delivering torque from the motors via a chain-and-sprocket transmission that interfaced with a Bowden cable transmission, which in turn terminated on pulleys mounted colinear with the ankle joint. To track a desired torque signal and address friction and losses in the transmission system, a custom torque sensor, located at the ankle joint, was used for low-level closed-loop torque-feedback control [18]. The exoskeleton could provide a peak torque of ~30 Nm. More details on the mechanical design, including torque sensor validation information, are reported in [18].

Force sensitive resistors (FSRs, Tekscan, A502) were embedded on each carbon footplate under the ball of the foot. These sensors were used in three capacities: (1) for informing a finite state machine that distinguished stance and swing phase, (2) for informing the high-level torque command controller that was used to prescribe adaptive resistance that matched the shape of the biological ankle moment during stance-phase, and (3) for real-time plantar pressure biofeedback. More details and validation results of the high-level control strategy used to prescribe resistive torque proportional to the biological ankle moment are reported in [17]; resistance was not provided during swing phase.

B. Audio-Visual Biofeedback System

We sought to develop a practical biofeedback system that leveraged sensors integrated within the exoskeleton. While biofeedback utilizing real-time electromyography (EMG) measurements and a real-time display of a user's muscle activity [19]–[21] has been reported on previously, we purposely sought to design a system that could elicit the same response (increased muscle recruitment) without the disadvantages of EMG-based systems, such as skin-electrode interface reliability challenges (e.g., hair and sweating) and the necessity and complexity of proper anatomical placement of the sensors, particularly when placing sensors on small limbs.

Our solution utilized the embedded forefoot FSRs to provide biofeedback of plantar pressure as a surrogate measure for plantar flexor muscle activity. During operation, the system first calibrated the FSRs by recording typical pressure during 5-seconds of walking. Next, we divided the instantaneous FSR reading by the average peak value from the calibration period. This normalized FSR reading was then transmitted at 100 Hz to a computer operating a real-time MATLAB graphical user interface (GUI) and used as an input into an adjustable thresholding algorithm whereby a technician could prescribe a target plantar pressure value.

Audiovisual biofeedback of plantar pressure performance was provided to the user via a real-time bar plot rendered on an eye-level display and a "ding" sound. If the user reached the target, the bar plot changed from red to green and a "ding" sound was emitted from speakers; the bar plot changed back to red once the FSR value returned to below the target. The target pressure was initially set to 10% above baseline. From there, to keep the experience engaging in the event of too high or too low performance, we adjusted the target based on user performance: if the target was reached more than 75% of steps in a minute, the target was increased by 10%; if the target was reached during less than 50% of steps in a minute, the target was decreased by 10%; otherwise, the target was held constant.

C. Study Approval and Participants

We received approval for this study by the Institutional Review Board of Northern Arizona University (protocol: #986744-27) on 12/03/2020 as a part of Clinical Trial

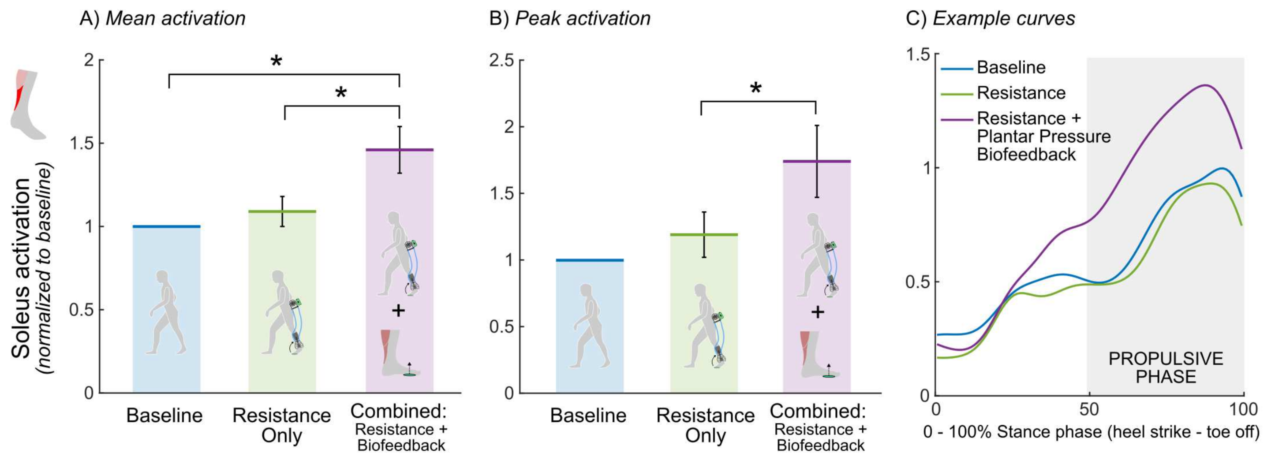

Figure 2. Average A) mean and B) peak propulsive phase soleus activation relative to baseline activity for baseline walking and walking with ankle exoskeleton resistance with and without biofeedback. Error bars represent standard error of the mean, brackets indicate pairwise comparisons between resistance alone and combined with plantar pressure biofeedback, *$p < 0.05$; there are no error bars for baseline because of normalization. C) Example soleus activation curves (average of 20 gait cycles) across the three walking conditions from one participant: baseline (blue), exoskeleton resistance alone (green), and exoskeleton resistance with plantar pressure biofeedback (purple); curves from this participant may not reflect group level results.

NCT04119063. Following participant recruitment, we gained informed written consent by each participant if 18 years or older, or the parent/legal guardian in the case of minors, with minors also providing verbal assent. Inclusion criteria for participation included the following: confirmed diagnosis of hemi- or diplegic CP, ability to walk on a treadmill with or without support for more than 10 minutes, Gross Motor Function Classification System (GMFCS) level I – III, age between 10 – 21 years, no orthopedic surgery within the past six months, no botulinum toxin injections to the triceps surae muscles within the past six months, and the absence of any other condition(s) that would preclude safe participation. Eight individuals met our inclusion criteria and participated in this study (Table 1).

D. Experimental Protocol

First, we measured weight, height, and leg length for each participant, and determined their preferred treadmill walking speed. Next, wireless surface EMG electrodes (Noraxon, 1000 Hz; Scottsdale, AZ, USA) were placed on each participant's more affected lower-limb's soleus muscle according to SENIAM recommendations [22]; the calf-cuff of the device prevented accurate measurement of gastrocnemius muscle activity because of motion artifact. To validate plantar pressure biofeedback as an effective mechanism to increase plantar flexor muscle recruitment during walking with ankle exoskeleton resistance, participants completed three 2.5 minute walking trials at a self-selected speed on the treadmill while we recorded muscle activity. First, participants walked while wearing the device when it was powered off and the footplates were disconnected (Baseline). Second, participants walked while wearing the device as it provided plantar flexor resistance set to 0.15 Nm/kg (nominal) delivered to their more impaired limb (Resistance only); because resistance torque was adaptive, there were slight stride-to-stride variations in peak applied torque. Third, participants walked with audiovisual biofeedback of plantar pressure and with the same amount of resistance as before (Resistance + Plantar pressure biofeedback). This order was purposeful to eliminate any persisting effects of biofeedback on the resistance alone condition. Walking speeds were matched across conditions within each participant. To ensure proper acclimation to resistance, each participant walked for at least 15 minutes prior to the robotic resistance alone trial analyzed in this study.

D. Data Analysis

EMG data were bandpass filtered (20 - 400 Hz, 4th order Butterworth), rectified, and low-pass filtered (4 Hz, 4th order

TABLE 1. PARTICIPANT CHARACTERISTICS

	Gender	Age (y)	Height (m)	Weight (kg)	GMFCS[a]	CP Type
P1	M	13	1.48	38.6	II	Diplegic
P2	M	15	1.58	59.4	II	Diplegic
P3	F	11	1.43	41.7	III	Diplegic
P4	M	13	1.58	38.5	III	Diplegic
P5	M	16	1.61	48.5	II	Diplegic
P6	M	18	1.75	60.3	II	Diplegic
P7	M	17	1.65	65.8	I	Hemiplegic
P8	M	12	1.40	39.5	I	Hemiplegic

[a]GMFCS: Gross Motor Function Classification System level

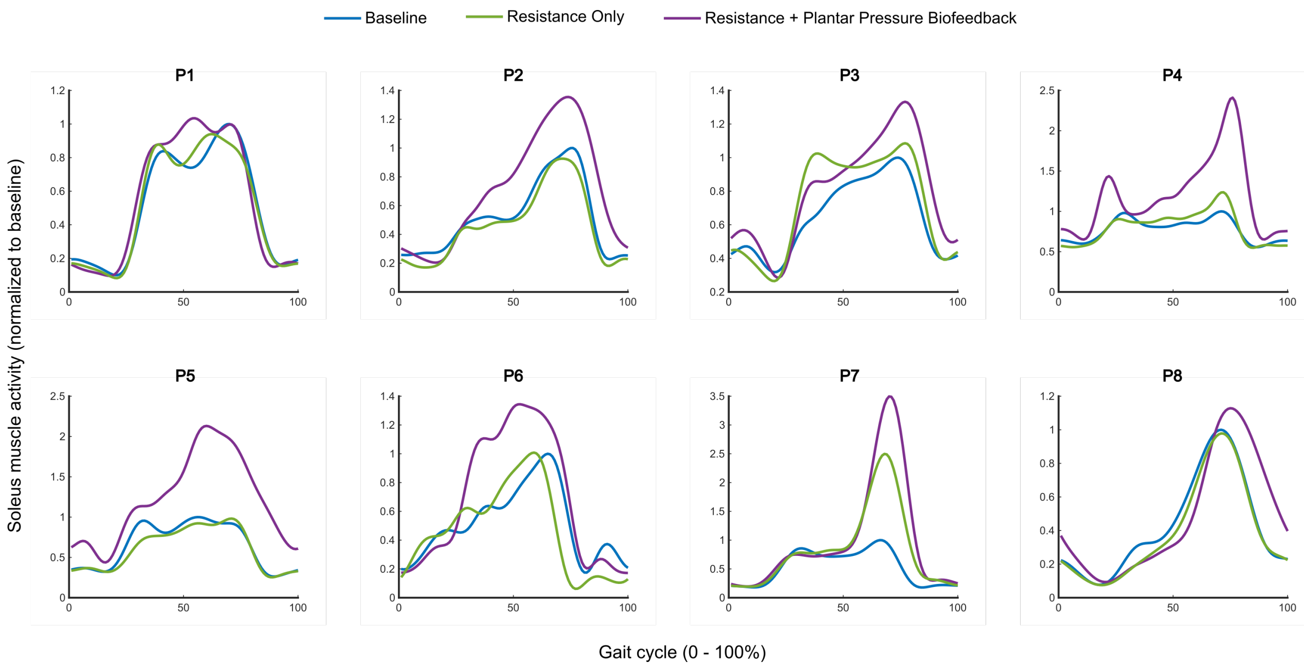

Figure 3. Mean soleus muscle activation curves for each participant. Muscle activity was averaged over 20 gait cycles and normalized to peak baseline activation, across baseline (blue), exo resistance only (green), and exo resistance plus plantar pressure-based biofeedback (purple) conditions.

Butterworth) [23], and then time normalized to percent gait cycle (heel strike to heel strike). We analyzed 20 consecutive cycles for each condition and averaged them together for each participant. Each average muscle activation curve was then normalized to peak baseline activation. We then computed mean and peak propulsive phase soleus activation.

To assess our objective of evaluating the application of the plantar pressure-based biofeedback system while used in conjunction with ankle exoskeleton resistance, we performed one-way RM ANOVA to compare mean and peak soleus activation between baseline walking, ankle exoskeleton resistance alone, and ankle exoskeleton resistance with plantar pressure-based biofeedback. Significant main effects were followed up with two-tailed pairwise comparisons with Holm-Bonferroni correction for multiple comparisons. All p-values reflect the adjustment from Holm-Bonferroni correction; the adjusted p-value significance level was set at $p < 0.05$. Error bars depict standard error of the mean (SEM). The Lilliefors test was used to assess data for normality; all data were normally distributed.

III. Results

There was a significant effect of walking condition on mean soleus activity ($p < 0.01$; Fig. 2A). Pairwise comparisons indicated a significant increase for the combined ankle exoskeleton resistance and plantar pressure biofeedback condition relative to baseline (47 ± 15.6%, $p = 0.036$; mean ± SEM) and resistance alone (36 ± 14.7%, $p = 0.044$) conditions; no difference was found between baseline and resistance alone ($p = 0.31$). Similarly, a significant effect of walking condition was found for peak soleus activity ($p = 0.01$; Fig. 2B), with significantly higher peak activity for the combined system versus resistance alone (46 ± 15.6%, $p = 0.03$), but no difference was observed between the combined system and baseline ($p = 0.08$), or resistance alone versus baseline ($p = 0.34$). Individual soleus activation curves are reported in Fig. 3 to provide full visibility of the effects of the Resistance and Resistance + Plantar Pressure Biofeedback conditions across the entire gait cycle.

IV. Discussion

We have been working to develop wearable robotic ankle exoskeleton resistance to improve neuromuscular control and gross mobility in children with CP [7], [8]. It was previously observed that multi-week resistive gait training with the device used in this study resulted in significant improvement in ankle plantar flexor strength, coordination at the ankle while walking, walking efficiency, and performance on clinical tests of mobility [7], [8]. While these findings demonstrated the potential of this novel robotic gait training system for individuals with neuromuscular impairments, effective engagement with the device required regular verbal cues and coaching, which was consistent with other robotic gait training interventions for pediatric populations [13]–[15]. Therefore, the main goal of this study was to determine if plantar pressure-based biofeedback would elicit improved engagement with robotic ankle resistance for the purpose of increased plantar flexor muscle recruitment during functional gait training in CP.

There were large increases in mean and peak soleus activity (36% and 46%, respectively) between the resistance plus biofeedback and resistance alone conditions, which suggests that this simple biofeedback system can increase user engagement with robotic resistance. The 47% increase in mean soleus activity during walking with resistance plus biofeedback compared to baseline observed in the present study was similar to the 45% increase that we observed previously between resistance plus coaching relative to baseline [17]; the resistance plus coaching results were observed after 4-5 visits and 80-100 minutes of resisted walking acclimation. The findings from the present study are particularly encouraging, therefore, as we found that the application of the plantar pressure biofeedback system resulted in rapid (within ~3 minutes) and significant increases in neuromuscular engagement with the device without the need for constant verbal cues or a long acclimation period. While not a perfect head-to-head comparison, this finding suggests that biofeedback may result in the desired device engagement without the need for constant human oversight. This finding paves the way for non-supervised gait training with the robotic system, including the potential for training at home.

The study had several limitations that are worth considering. First, we neglected to collect a resistance plus coaching condition, which would have allowed us compare how resistance plus plantar pressure-based biofeedback stacked up to the common implementation of resistive gait training. However, as mentioned above, when we compare the findings from the present study to our prior validation work on resistance plus coaching that was conducted with several of the same participants, we saw a similar increase in soleus activation (resistance + audiovisual biofeedback: 47 ± 39%; resistance + verbal coaching: 45 ± 35%). While outside the scope of this validation study, the second limitation was that the walking trails were relatively short, and there were no follow-up assessments.

V. Conclusion

To the best of our knowledge, this is the first study to develop a plantar pressure-based biofeedback system to augment plantar flexor muscle recruitment during robot-resisted gait training. Plantar pressure biofeedback was successful in improving neuromuscular engagement with the exoskeleton. The simplicity and integrated nature of this biofeedback modality was purposeful to drive clinical translation of robot-aided functional gait training at home and in the community. In our future work, we plan to explore long-term rehabilitation outcomes with robotic ankle resistance combined with plantar pressure biofeedback. We also plan to assess the integration of plantar pressure biofeedback during walking with the exoskeleton in ankle assistance mode [24], [25] (as opposed to resistance) for individuals with more significant walking impairments.

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