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Priming Robotic Plantarflexor Resistance with Assistance to Improve Ankle Power during Exoskeleton Gait Training

Karl Harshe, Emanuella Tagoe, Collin Bowersock and Zachary F. Lerner

***Abstract*— Robotic exoskeletons are increasingly being used for gait rehabilitation in individuals with neuromuscular disorders, such as cerebral palsy (CP). A primary rehabilitation goal for those with CP is to improve ankle push-off power, which is crucial for enhancing gait function. Previous research suggests that interleaving assistance and resistance within the same training session may improve certain aspects of gait, such as joint trajectories and torque profiles. This feasibility study sought to investigate the efficacy of priming the plantar flexor muscles with ankle exoskeleton plantar flexor assistance to facilitate increased ankle push-off power during subsequent resisted gait training bouts in individuals with CP. Specifically, we hypothesized that providing plantar-flexor assistance immediately prior to walking with resistance would increase peak biological ankle power and muscle activity compared to walking with resistance alone. We found that peak biological ankle power increased by 25% (p = 0.021) during assistance-primed resisted walking compared to the baseline resisted walking trail. While ankle angular velocity also increased alongside power, there was no significant difference in plantar flexor muscle activity, suggesting more efficient recruitment. These results contribute to our overarching goal of optimizing robotic exoskeleton interventions, potentially leading to the future design of more effective gait rehabilitation strategies.**

Index Terms – Exoskeletons, Resistance Training, Biofeedback, Muscular Priming, Rehabilitation, Cerebral Palsy

I. Introduction

Cerebral Palsy (CP) is a neurological disease affecting millions globally and presents a significant challenge as the most commonly occurring pediatric physical disability in the United States [1], [2]. Characterized by diminished motor function and motor control, CP often impedes basic locomotive activities contributing to a lower quality of life and potentially, a shorter life [3], [4], [5]. Despite CP not being classified as a progressive illness, the absence of effective therapies may exacerbate symptoms over time [6]. Traditional treatments for CP include intensive manual therapies and resistance training, as well as multi-level surgery and muscle injections [7].

Positive ankle joint power during push-off (i.e., push-off power) is critical for efficient bipedal locomotion[8]. Individuals with CP have significantly reduced ankle push-off power compared to their unimpaired peers [9]. Research suggests that power-based gait training may be more effective than traditional strength-focused gait training in CP [10]. As such, there is an increasing focus during gait training in CP to encourage greater ankle push-off power, a key metric for improving walking ability [11]. However, increasing ankle power through traditional physical therapy is limited by the intensive and repetitive manual labor requirements from the clinician. Moreover, these traditional, non-robotic techniques have failed to demonstrate a consistent, lasting link between the manual therapy and retention of altered gait patterns.

The emergence of robotic gait training exoskeletons that can automate the delivery of both assistance and resistance appear to be growing in popularity for research on augmenting ankle push-off power [12]. Gait training with assistance is often intended to reinforce favorable gait patterns and reduce the burden of increasing doses (repetitions) [13]. Resistance, on the other hand, is used as a tool for reinforcing context-specific muscle activity (e.g., Plantarflexor muscle recruitment during the push-off phase of walking) [14], [15]. Additionally, powered exoskeletons can be combined with biofeedback to provide visual and auditory stimuli of a target neuromuscular or walking performance metrics [16], [17]. However, there has been limited prior research on multi-faceted techniques to optimize effective ankle push-off power training.

While robotic resistance training has gained substantial traction in academic literature [18], the exploration of "priming," which we define here as a sub-set of an intervention that encourages a targeted functional response [19], [20], remains relatively unexplored, especially in the context of biofeedback-informed interventions [21], [22]. The traditional purpose of priming has been to increase biological joint power, velocity, or position while reinforcing a functional task [23], [24]. In robot-aided gait rehabilitation, the use of powered assistance at the ankle, for example, could be used to "prime" heightened ankle push-off power as a way for users to experience the exaggerated motion and encourage more effective subsequent training bouts with powered resistance. This would be in contrast with providing ankle resistance alone (i.e., never providing assistance), which may cause users to underperform (i.e., have lower ankle push-off power) because they have not experienced walking with exaggerated push-off, as enabled by assistance.

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This work involved human subjects or animals in its research. The Institutional Review Board of Northern Arizona University approved this study under protocol #986744-43.

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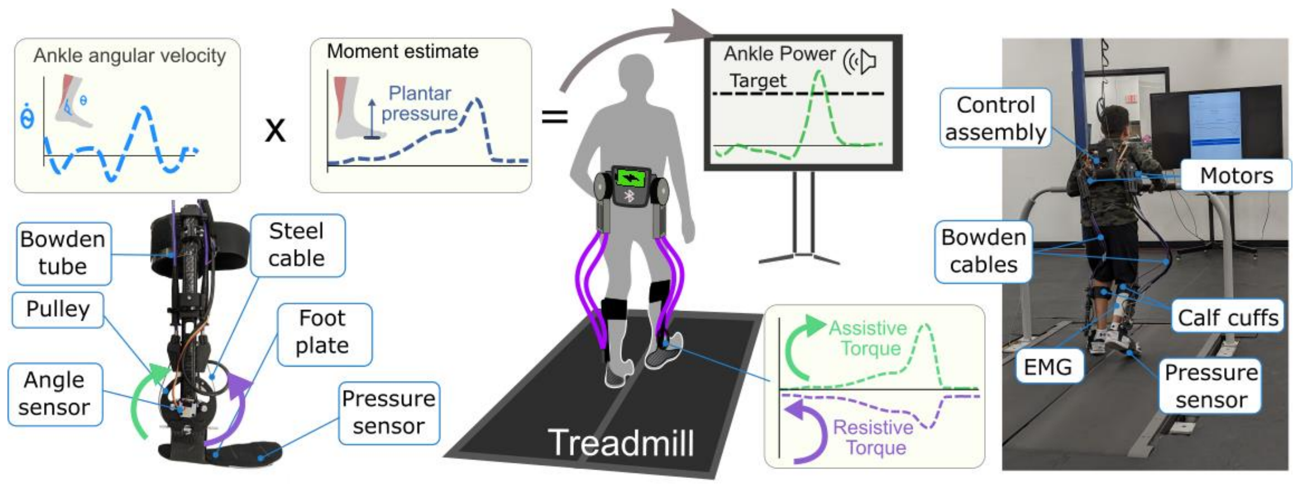

Figure 1. Schematic and pictorial depictions of our experimental device and setup. Participants wore a custom ankle exoskeleton that either assisted or resisted plantar flexion during stance phase, depending on the prescribed condition. On the top left, we depict how on-board sensing of ankle angular velocity and plantar pressure were used to generate an estimate of real-time ankle power. A calibration procedure was used to estimate the ankle moment from plantar pressure. On the bottom left, we show the primary components of the ankle exoskeleton. On the right, we show how the real-time ankle power biofeedback was displayed to each participant in real time relative to the threshold target (110% of unresisted normal walking power); visual and audio cues incentivized participants to generate ankle power that exceeded the target.

The objective of our study was to investigate the efficacy of priming the plantar flexor muscles with ankle exoskeleton plantar flexor assistance to facilitate increased ankle push-off power during subsequent resisted gait training bouts in individuals with CP. Leveraging the ability to rapidly alternate priming assistance, with resistance using our custom powered ankle exoskeleton, we conducted short, intense "priming" bouts of assisted walking followed by resisted walking. We hypothesized that assistance-priming would enhance ankle push-off power during the following resisted walking bouts. This study aims to increase the effectiveness of wearable robotic gait training interventions for individuals with walking disabilities, shedding light on the effectiveness of joint power priming in the pursuit of optimized gait training outcomes.

II. Methods

A. Overview

The objective of this feasibility study was to implement a foundational scientific comparison evaluating the potential neuromuscular and biomechanical differences between gait training with the status quo (resistance alone) vs a new intervention leveraging robotic priming (assistance-primed resistance) (Fig. 1). Therefore, we intentionally designed our study with a focus on comparing our new intervention (assistance-primed resistance) to the existing approach (non-primed resistance), rather than making comparisons to walking without the device. In a baseline-resisted trial, participants walked for four minutes with only resistance. Next, we had participants complete two primed resistance trials, which included two minutes of walking with plantarflexion assistance immediately followed by two minutes of walking with resistance. Finally, an "exposed" resistance-only walking trial was completed for four minutes; note: here we use "exposed" to point out that the participant had already completed two bouts of priming. All trials were included audio-visual biofeedback of real-time estimated ankle power.

Our primary outcome measure was biological joint power. Secondary outcome measures included stride length, ankle excursion, and targeted muscle (plantar flexor) engagement. Outcome measures were compared across the resistance portion of each bout (Fig. 2) relative to the initial baseline resistance trial that did not have any priming exposure so as to capture the naïve resisted walking behavior. We received approval for this study from The Institutional Review Board of Northern Arizona University (#986744-43) and all methods and hypotheses were registered with the Open Science Framework prior to any data for this study being collected [25].

B. Participants

Eight males diagnosed with CP were recruited for participation (Table I). Inclusion criteria were, an age between 10-65 years old; a body mass between 40 and 85 kg; a confirmed CP diagnosis with Gross Motor Functionality Classification System (GMFCS) level I-III; the ability to walk continuously on a treadmill for at least six minutes; the ability to follow both verbal and simple visual instructions; finally,

TABLE I. PARTICIPANT INFORMATION

	Impairment level	*Age (Years)*	*Height (cm)*	*Weight (kg)*	*Walking speed (m/s)*
S1	I	37	183	71	0.82
S2	II	17	170	58	0.60
S3	I	14	172	58	0.85
S4	II	40	180	72	0.60
S5	II	14	149	47	0.45
S6	II	18	171	52	0.65
S7	I	19	167	54	0.75
S8	I	13	170	56	0.85

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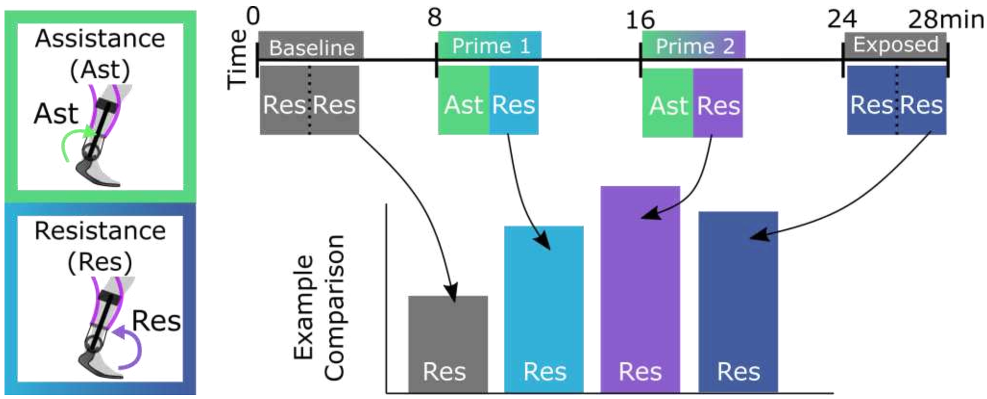

Figure 2. Schematic depictions of the conditions (left), experimental protocol (top), and example comparisons (bottom right). For the trials with "Assistance", the ankle exoskeleton provided 0.2 Nm/kg of plantar flexor assistance torque during stance phase. For the trials with "Resistance", the ankle exoskeleton provided 0.1 Nm/kg of plantar flexor resitance (dorsi-flexor directed torque) during stance phase.

the absence of any known medical condition that could cause harm or injury during participation.

C. Robotic Ankle Exoskeleton

We used a purpose-built untethered robotic ankle exoskeleton to provide each participant with assistive and resistive ankle torque (Fig. 1). Peak nominal torque, delivered during the push-off phase, was set to 0.1 Nm/kg for resistance and 0.2 Nm/kg for assistance. These values have been used in previous experiments in individuals with CP [15], [26]. The exoskeleton had a total mass of about 3.5 kg. The device was able to provide both assistance and resistance bilaterally and bidirectionally to each ankle independently. A waist belt, weighing approximately 2.7 kg, housed a custom printed circuit board and microcontrollers, as well as two AK60v1.1 brushless DC motors which were powered by an 1800 mAh LiPo battery.

Mechanical work from the motors was transferred to the ankle assembly by steel cables running through Bowden sheaths. The steel cables rotated a pulley collocated with the ankle, which drove a carbon fiber footplate that rotated with the participants' ankle during assistance or against it during resistance.

Force-sensitive resistors (FSRs), embedded on each footplate and located under the heads of the 1st and 2nd metatarsals (i.e., the "ball of the foot"), measured plantar pressure and provided data for identifying stance and swing phases via a finite state machine. We also used the FSRs to estimate the ankle joint moment during stance, which was the input for our high-level control scheme based on providing assistance or resistance proportional to the real-time estimate of the ankle joint moment [27]; this controller results in an instantly-adaptive desired torque profile. We used a custom torque sensor for low-level closed-loop torque-feedback proportional derivative (PD) control [28]. Reliable torque delivery from wearable devices is critical for consistent intervention delivery. Iterations of our exoskeleton, which has been under development for 7 years, including this version, have been used reliably across a variety of walking conditions and patient populations [27], [29], [30], [31].

The device also included angle sensors for each ankle. These Hall effect-based angle sensors provided angular velocity and were used in conjunction with the FSR in the footplate to estimate ankle power in real-time. A custom low-profile torque sensor located at each ankle joint recorded real-time applied torque and was used by a closed-loop proportional-derivative controller, operating at 500 Hz, to ensure proper torque tracking. The exoskeleton was monitored and controlled with a custom iOS app wirelessly over Bluetooth. System state data were displayed to researchers and participants, as well as recorded, at 60 Hz.

D. Biofeedback

Biofeedback based on the real-time estimate of ankle power was displayed to the participant in real-time similar to previous work [26], [32], [33]. Ankle power was *approximated* in equation 1, as follows:

$$\boldsymbol{P} = \boldsymbol{M} * \boldsymbol{\omega} \tag{1}$$

where P = Power, M = estimated moment, and ω = ankle angular velocity. The estimated moment was measured using the FSRs integrated into the footplates, these sensors measured the variable downward force at a constant radius [34]. Multiplying the ankle moment and angular velocity together at each exoskeleton timestep resulted in our *approximation* for ankle power. When the estimated ankle power exceeded the target level the participant received a visual reward, in the form of a green background flash and confetti drop, as well as an auditory reward in the form of an ascending chime. The target level, held constant throughout the experiment, was set to 110% of the mean peak power measured while walking without biofeedback.

E. Motion Capture and Modeling

We used an eight-camera motion capture system (Vicon, USA), collecting at 120Hz, to record the motion of the feet and shank. We used surface wireless electrodes (Trigno; Delsys, USA) to collect electromyography (EMG) data of the lateral gastrocnemius at 1200 Hz. Ground force reactions were collected at 1200Hz using an instrumented treadmill (Bertec, USA).

F. Musculoskeletal Modeling

A custom OpenSim model was created to compute stride length and sagittal-plane ankle angle, velocity, moment and power [35]. Inverse kinematics and dynamics analyses were used to compute kinematic and kinetic outcomes, respectively [26]. This model was used in data analysis and was not implemented in real time.

Our custom OpenSim model was used to define the feet and the shank of the participants' more affected limb. Markers placed on the medial and lateral malleolus and the medial and lateral condyles defined the ankle and knee joint center of the more affected limb. Three markers placed on the less affected limbs first toe, fifth toe, and heel defined and tracked the less affected foot. Four markers placed at the first toe, fifth toe, heel and in line with the styloid process defined and tracked the more affected foot. A single cluster of four markers was attached to the shank of the more affected leg to track this segment. Our custom lower-leg OpenSim model included 0.4 kg to the shank during trials in which the participant wore the ankle exoskeleton to account for the added mass of the lower leg assembly. To calculate the biological components of ankle joint moments and power, vector addition was used to add the exoskeleton torque (measured from on-board torque sensors) to total ankle joint moment computed from inverse dynamics analysis [36].

G. Experimental Data Collection

***Session 1**: Acclimation*

In the first session, participants were introduced to treadmill walking and the ankle exoskeleton. Participants initially walked on the Bertec split-belt treadmill without the device (normal shod) to identify their preferred walking speed. The subject was then fitted with the exoskeleton, and they walked at that preferred speed while the device was in the zero-torque mode. While in the zero-torque mode, a closed-loop torque-feedback PD controller minimized imparted assistance or resistance to walking. Additionally while in zero-torque mode, the target power threshold was set to 110% of the mean peak power measured while walking without biofeedback. After the participant verbally confirmed their comfort in the device, they began to receive biofeedback based on their estimated ankle power. Once the participant demonstrated that they understood how to achieve their target in the zero-torque mode biofeedback was removed and resistance was slowly introduced. The prescribed resistance level was slowly increased until 0.1 Nm/kg of nominal peak resistance was delivered. Biofeedback was then reintroduced, and the participant walked until they demonstrated how to properly engage with biofeedback. Finally, the participant was introduced to the assistance mode. Similar to the resistance mode's introduction, the assistance level slowly increased until the desired assistance level (0.2 Nm/kg) was delivered.

The acclimation session lasted between 30 and 60 minutes depending largely on the comfort level of the participant. Both sessions included scripted prompting and explanations from the researchers.

We implemented a 2-hour washout period in between sessions during which participants ate, rested, and engaged in light walking activities. The participants did not wear the device nor receive feedback while walking during this rest period.

***Session 2**: Reacclimation and testing*

In the second session, we placed the motion capture markers and an EMG sensor on the belly of the lateral gastrocnemius. Each participant completed a shod walk, in which they walked without the device. Following the shod walk, they donned the exoskeleton and received a reminder of how biofeedback was linked to walking mechanics (i.e., push-off power). Participants walked briefly in zero-torque to confirm their comfort with the walking speed and set the target power (110%, as in acclimation) prior to receiving feedback. Participants were then given biofeedback while walking in the device in each mode of operation, zero-torque, resistance, and assistance. The mode was changed after they achieved at least 10 successful steps in each condition and were able to receive rewards on five consecutive steps.

Testing: Each participant went through four bouts of walking with four minutes of rest in between (Fig. 2). Resistance with biofeedback was delivered for the entirety of the baseline and exposed resistance bouts. Assistance for 2 minutes immediately followed by resistance for 2 minutes, was delivered during both the first and second primed condition.

H. Data and Statistical Analysis

We recorded and report exoskeleton and motion capture (Vicon, Bertec and Delsys) data from last two minutes of each trail. Trials were segmented into individual steps based on gait events recorded by the exoskeleton and the Bertec treadmill and normalized to percent duration of the gait cycle. For each participant, ankle angle, moment, angular velocity, total observed power, EMG (lateral Gastrocnemius), biological ankle moment, and biological ankle power were averaged across gait cycles within each condition.

Power was calculated as the product of moment and joint angular velocity. Peak biological power was calculated by averaging the biological power for all of the steps in the trial, and identifying peak output during stance phase. EMG data were filtered using a band-pass filter between 15 and 380 Hz, rectified, then low-pass filtered with a 7 Hz cutoff [29].

To evaluate the impact of assistance priming on resisted walking, we compared the average peak ankle power, total ankle excursion, as well as step length and peak lateral Gastrocnemius activity in each condition (Prime 1, Prime 2, Exposed) to the baseline resistance condition. We used two-tailed paired t-tests to compare each condition to baseline. Significance was set to $p = 0.05$. Due to challenges in participant recruitment in the northern Arizona region, the study did not achieve the statistical power necessary to implement an ANOVA. With 8 participants, the achieved power was approximately 0.39 for biological ankle power,

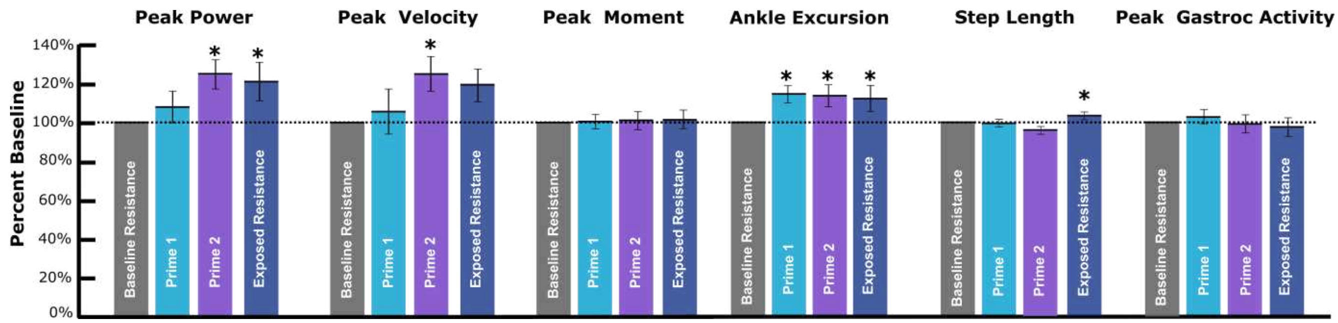

Figure 3. Primary outcome measures across conditions. All measures were normalized to the resisted baseline condition. Prime 1 & Prime 2 represent the first and second assistance-primed resistance conditions, while "exposed resistance" corresponds to the final resistance-only condition. Peak Power was computed via scalar multiplication of angular velocity and moment. The dashed line identifies the level of each variable at the resisted baseline; any subsequent bars above the dashed line indicate elevated mean values. Error bars indicate the 95% confidence intervals associated with the means, and * indicates statistically significant differences.

and an additional 9 participants, effectively doubling the cohort, would have been required to reach the standard power of 0.8 for performing an [37].

To explore participant responses within trials, temporal effects of priming were assessed by analyzing peak values of power, excursion, and EMG throughout each trial. We fit a linear regression equation to the maximum values attained during each step versus time. Subsequently, the gradient of this line was normalized by the mean of the maximum values, thereby yielding percent change of the mean maximum value.

III. Results

A. Peak Biological Ankle Power

Peak biological ankle power (Fig. 3) in the first primed condition was statistically similar to the baseline ($p = 0.498$), while the second primed condition was 24.91% higher ($p = 0.021$), and exposed resistance was 21.18% above baseline ($p = 0.050$). A typical power progression through the trials can be seen in Fig. 4, where the initial primed, as well as the exposed resistance conditions, are slightly elevated from baseline, while the second primed condition is significantly elevated. Ankle power in the baseline resistance condition was insignificantly different from the in the shod condition ($p = 0.647$).

B. Peak Angular Velocity

Peak ankle velocity (Fig. 3) in the first primed and exposed resistance conditions were insignificantly different from baseline ($p = 0.680$, $p = 0.058$), but the second primed condition was a significant 24.49% ($p = 0.036$) higher than baseline. Peak ankle velocity in the baseline resistance condition was insignificantly ($p = 0.264$) different from the shod condition.

C. Peak Biological Ankle Moment

Biological ankle moment (Fig. 3) in all three conditions were insignificantly different than baseline ($p = 0.972$, $p = 0.782$, and $p = 0.747$). Peak ankle moment in the baseline resistance condition was significantly higher (12.95 ± 14.75% $p = 0.045$) than in the shod condition.

D. Ankle Excursion

Ankle excursion (Fig. 3) in the first primed condition was a significant 14.57% higher than baseline ($p = 0.038$), the second primed condition was 16.47% higher ($p = 0.037$) than baseline, and the exposed resistance was 11.24% higher ($p = 0.047$). A typical ankle angle progression through the trials can be seen in Fig. 4, where the initial primed condition is similar to baseline, while the second primed and exposed resistance conditions show elevated peak angular displacement. Ankle excursion in the baseline resistance

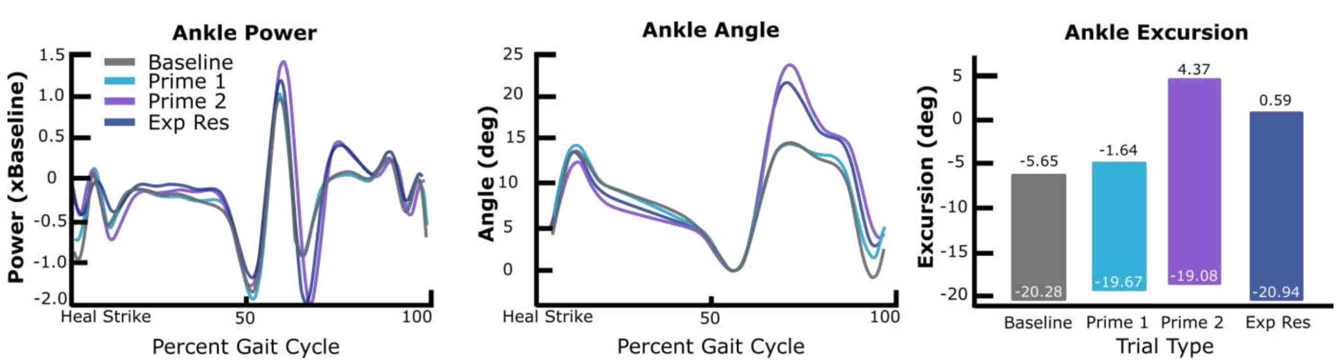

Figure 4. Representative ankle mechanics plots. Ankle Power shows representative biological ankle power profiles for each condition selected from a consistent responder (S8) and each subsequent condition was scaled to the peak positive power of the baseline. Ankle Angle was the mean ankle angle profile for each condition from the same participant. Ankle Excursion was offset to the minimum angle during stance phase for clarity. The raw angles from Angular Displacement are shown in their original ranges with the minimum and maximum ranges labeled respectively.

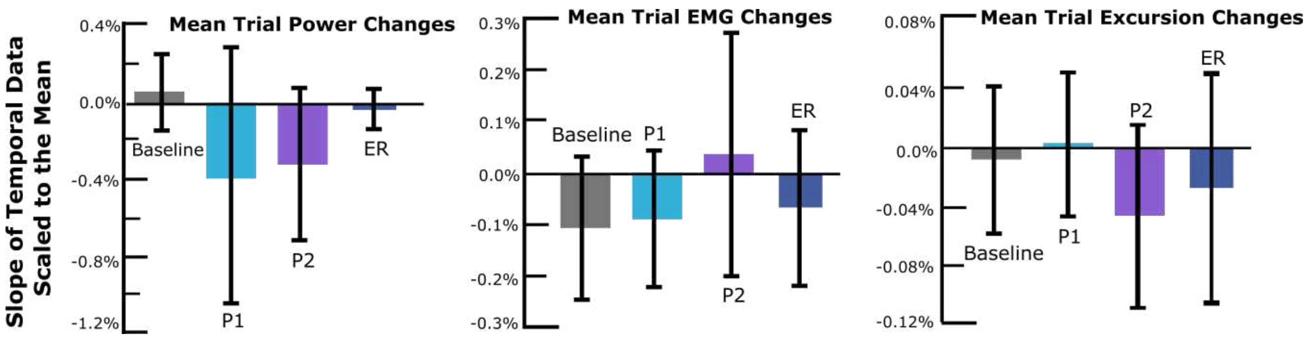

Figure 5. Confirmation of temporal consistency across trials. Mean Trial Power, Trial EMG and Trial Excursion Changes each show the average change in the slope of a linear regression which was fit to each outcome measure's peak value for each step throughout each trial. The slopes were scaled relative to the average of the metric to ensure measurement units did not obscure the visibility of influential or noninfluential slopes. Error bars represent 95% confidence intervals. A slope of 0% represents zero temporal change in the outcome measure across the trials.

condition was insignificantly higher (p = 0.256) than in the shod condition.

E. Step Length

Step length (Fig. 3) in the first and second primed condition P1 were insignificantly different from baseline (p = 0.938, p = 0.137), and exposed resistance was 4.01% higher (p = 0.040). Step length in the baseline resistance condition was not statistically different (p = 0.906) from the shod condition.

F. Peak Muscular Engagement

Muscular activation (Fig. 3) in all three conditions was insignificantly different from baseline (p = 0.794, p = 0.941, p = 0.771). Peak muscular activation in the baseline resistance condition was similar (p = 0.456) to the shod condition

G. Temporal Effects

Due to the variability between trials, we examined the variability within trials, and found that conditions were internally consistent (Fig. 5). When examining each trial on a step-by-step basis, it was confirmed that changes in peak biological power, peak EMG and ankle excursion were all insignificantly (p > 0.05) different from zero.

IV. Discussion

The main goal of this study was to investigate the efficacy of using powered ankle exoskeleton assistance to "prime" push-off power during resisted exoskeleton gait training for participants with CP. Our primary outcome measures included ankle power, plantar flexor activity, ankle joint excursion and step length. Our hypotheses were partially supported. We saw significant increases in ankle power and excursion, however we did not identify accompanying increases in plantar flexor activity from the lateral gastrocnemius, or increased step length. These results are encouraging as they have the potential to improve the effectiveness of robot-resisted gait training in individuals with CP and other movement disorders.

The observed increases to ankle power and excursion imply that priming had a positive impact on the resistance training our device provided. These results were consistent with prior work on interleaved assistance and resistance torque with a knee exoskeleton which demonstrated improved joint extension during walking [38]. Additionally, the downward-trending EMG signals suggest potentially decreased neurological load or tonic plantarflexion activation during walking, further encouraging engagement in physical activity among individuals with CP [39]. These two outcomes hold particular promise for fostering long-term health and quality of life by promoting increased activity levels and independence in daily living tasks [40].

Results from the final "exposed" resistance trial was principally intriguing, revealing that the priming effects persisted for several additional minutes. Ankle power remained nearly at the level of the most recent priming, suggesting sustained effects over time. Although the angular velocity did not maintain statistically significantly different from the baseline due to participant variability, excursion remained increased.

The lack of increased muscular engagement was initially surprising; contrary to our expectation, we observed no difference in plantar flexor activity during primed resistance walking compared to baseline resistance. However, considering the increase in ankle power following priming, this may indicate more efficient plantar flexor muscle recruitment. There is a need for further investigation into the neuromuscular responses and the mechanisms underlying potential improvements in efficiency.

We were also initially surprised at the absence of an increase in step length, as previous research indicated that step length correlates strongly with ankle joint power [41], [42]. However, upon reflection, we note that the treadmill speed was held constant, and we realized that participants were essentially instructed to maximize the number of rewards from the biofeedback system, which may have inadvertently encouraged them to shorten their steps to receive the greatest number of rewards. Several options exist to rectify this oversight. Researchers could provide step indicators that encourage the participants to maintain their step length, or an additional metric could be included in the biofeedback system that takes step length into account. But, it is possible that this additional information could overwhelm some participants and result in disengagement with the protocol.

The primary limitations of this study were related to sample size. However, our recruited cohort is of a comparable size when looking at similar studies in the literature [43], [44] and was limited by physical proximity of participants and willingness of a specific target population. An additional limitation was that we only monitored lateral gastrocnemius activity. The other plantar flexor muscles, namely the soleus, may have exhibited different neuromuscular responses. In addition to this, it is possible that the tibialis anterior had decreased activation and if we had monitored that muscle, reduced co-contraction may have explained the increase in ankle power. The relatively short washout period in this study likely resulted in the conservative assessment of assistance-priming; the benefits of assistance-primed resistance training are likely greater than our results indicate.

Moving forward, future research should delve into the long-term effects of assistance-primed resistance gait training on functional outcomes and gait patterns, and compare the results to other power training protocols. Previous studies using similar audio-visual biofeedback modalities have shown consistent increases in muscle engagement within and across sessions [31]. Investigating the underlying mechanisms behind the observed improvements in ankle power and excursion is also warranted, perhaps evaluating how gait speed or specific impairment may correlate to change in muscle recruitment. Our findings here are likely applicable to individuals of all ages with similar or less impairment, including the elderly with sarcopenia [29]. These results are encouraging as they have the potential to improve the effectiveness of robot-resisted gait training in individuals with CP and other movement disorders. If the benefits seen in this study indeed translate to improved functional mobility, further optimizing the alternating delivery of robotic ankle assistance and resistance could be done to minimize the intervention time and maximize the positive long-term impacts.

The findings in this study hold promise for enhancing the effectiveness of wearable targeted resistance used in gait rehabilitation for individuals with neurological conditions. The observed increases in targeted ankle joint power and improved joint excursion underscore the potential of priming resistance training with powered assistance. Although the anticipated enhancements in step length and muscular engagement were not realized, this does not diminish the overall impact of the intervention. Conversely, these findings highlight the importance of continued research into the potential benefits and optimization of priming resistance training with assistance in gait rehabilitation for individuals with CP. We hope that this work will inform the development of more effective rehabilitation strategies and ultimately enhance the overall quality of life for individuals with walking disability.

CONFLICT OF INTEREST

Dr. Zachary Lerner is a co-founder with shareholder interest in a start-up company that is seeking to commercialize the sensorimotor biofeedback system used in this study. There are no other conflicts of interest to disclose.

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