Design and Validation of a Wearable Ankle Push-off Device in Cerebral Palsy: Is Spring Resistance as Effective as Motorized Resistance?

Emmanuella A. Tagoe, Karl Harshe, Collin D. Bowersock, and Zachary F. Lerner*

***Abstract*— *Objective:* Powered ankle exoskeletons with biofeedback systems have proven effective at improving ankle plantar flexor muscle recruitment and push-off power in individuals with cerebral palsy (CP). However, their clinical translation and feasibility for at-home training remain limited. This study sought to design an unpowered wearable ankle device with spring resistance combined with a gamified ankle power biofeedback system. Our primary goal was to validate the device's ability to increase plantar flexor muscle recruitment and push-off power relative to baseline, and ensure that these improvements were comparable to those achieved with motorized resistance. *Methods:* Seven ambulatory individuals with CP completed walking sessions with (1) a powered ankle exoskeleton with motorized resistance, (2) our novel ankle device with spring resistance, and (3) shoes only (baseline); Both devices utilized the same biofeedback system. *Results:* Relative to baseline, both the motorized and spring resistance increased peak (48%, p<0.05) and mean (43-45%, p<0.05) soleus activation and mean (37-39%, p<0.05) medial gastrocnemius activation. No differences in muscle recruitment between spring and motorized devices were observed. Walking with spring resistance increased average ankle push-off positive power by 22% (p = 0.003) compared to motorized resistance and by 23% (p = 0.013) compared to baseline. *Conclusion:* An ankle device providing targeted spring resistance with ankle power biofeedback can effectively improve push-off muscle recruitment and power in individuals with CP. *Significance:* This supports future research studying outcomes following training with spring-based ankle resistance devices that lower barriers for clinical translation.**

***Index Terms*— Exoskeleton, Gait, Motorized**

I. Introduction

PROPER ankle function is crucial for efficient human walking. Effective recruitment of the plantar flexor muscles generates the majority of the mechanical power needed for support, forward progression, and leg swing initiation, when walking [1], [2], [3]. Many individuals with neurological conditions like cerebral palsy (CP), the most prevalent childhood physical disability [4], often experience ankle muscle weakness [5] and reduced ankle power during the push-off phase of walking [6]. This results in impaired propulsion and forward progression that significantly limits their mobility, independence, and quality of life [7]. Therefore, interventions that target plantar flexor muscle recruitment and ankle power generation have the potential to improve the mobility and independence of individuals with CP, allowing for more activity and social participation that can improve physical and mental health [7], [8].

Gait rehabilitation interventions are a key aspect in the management of CP [9]. Over the past decade, functional resistance training with robotic devices has become recognized for its ability to enhance rehabilitation by providing targeted resistance training in a more consistent manner. This approach has shown to significantly improve ankle muscle recruitment and strength for individuals with CP [10], [11], [12]. Compared to conventional or manual therapy, robotic devices like powered exoskeletons provide an effective means of delivering the intensity, duration and progressive training needed to facilitate better mobility outcomes [7], [13], [14], [15], [16].

More recently, biofeedback systems have increasingly been studied for their use in conjunction with robotic devices for functional resistance training. These systems provide real-time feedback on patients' specific walking outcomes, making the training more engaging and effective in eliciting further improvements in ankle muscle recruitments and other mobility outcomes, especially for the pediatric impaired population may struggle to maintain engagement during training [13], [17], [18], [19], [20], [21]. Notably, biofeedback systems, when combined with a complementary intervention like resistance training with powered exoskeletons, have shown to more effective for improving mobility outcomes than biofeedback alone [17], [22], [23]. Thus, in theory, resistance training with powered robotic devices in combination with biofeedback systems represents the most ideal intervention for improving mobility outcomes as it addresses the relevant criteria for effective rehabilitation. However, these devices can be

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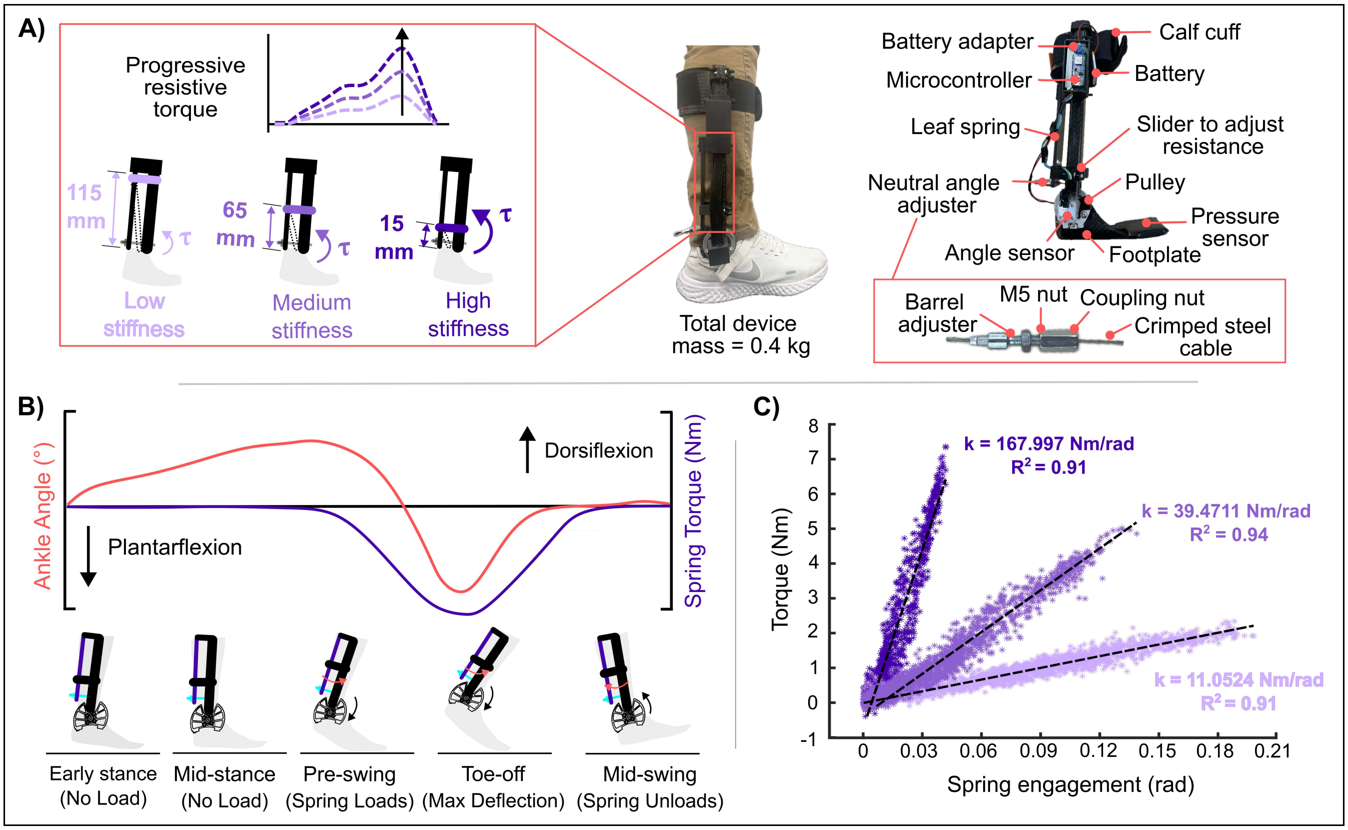

Fig.1. A) Our ankle device with spring resistance, its progressive resistance mechanism and its labelled parts. B) Schematic depiction of device operation (spring engagement) across the gait cycle. The spring (purple) was loaded by the cable wrapping around the pulley during regions of ankle plantarflexion to provide resistive torque. The spring remained unloaded during swing. C) Leaf Spring torque-angle profiles for the low, medium, and high spring lengths for each step during a 1-minute walk with the ankle device for one unimpaired individual.

expensive, bulky, and often require expert knowledge to operate, which can pose as barriers to clinical translation and practical at-home training [24].

It remains unknown whether any unpowered systems could be as effective as powered robotic devices in eliciting improved ankle push-off muscle recruitment and joint mechanics [10]. There is a clinical need for practical yet effective wearable rehabilitation systems for individuals with impaired mobility. Working to address this need, the overarching objective of this study was to develop an unpowered ankle device to elicit increased plantar flexor muscle recruitment and ankle power during push-off, using adjustable spring resistance integrated with a novel gamified ankle power biofeedback system. Our first goal was to determine if our novel passive resistance device could elicit increased plantar flexor muscle recruitment and push-off power relative to baseline (just shoes), and to also evaluate if these improvements would be comparable to those achieved with motorized resistance provided by powered exoskeletons. Next, we sought to determine the utility of adjustable spring resistance by evaluating individual responses to different spring stiffnesses. We hypothesized that (1) walking with spring-based ankle device would result in increased plantar flexor muscle recruitment and ankle push-off power relative to baseline, and (2) that these improvements would be similar when compared to walking with motorized resistance from a powered ankle exoskeleton.

II. METHODS AND PROCEDURES

We developed a novel wearable ankle rehabilitation device that provided adjustable plantarflexion resistance via a leaf spring with a moveable pivot point (Fig 1A) and an audio-visual biofeedback estimate of real-time ankle power (Fig 1C). To validate the effectiveness of our non-motorized spring resistance device, we compared it to a powered ankle exoskeleton with motorized resistance and an identical biofeedback system. We considered the powered ankle exoskeleton as the 'gold standard', as several studies have demonstrated that such devices can increase targeted muscle recruitment and produce clinically meaningful improvements in mobility outcomes after training [10], [21], [25].

A. Our Ankle Training Device with Spring Resistance

Our novel ankle device was comprised of interchangeable footplates and calf cuffs and included a carbon fiber leaf spring to deliver targeted plantarflexion resistance. Onboard pressure sensors (force sensitive resistor (FSR), Tekscan, FlexiForce A502) and angle sensors (Hall-effect sensor, AS5600, AMS OSRAM) were used to provide inputs to the onboard microcontroller to deliver real-time estimated ankle power

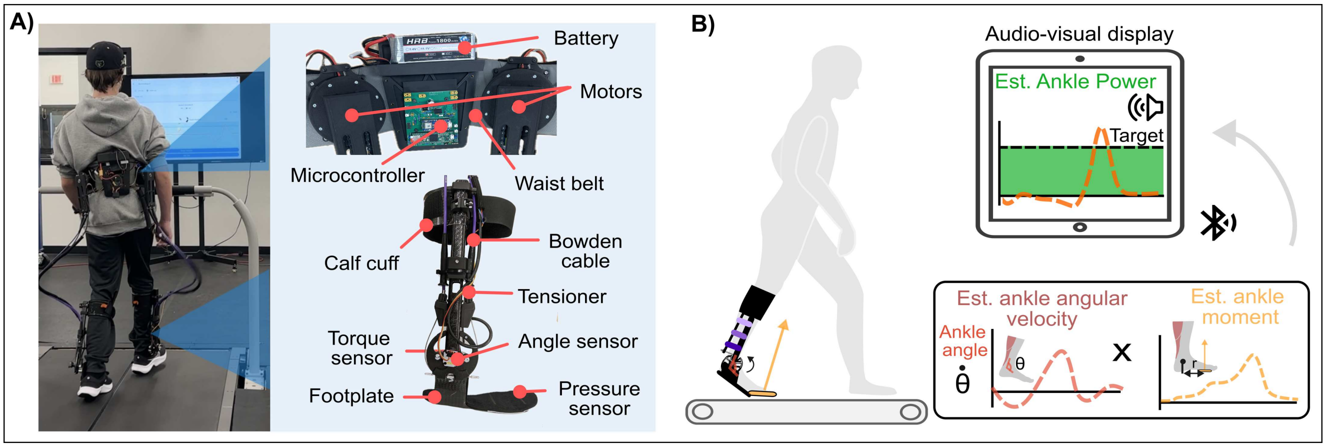

Fig. 2. A) A participant wearing the ankle exoskeleton with motorized resistance (left) and close up pictures of the device (right). B) The biofeedback system used by both devices during study. Audio-visual display showed a horizontal target line and real-time estimated ankle power of participant's more affected limb. Once the peak of the estimated ankle power exceeded the target line, a green background with confetti showed up on the screen with an audible "ding."

biofeedback during walking. The leaf spring was a 6.35 mm thick 0/90 ply carbon fiber bar (8194K111, McMaster-Carr), selected to achieve a resistive torque of up to 0.1 Nm/kg suitable for CP robotic resistance studies [26], [27]. The functional length of the spring was 115mm and the overall length on the ankle device was 151mm. A custom-made 3D printed slider with carbon fiber reinforcement (Onyx, Markforged) was used to adjust the pivot point of the spring, and thus the effective length of the spring to adjust the level of resistance (Fig. 1A & B). Spring engagement timing was customized for each participant via the neutral angle (the angle at which the spring begins to engage) adjuster to accommodate for various gait pathologies. The neutral angle adjuster consisted of a barrel adjuster and a steel coupling nut, which interfaced with the spring via a steel cable that terminated at an ankle pulley. The neutral angle was set for each participant such that the spring would engage at the start of plantarflexion.

To determine the estimated torque delivered by the leaf spring during walking at the different lengths used in this study, we instructed an unimpaired individual (male, 23 years old, mass = 80 kg and height = 1.73 m) to walk continuously at 0.75 m/s on the treadmill with each spring length for one minute each. The effective spring lengths were 15mm, 65mm, and 115mm for high, medium, and low, respectively. These corresponded with the shortest, mid-point, and longest functional lengths of the spring. We mounted a custom torque sensor (validation reported in [28]) on the medial side of the ankle pulley to directly record the resistive joint torque. The peak torque was averaged across all gait cycles (steps) for each spring configuration walk. The low, medium, and high spring lengths resulted in a mean peak torque of 0.024 Nm/kg, 0.048 Nm/kg, and 0.073 Nm/kg, respectively. To estimate the bending stiffness of the different effective lengths of the leaf spring, we fit a linear regression to the loading region of the leaf spring for the measured torque and ankle angle for each step [29]. The low, medium, and high spring lengths resulted in a bending stiffness of 11.05 Nm/rad ($R^2 = 0.91$), 39.47 Nm/rad ($R^2 = 0.94$) and 168 Nm/rad, respectively ($R^2 = 0.91$) (Fig 1C). Since the low and high spring lengths represented the total and least functional length of the leaf spring, the available range of

TABLE I
PARTICIPANTS CHARACTERISTICS

Participant	Age (Years)	Mass (kg)	Height (m)	Preferred speed (m/s)	GMFCS Level	Gait type
P1	40	72.0	1.80	0.60	II	Moderate ankle PF dysfunction and unilateral crouch
P2	17	58.3	1.70	0.60	II	Moderate ankle PF dysfunction and bilateral crouch
P3	14	58.0	1.71	0.85	I	Mild ankle PF dysfunction and bilateral crouch
P4	13	47.0	1.49	0.45	II	Moderate ankle PF dysfunction and asymmetric crouch gait*
P5	18	52.0	1.67	0.65	I	Mild ankle PF dysfunction and bilateral crouch
P6	15	53.0	1.62	0.75	II	Moderate ankle PF dysfunction and unilateral crouch
P7	13	56.2	1.70	0.85	I	Mild ankle PF dysfunction and bilateral crouch

GMFCS: Gross Motor Function Classification System. PF: Plantarflexion. *P3 has severe crouch gait on the right side and moderate crouch on the left side. All participants were males and more affected on their right side.

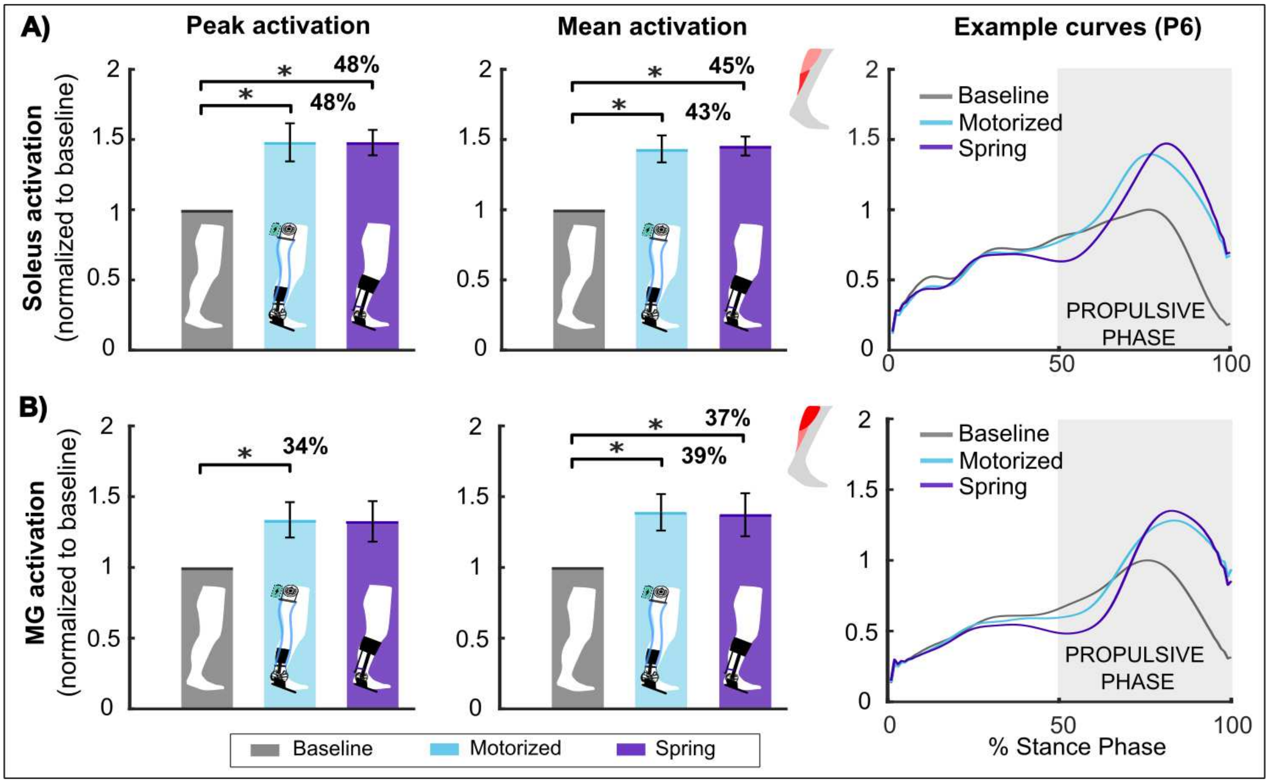

Fig. 3. Group level peak and mean propulsive phase activation and example curves (average of all gait cycles) for P6 normalized by baseline for baseline walking (gray), walking with ankle exoskeleton with motorized resistance (blue) and walking with the ankle device with high spring resistance (purple) for A) Soleus and B) Medial gastrocnemius muscles. Error bars represent standard error of the mean, brackets represent pairwise comparisons between respective conditions and * indicates statistical significance (p-value) less than 0.05.

stiffness was 11.05 – 168 Nm/rad.

B. Ankle Exoskeleton with Motorized Resistance

A battery-powered, untethered ankle exoskeleton device with control strategy previously reported in [28] was used to provide plantarflexion resistance and real-time biofeedback in this study (Fig. 2A). Briefly, the ankle exoskeleton consisted of a waist assembly that housed two DC motors (T-Motor, AK60v1.1), a custom printed circuit board, microcontrollers and a 1800mAh lithium-ion battery, and an ankle assembly that included footplates embedded with pressure sensors (or FSRs, Tekscan, FlexiForce A502), custom torque sensors, Hall-effect ankle sensors (AS5600, AMS OSRAM), pulley, and calf cuffs. It utilized the motors to deliver resistive torque to the ankle assembly via a chain-and-sprocket transmission that interfaced with a Bowden cable transmission which terminated at the ankle pulley. The control strategy of the exoskeleton provided resistive torque proportional to the real-time estimated biological ankle joint moment [10], [30]. The torque sensors located at each ankle recorded applied resistive torque and was used for closed-loop torque feedback control. FSRs located on the footplates were used to inform a finite state machine to determine the stance and swing phases of the gait cycle. The peak torque for motorized plantarflexion resistance was set to 0.08 Nm/kg so that it was similar to the torque generated in our passive ankle rehabilitation device in the high spring stiffness configuration.

C. Audio-visual Biofeedback System

The audio-visual biofeedback system utilized the FSR and angle sensors on the devices to provide real-time audiovisual biofeedback of estimated ankle power similar to previous work [20]. Estimated ankle power was calculated as a product of the angular velocity and estimated moment from the FSR [31] (Fig. 2B). An iOS application (Biomotum, Portland, US) received, processed, and streamed real-time ankle power biofeedback via Bluetooth, and projected on a TV in front of the participants (Supplementary Video). During operation, the TV displayed a horizontal target line and real-time estimated ankle power of the participant's more affected limb. The target line was set as a 10% increase of participants' peak estimated power while walking with no resistance and biofeedback. When the peak of the estimated ankle power exceeded the target line, a green background with confetti appeared on the screen with an audible "ding".

D. Participants

This study was approved by the Northern Arizona University's Institutional Review Board (#2137266). Prior to enrolling any participants, the protocol was registered with the Open Science Framework [32]. Seven individuals with CP between ages 13-40 years old participated in this study (Table I). Prior to participation, we obtained informed written consent from adult participants and the parents of participants below the age of 18; minor participants also provided verbal assent.

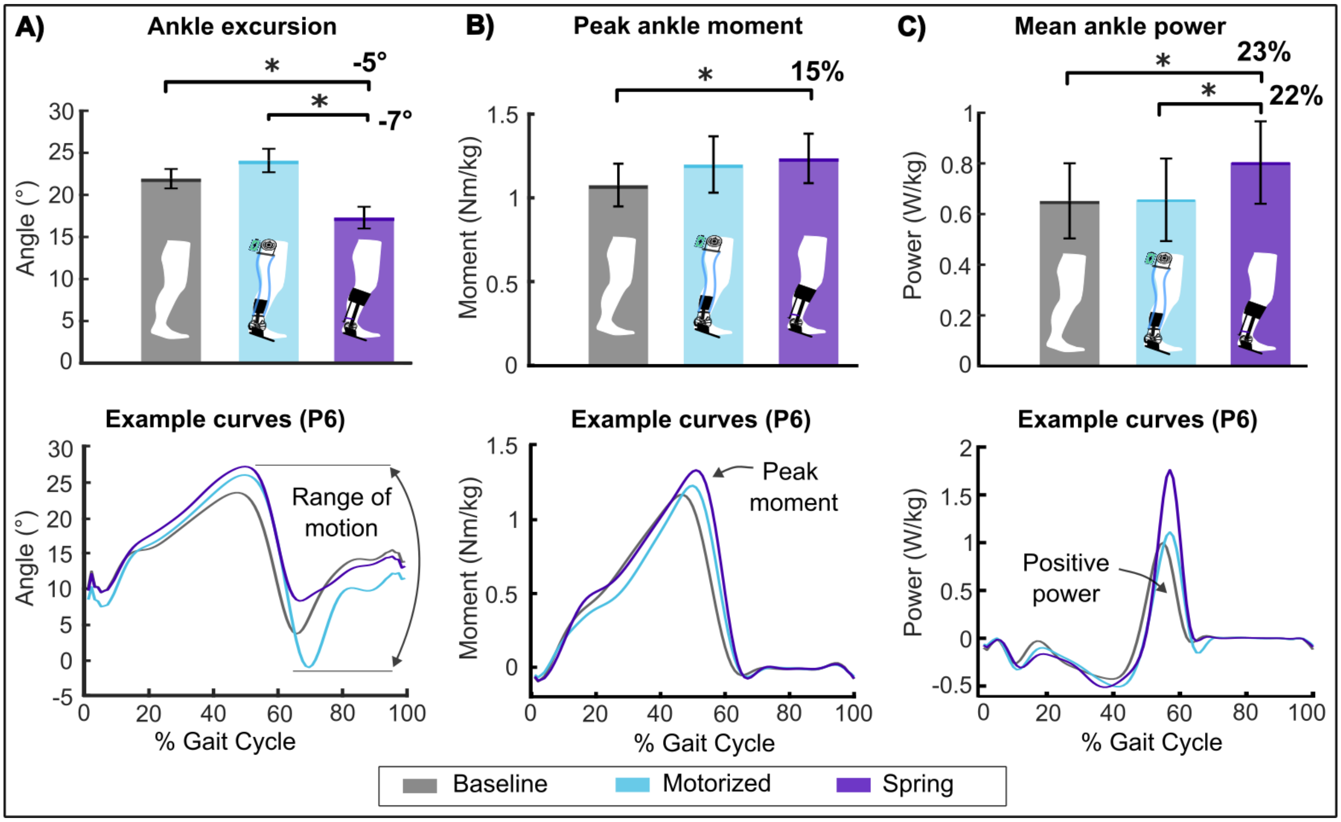

Fig. 4. A) Ankle excursion B) Peak ankle moment and C) Mean ankle positive power for baseline walking (gray), walking with motorized resistance (blue) and walking with high spring resistance (purple) for all participants and their example curves (average of all gait cycles) for one participant (P6) across all conditions. Error bars represent standard error of the mean, brackets represent pairwise comparisons between respective conditions and * indicates statistical significance (p-value) less than 0.05.

Inclusion criteria included a diagnosis of CP, Gross Motor Function Classification System (GMFCS) level I, II, or III, and the ability to walk on a treadmill continuously with or without support for at least six minutes. Exclusion criteria included orthopedic surgery within the past six months, any botulinum toxin injections within the past six months, and any other conditions that would prevent safe participation. A licensed physical therapist completed a physical evaluation with each participant to assess function and confirm eligibility.

E. Experimental Protocol

Participants first walked without any devices on the treadmill to identify their preferred walking speed. Participants then walked with real-time biofeedback at their preferred speed in the ankle device with spring resistance and the ankle exoskeleton with motorized resistance for four minutes each or until they hit target line ten consecutive times in the biofeedback system, whichever came later. This was done to allow the participants to acclimate to both devices and understand how the biofeedback system works. A twenty-minute seated resting period was given to each participant after acclimating to the devices.

Next, we placed reflective markers on the lower limbs to define the foot and shank segments. Wireless electromyography (EMG) sensors (Trigno, Delsys, Natick, MA) were placed on the soleus and medial gastrocnemius muscles of the more affected limb. Participants then walked under the following conditions while recording EMG at 1200 Hz and lower limb kinematic data at 120Hz using an eight-camera motion capture system (Vicon, Oxford, UK): (1) shoes only *(Baseline)* (2), ankle device with low spring resistance *(Low Stiffness)* (3), ankle device with medium spring resistance *(Medium Stiffness)* (4), ankle device with high spring resistance *(High Stiffness)* and (5) ankle exoskeleton with matched resistance for the high spring resistance condition *(Motorized)*. The *High Stiffness* condition when compared to the *Motorized* condition is referred to simply as *Spring* to compare the difference in devices between conditions. The spring device was worn unilaterally on the more affected limb. Participants walked for two minutes for the baseline condition. For the conditions with devices, participants walked for four minutes in total; the first two minutes with no biofeedback and the last two minutes with biofeedback. A trigger system synchronized with Vicon Nexus system was used to separate between the first and last two minutes. All participants started with the baseline condition, followed by either the motorized or a spring condition in a block-randomized order. Within the spring condition, participants always completed low, medium, and then high stiffness trials to replicate how resistive devices and training paradigms are implemented clinically in physical therapy [33],

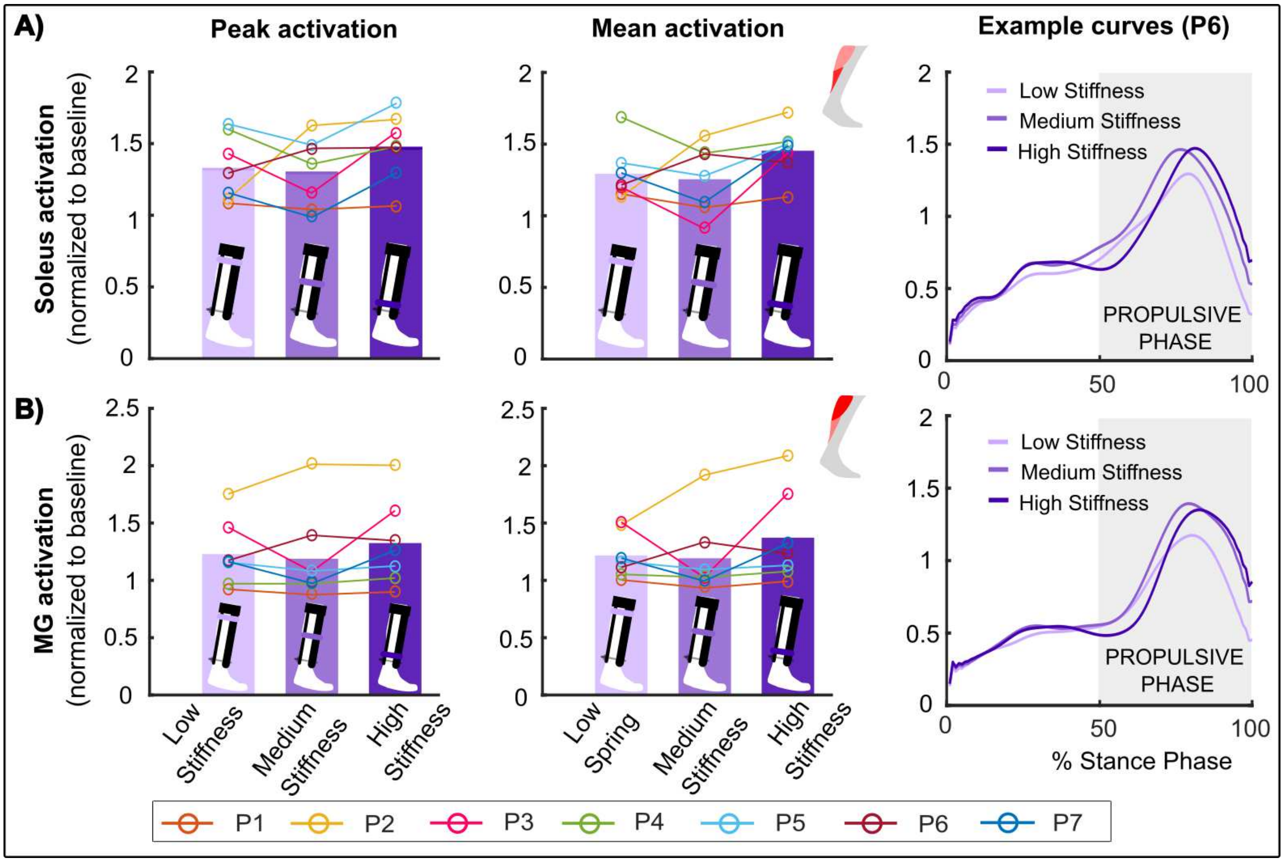

Fig. 5. Group level peak and mean propulsive phase activation and example curves (average of all gait cycles) for P6 normalized by baseline for walking with low stiffness (very light purple), medium stiffness (light purple) and high stiffness (deep purple) for A) Soleus and B) Medial gastrocnemius muscles. Colored dots with lines represent each participant.

[34]. The total duration of the protocol was approximately two hours, including the placement and removal of EMG sensors and reflective markers. This consisted of 40 to 45 minutes of walking time, with the remaining time in seated rest.

F. Data Analysis

The full two minutes for the baseline condition and the last two minutes for all other conditions were analyzed for the more affected leg. EMG data were bandpass filtered between 15 and 380Hz, rectified, and lowpass filtered with a 7 Hz cutoff to generate the linear envelope. We normalized the linear envelope EMG signal by the peak value from the baseline condition. We calculated the peak EMG and the integrated EMG (iEMG) during the push-off phase of the gait cycle (51-100% of the stance phase [35]). iEMG was calculated by summing the area of the EMG curve for the push-off phase and dividing it by push-off time.

We identified gait events using Vicon Nexus and used OpenSim 4.4 to derive the sagittal plane joint kinematics and kinetics. We first scaled a 3D generic musculoskeletal model for each participant, and then computed ankle angles and moments using the inverse kinematics and inverse dynamics analyses, respectively. Inertia properties from each device were incorporated into the respective OpenSim models by rigidly attaching the ankle assemblies to the tibia and the waist assembly to the pelvis for the motorized device. Ankle excursion was calculated as the absolute difference between the peak dorsiflexion and peak plantarflexion angle. Ankle power was calculated as the product of the ankle moment (without resistive torque from devices) and the respective ankle angular velocity. The average positive ankle push-off power was calculated by integrating the positive area of the joint power curve during push-off and dividing by push-off time.

G. Statistical Analysis

To validate our primary objective of evaluating the performance of our ankle device with spring resistance compared to the ankle exoskeleton with motorized resistance, we compared all measured outcomes between the Baseline, Motorized, and Spring conditions. To test our secondary objective of evaluating the performance of the progressive spring of our device, we compared the Low Stiffness, Medium Stiffness, and High Stiffness conditions for all measured outcomes. We conducted normality tests on the differences between pairs for all measured outcomes using the Shapiro-Wilks tests and Q-Q plots. For those that passed the normality test, we used one-way repeated measures analysis of variance (ANOVA) to analyze the differences between the given three conditions (p-value set at 0.05). A Mauchly's Test of Sphericity was also performed to confirm if data meets the sphericity assumption for a repeated measures ANOVA test; for data that did not pass the sphericity test, we used the Greenhouse-Geisser correction to determine significance. Subsequently, pairwise comparisons were made when significant main effects were

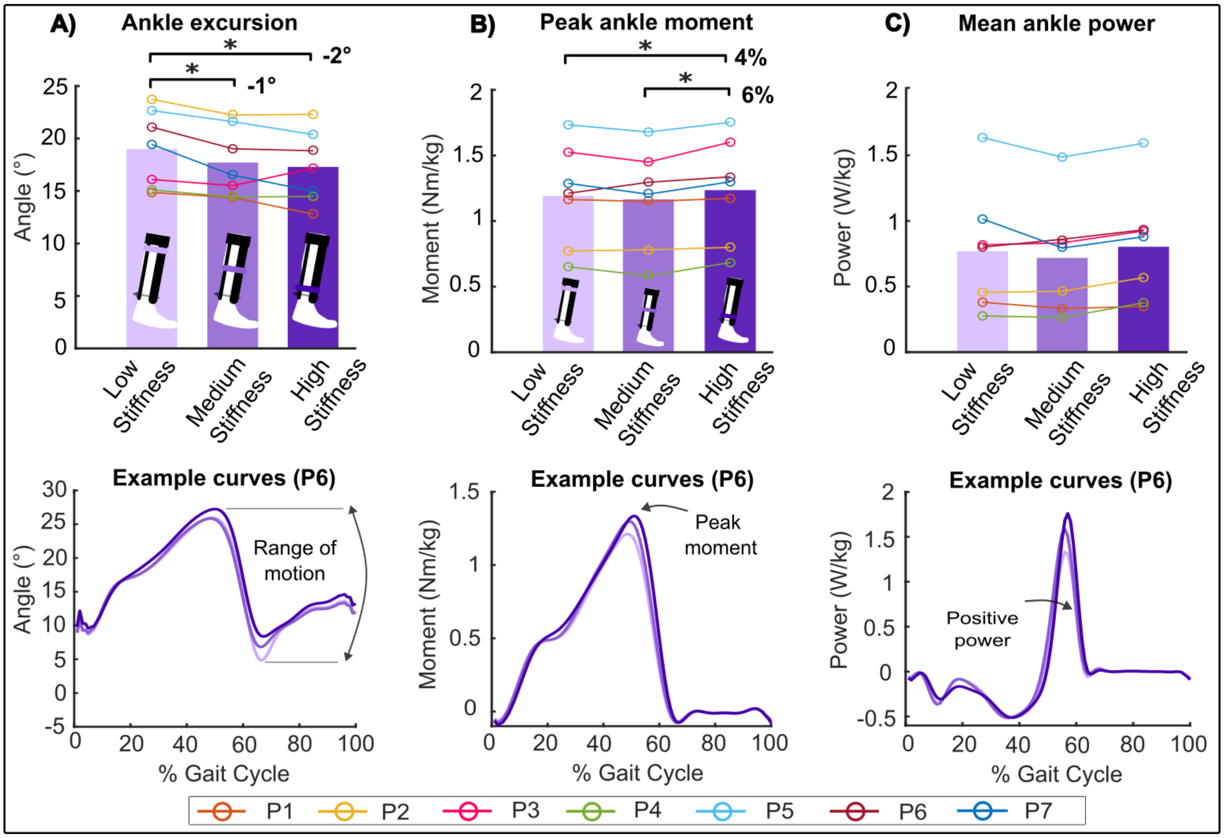

Fig. 6. A) Ankle excursion B) Peak ankle moment and C) Mean ankle positive power for walking with low stiffness (very light purple), medium stiffness (light purple) and high stiffness (deep purple) for all participants and example curves (average of all gait cycles) for one participant (P6) across all conditions. Colored dots with lines represent each participant, brackets represent pairwise comparisons between respective conditions and * indicates statistical significance (p-value) less than 0.05.

observed between conditions using paired two-tailed t-tests with Holm-Bonferroni correction for multiple comparisons (adjusted significance level set at 0.05). For those that did not pass the normality test, we used the Friedman test to analyze the differences between the three conditions (p-value set at 0.05). No pairwise comparisons were conducted using a Wilcoxon signed rank test as no significance was observed with the Friedman tests.

III. RESULTS

A. Effect of spring resistance vs motorized resistance

Compared to baseline, walking with spring resistance increased peak and mean soleus activation by 47.8% ± 9.1% and 45.4% ± 6.8% (mean ± standard error of the mean; $p = 0.002$, Effect Size (ES) = 2.0; $p < 0.001$, ES = 2.5, Fig. 3A) respectively. Participants' peak and mean soleus activation was similar during the spring resistance and motorized resistance walking conditions (Fig 3A). Mean medial gastrocnemius activation increased by 37.2% ± 15% while walking with spring resistance relative baseline ($p = 0.05$, ES = 0.9, Fig. 3B). Peak and mean activation of the medial gastrocnemius muscle were similar between walking with spring and motorized resistance (Fig 3B).

Participants walked with 6.8° ± 1.4° less ankle excursion with spring resistance compared to walking with motorized resistance ($p < 0.001$, ES = 2.6, Fig. 4A). Compared to baseline, participants walked with 4.6° ± 1.7° less ankle excursion with spring resistance ($p < 0.032$, ES = 1.1, Fig. 4A).

Walking with spring resistance resulted in a similar ankle moment as walking with motorized resistance (Fig. 4B). Compared to baseline, walking with spring resistance resulted in 15% more ankle moment (0.16 Nm/kg ± 0.03Nm/kg; $p = 0.002$, ES = 1.9, Fig. 4B) and 23% more average push-off positive power (0.15 W/kg ± 0.04Nm/kg; $p = 0.013$, ES = 1.3, Fig. 4C). Walking with spring resistance also increased average push-off positive power by 22% relative to walking with motorized resistance (0.15 W/kg ± 0.03W/kg; $p = 0.003$, ES = 1.8, Fig 4C).

B. Effect of progressive spring resistance

Peak and mean soleus and medial gastrocnemius activations were similar across walking with low, medium, and high stiffnesses on a group level (Fig 5).

Compared to walking with low stiffness, participants walked with 1.3° ± 0.3° and 1.7° ± 0.6° less ankle excursion with medium and high stiffness conditions respectively ($p = 0.01$, ES = 1.4; $p = 0.037$, ES = 1.0, Fig. 6A). Walking with high stiffness also resulted in 4% more total ankle moment relative to walking with low stiffness (0.04 Nm/kg ± 0.02Nm/kg; $p = 0.034$, ES = 1.0, Fig. 6B). Compared to walking with the medium stiffness, walking with high stiffness resulted in 6% larger ankle moment

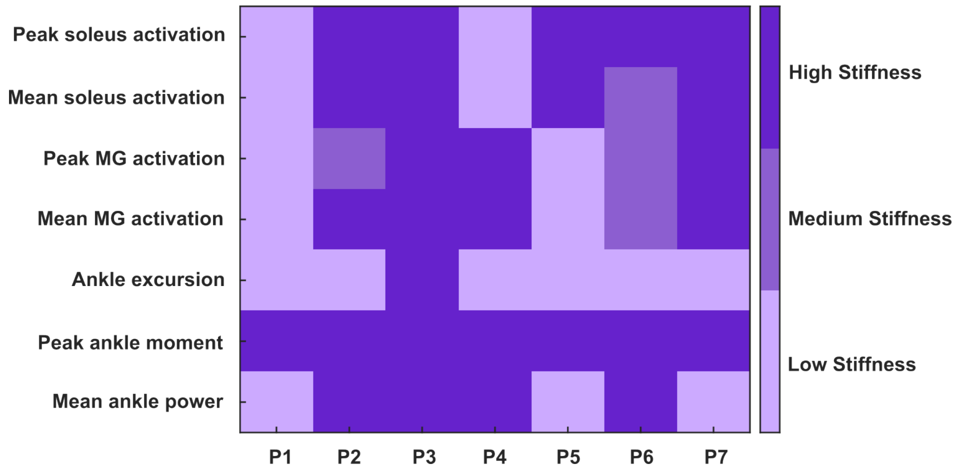

Fig. 7. Depiction of which spring condition elicited the most biomechanically desirable value (i.e., highest value), across all primary outcomes for each participant.

(0.07 Nm/kg ± 0.02Nm/kg; p = 0.008, ES = 1.5, Fig 6B). The average push-off positive power was similar across all three spring conditions (Fig. 6C).

Except for ankle moment where the high stiffness condition resulted in the most improvement for all participants relative to baseline, each participant responded to the low, medium and high stiffness conditions differently (Fig 7).

IV. DISCUSSION

The purpose of this study was to develop and validate a non-motorized wearable ankle device to elicit increased plantar flexor muscle recruitment and ankle power during push-off. Our design used an adjustable carbon fiber leaf spring with an ankle power biofeedback interface. We confirm our first hypothesis by finding that walking with the device resulted in increased plantar flexor muscle recruitment and push-off ankle power compared to baseline. We partially confirm our second hypothesis by finding that while spring and motorized resistance similarly increased muscle activity, only spring-based resistance increased push-off power relative to baseline. We observed variable outcomes in our investigation of individual responses to different spring stiffnesses, suggesting that stiffness adjustability may be beneficial for customizing the intervention.

We observed similar neuromuscular responses to the spring and motorized devices. Both devices resulted in increased plantar flexor muscle activity during the targeted push-off phase of walking. This is encouraging because prior research has found that training with motorized resistance can improve neuromuscular and clinical outcomes in people with CP [10], [21]. Interestingly, only the spring device resulted in increased positive ankle power compared to baseline, a relevant biomechanical outcome [3]. Upon close examination of the constituent components of joint power, we observed that the spring device increased ankle moment relative to baseline while the motorized device did not. Additionally, ankle angular velocity at the time of peak moment was similar across conditions (Supplementary Fig.1&2), suggesting that the differences in positive ankle power was due to ankle moment and not angular velocity. We plan to implement a pilot training study with the spring device to better understand the potential rehabilitation implications for these differences between spring and motorized resistance.

Walking with both motorized and spring resistance combined with ankle power biofeedback increased peak and mean soleus activation by up to 48% and mean medial gastrocnemius activation by up to 39% relative to baseline. These improvement levels are similar to the 47% increase in mean soleus activation seen in individuals with CP that walked with motorized resistance and plantar pressure biofeedback [21]. Additionally, spring resistance and ankle biofeedback also increased positive push-off power by 23%, which was lower than the 37.7% improvement in ankle power in a study using an immersive VR environment providing ankle power biofeedback for children with CP [36]. Future studies will investigate the isolated effects of spring resistance and ankle power biofeedback to better understand their individual contributions to these outcomes.

Ankle excursion varied between the spring and motorized devices. Despite this variation, both devices appeared to increase peak dorsiflexion during stance in some participants (P4 and P6, Supplementary Figure 3) compared to baseline, yet still resulted in improved plantar flexor muscle activity. Similar observations have been reported in previous studies [19], [37]. This indicates that ankle resistance may induce a more crouch posture in some individuals with CP, but does not seem to negatively affect muscle recruitment. Still, these findings emphasize the importance of monitoring compensatory strategies during training with resistive devices to ensure reinforcement of biomechanically-favorable gait mechanics.

Our assessment of individual participant responses to spring stiffness on muscle activity and ankle mechanics revealed that at least one participant responded most favorably to each of the three stiffness levels. This finding is understandable, as participants had varying levels of function, strength, and gait pathology, which likely explains their differing responses to the three stiffness conditions. Importantly, this finding indicates that customization of spring resistance is useful for eliciting favorable responses, validating a key feature of our device, the hand-operable simple spring stiffness adjustment slider. This slider would not only allow for personalized resistance but also enable progressive changes during a training intervention so that the resistance torque could increase alongside gains in muscle recruitment. Furthermore, if participant responses can be estimated in real-time as in Harshe et al. [38], or the most suitable resistance level for each participant determined based on their specific presentation, future rehabilitation efforts using this adjustable system could personalize stiffness levels during training. Such customization could elicit the best response for each individual, potentially facilitating faster and more effective recovery.

Notably, one participant, P1 was the only adult with CP in the study, while the others were teenagers. For this participant, P1, the low stiffness condition led to the highest improvement in most measurable outcomes relative to baseline; in contrast the high or medium stiffness condition resulted in the highest improvement for all other participants. Examining the soleus and medial gastrocnemius recruitment curves across all walking trials, we found that P1 was the only participant unable to considerably increase push-off muscle recruitment relative to baseline, regardless of device type or resistance magnitude, unlike the other participants (Supplementary Fig. 4 & 5). Future studies should investigate whether there are differences in effective resistance magnitudes between adults, adolescents, and children with CP.

There remains a need for gait training tools for individuals with CP of all ages and other neurological conditions like stroke. A primary motivation for this work was to foster the development of a new tool that could expand access to effective physical therapy interventions. A passive spring-based ankle gait rehabilitation system would likely be less expensive than a motorized system; additionally, a non-motorized device may be less intimidating and safer to use, which could further foster adoption [39]. While the use of such a system is likely to be first introduced in a clinical setting, it holds potential for use at home where daily training could prove transformative in the care of walking disability.

This study has several limitations that warrant future investigation. First, the number of participants, at n = 7, was small. While similar to other exploratory technology studies in CP [20], [40], we cannot generalize our results to the broader CP population. A second limitation was that our study included only male participants, so our findings cannot necessarily be generalized to females with CP. However, we are not aware of any prior exoskeleton resistance studies in CP that suggest the benefits would differ between males and females. Another limitation was that we focused on an acute comparison following only a small amount of acclimation. It is uncertain how additional acclimation would affect our findings. Also, we designed our study such that the high stiffness level was comparable to resistance levels used in CP robotic resistance studies [26], [27], making the low and medium stiffness configurations relatively low. The torque magnitude delivered by our resistive device in the stiffest configuration (0.1 Nm/kg) was much lower than the torque delivered when ankle devices provide supportive assistance (typically in the 0.35-0.5 Nm/kg range) [40], [41], [42], [43]. This is because the user's plantarflexor muscles must satisfy the biomechanical requirements of walking while also overcoming the added resistive constraint. The decision of using relatively lower stiffnesses was because we observed that relatively higher spring resistances tended to block plantarflexion, preventing effective training of push-off power. Still, future studies should explore higher resistance levels by increasing the thickness of the leaf spring, allowing for the investigation of the effects of resistance both above and below the levels typically in resistance studies. Finally, while the order of the spring and motorized device conditions was block randomized across participants, the order the three stiffnesses within the spring condition was not. However, if an ordering effect was present across the spring stiffness, it would not change the primary conclusions of this study. Ultimately, additional work is necessary to further evaluate this technology. A training study using the spring-based device with a larger number of participants, including females would be necessary to demonstrate clinical relevance.

V. CONCLUSION

In this study, a wearable ankle device with spring-based adjustable resistance was designed and validated to elicit increased plantar flexor muscle recruitment and ankle power during push-off in individuals with CP. This device offers a promising alternative to a powered ankle exoskeleton with motorized resistance, holding potential to facilitate clinical translation efforts and practical at-home training. Additionally, this study showed that stiffness adjustability may be beneficial for customizing the intervention to an individual's specific mobility impairment, as variable individual responses to different spring stiffnesses were observed. Future research will explore the long-term effects of functional training with the ankle device with spring resistance.

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