Robotic Ankle Exoskeleton and Limb Angle Biofeedback for Assisting Stroke Gait: A Feasibility Study

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***Abstract*—Post-stroke gait is slow, energetically costly, and unstable. Rehabilitation is necessary to encourage, retrain, and assist proper gait mechanics in stroke survivors. Evidence indicates robotic ankle exoskeletons can improve gait outcomes in stroke survivors, however challenges remain with proper lower limb positioning for optimal receipt of the assistance. Biofeedback can be used to improve positioning of the limb for receipt of robotic ankle exoskeleton assistance. In this study, four stroke survivors used bilateral powered robotic ankle exoskeletons (Dephy Exoboots) and an innovative, custom-designed vibrotactile-audio biofeedback interface targeting trailing limb angle to test the hypotheses that each intervention alone improves gait outcomes over baseline, and when combined they improve outcomes over either intervention alone. Compared to baseline, we found increases in average paretic propulsive impulse during the biofeedback-only and exoskeleton-plus-biofeedback conditions. Biofeedback alone induced the greatest increase on average self-selected walking speed, and the combination of exoskeleton assistance and biofeedback increased speed more compared to the robotic exoskeleton-only condition. Our preliminary results indicate that biofeedback in combination with a robotic exoskeleton produces greater synergistic benefits on gait performance than the use of an exoskeleton alone.**

***Index Terms*—Biofeedback, gait, prosthetics and exoskeletons, stroke, wearable robotics.**

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I. Introduction

SEVEN million Americans are living post-stroke with an astounding 80% presenting with locomotor impairments [1]. In both America and Europe, stroke is the leading cause of disability [2], [3], [4], [5], with its sequelae including hemiplegia or hemiparesis, muscle weakness, and balance impairments [1], [6]. Stroke survivors commonly compensate for weak paretic ankle muscles through compensatory strategies at the hip to maintain walking function [7]. Clinical gait rehabilitation as well as prescribed passive assistive devices such as orthoses are used to help compensate for abnormal gait; however, these assistive devices can sometimes hinder aspects of normal function, as in the case of ankle foot orthoses (AFOs). AFOs are prescribed to treat foot-drop, but while improving swing phase ground clearance they may decrease ankle plantarflexion and cause muscle deconditioning [7]. Rehabilitation strategies, including the use of active wearable devices, can be useful to encourage, retrain, and assist proper gait mechanics following a stroke.

Post-stroke gait is characterized by slow, metabolically expensive [8], and unstable locomotion [7] leading to a reduced quality of life [4] and decreased physical activity [8]. Due to hemiplegia, impaired muscle coordination and muscle weakness are common [4], [7] leading to limb asymmetries in joint biomechanics [8] and spatiotemporal parameters [9]. Self-selected walking speed (SSWS), a common indicator of function after a stroke, is negatively influenced by reduced propulsion on the paretic limb in stroke survivors [10], [11]. The propulsive force, measured as the anterior ground reaction force (AGRF), is the pushoff force exerted by the person on the ground when transitioning from stance to swing [11] and enables forward movement of the body, encouraging faster walking speeds [12], [13], [14]. Both SSWS and paretic propulsive impulse are important primary outcomes commonly targeted for rehabilitation following stroke [15], [16], [17]. The trailing limb angle (TLA), defined as the angle between the vertical axis and the overall orientation of the lower limb measured as the vector connecting the greater trochanter and fifth metatarsal [12], [18], is highly correlated to AGRF [12]. Increases in propulsion, TLA, and step length asymmetries, can contribute to faster SSWS, which is an important rehabilitation goal [8]. Stroke survivors can increase their push-off force bilaterally by increasing the TLA [10]. Thus, the association between TLA and AGRF may be utilized to improve paretic leg propulsive deficits and overall post-stroke gait function.

A. Robotic Exoskeletons

Rehabilitation strategies that aim to increase propulsive forces are important for improving post-stroke gait. Robotic ankle exoskeletons or exosuits can improve walking function by increasing both propulsive force and symmetry in late stance compensating for the ankle plantarflexion deficits in stroke survivors [4], [8], [19], [20]. Other studies have shown reduced metabolic cost of transport with use of these devices [4]. However, benefits of assistive devices for stroke survivors have been mixed with important implications on personalization of the control strategy, particularly the magnitude and timing of the assistance [21].

If the assistance is not tuned properly, robotic exoskeletons may impose challenges for functionally impaired users, limiting their benefit [22], [23]. While McCain et al. found an increase in walking speed and paretic joint ankle power with use of a powered ankle exoskeleton in stroke survivors, sub-optimal lower limb posture (TLA) was identified as a potential cause of the conversion of exoskeleton assistance to upward (and not forward) propulsion observed in the study [8]. The use of biofeedback has been suggested as an adjunct method to encourage proper placement of the limb for improved receipt of ankle torque assistance [8]. Therefore, utilization of strategies to improve the exoskeleton assistance with active gait retraining (biofeedback) could further maximize the benefit of the robotic exoskeleton assistance in post-stroke gait.

B. Biofeedback

Biofeedback is the use of an external stimulus to provide information about ongoing performance to the user [13], [24]. Biofeedback can allow for targeted clinical rehabilitation without specialized facilities or intensive clinician time commitments [24]. Critically, the provided biofeedback must be easily understood to maximize the user's motor learning and minimize frustration [25], [26]. Biofeedback can enhance awareness of a targeted goal during a specific phase of the gait cycle and encourage a user to correct the targeted performance goal in real-time [7]. Biofeedback has been shown to improve push-off force [13] and gait symmetry [27] in stroke survivors. Increased awareness of movement encourages self-correction leading to sustained motivation and improvement in gait performance [2], [18], [25] in turn aiding faster learning and better motor performance [2].

Audiovisual gait biofeedback has been used to improve AGRF and TLA in both non-disabled individuals and stroke survivors. Liu et al. demonstrated increased propulsion in non-disabled individuals with real-time audiovisual TLA biofeedback [14]. Genthe et al. showed improvements in AGRF after real-time audiovisual AGRF biofeedback training in stroke survivors [18]. However, audiovisual biofeedback lacks capability for use in environments without access to a screen and is therefore traditionally implemented during treadmill walking, thereby limiting its utility for training in overground and community environments.

To date, it is unknown how the combination of biofeedback and a robotic exoskeleton may affect the kinematic, kinetic, and spatiotemporal gait outcomes of stroke survivors. In this work, we leverage a novel, wearable, vibrotactile-audio biofeedback system and robotic ankle exoskeletons to determine if stroke survivors may benefit more when these modalities are used together.

We hypothesize that: (1) biofeedback and robotic exoskeleton assistance individually will improve SSWS and paretic propulsion compared to the baseline gait condition (no exo or biofeedback), and (2) when gait biofeedback and exoskeleton assistance are combined, SSWS and paretic propulsive impulse will improve in stroke survivors compared to the robotic exoskeleton-only, biofeedback-only, and baseline conditions. Our underlying rationale is that the biofeedback will improve lower limb positioning (TLA), therefore enhancing the ability of the limb to generate increased AGRF as the exoskeleton assists, thus leading to greater benefits in these gait outcomes.

II. Materials and Methods

A. TLA Estimation & Validation

TLA is typically measured using a motion capture system by calculating the angle between the laboratory's vertical axis and the vector connecting the greater trochanter and 5th metatarsal joints [12]. We developed a method to estimate TLA using wearable sensors for real-world use outside of the laboratory. We estimate TLA through two high grade IMUs (Microstrain by HBK, Williston, VT, Model: 3DM-GX5-AHRS) located on the thigh and shank of the participant (Fig. 1(a)). This TLA estimation calculates the angle between the environment's vertical axis and the vector connecting the greater trochanter and ankle joint in the sagittal plane. This vector is formed by the combination of two vectors that connect 1) the greater trochanter and the knee joint (realized by the thigh IMU), and 2) the knee joint and ankle (realized by the shank IMU) (Fig. 1(b)). Estimation of TLA using thigh and shank angles in the sagittal plane and the corresponding lower limb segment lengths is shown in (1) where AB is the length of the thigh segment, BC is the length of the shank segment, and θ_1 and θ_2 are the angles in the sagittal plane of the thigh and shank segments, respectively.

$$TLA = \arctan \times \left(\overline{AB}\sin\theta_1 + \overline{BC}\sin\theta_2\right) \ / \arctan\left(\overline{AB}\cos\theta_1 + \overline{BC}\cos\theta_2\right) \quad (1)$$

Prior to formal data collection, real-time TLA estimation was validated using one stroke survivor while walking at 0.7 m/s for 1 minute on the treadmill. Regression analysis was performed to examine the correlation between the TLA obtained from gold standard motion capture and the TLA estimated by two IMUs. The average correlation coefficient R in this validation trial was 0.992± 0.003 and the mean-normalized RMSE between the estimated and collected TLA was $5.36 \pm 1.72\%$ indicative of a strong correlation between the TLA estimated from the wearable biofeedback system and the TLA from the motion capture system.

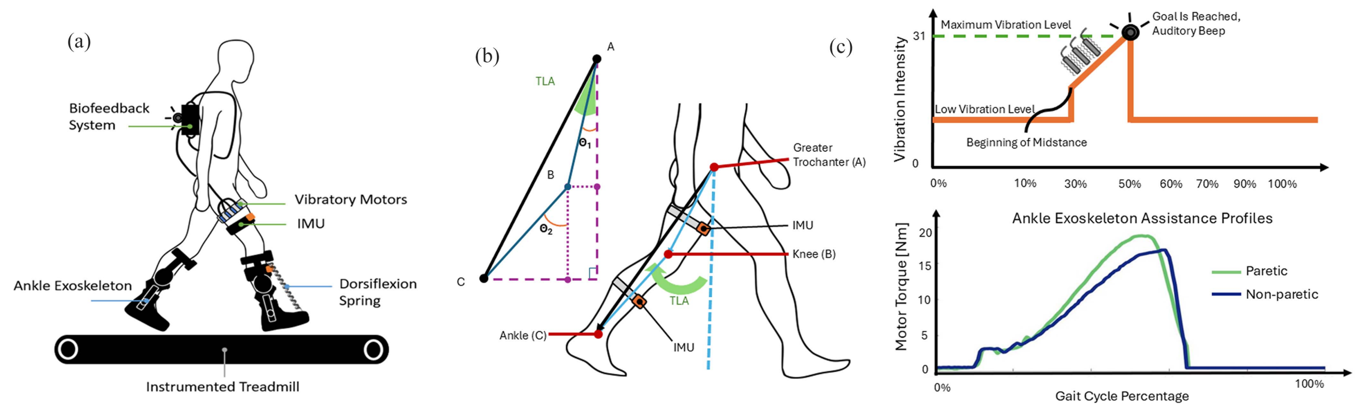

Fig. 1. (a). Experimental setup. (b). TLA estimation from two IMUs located on the thigh and shank. (c). Top: The assistive vibration scheme used during biofeedback showing that as the stance limb begins to trail, vibration linearly increases until the goal is reached. Bottom: Representative assistance profiles for the paretic and non-paretic limbs from the robotic ankle exoskeletons.

TABLE I
PARTICIPANT DEMOGRAPHICS

Subject	Gender	Paretic Side	Age [Years]	Weight [kg]	Height [cm]	Time post-stroke [months]	SSWS [m/s]	Community ambulation status [29]
P01	M	R	32	83.6	171	33	1.02	Community
P02	F	R	47	61.1	167	67	1.01	Community
P03	M	R	59	87.8	178	125	0.81	Community
P04	F	L	68	57.9	156	52	0.88	Community

B. TLA Biofeedback Coding Schemes & Location

A vibrotactile-audio biofeedback system is used to encourage the participant to achieve the targeted TLA. An assistive vibrotactile biofeedback scheme provides a vibration magnitude proportional to the TLA (Fig. 1(c)) at the selected location on the participant's body. The assistive vibration scheme linearly increases the vibration magnitude from a nominal level (corresponding to a TLA of zero degrees) to the maximum vibration level (corresponding to the TLA goal). Once the goal is reached, the speaker which is located on the biofeedback backpack plays an auditory sound indicating success, and the vibration stops until the limb is trailing behind the user on the next stride. If the goal is not reached, the vibrations continue as the leg swings forward and no auditory cue is played, indicating that the goal was not achieved. Location of the vibrotactile biofeedback was determined through psychophysiological testing [28] on each participant in which the vibration was tested on the participant's proximal thigh, distal thigh and lower back. The anatomical location with the greatest sensitivity to vibration was selected for use during the study. We also tested the participants frequency threshold for vibration perception of the feedback first during quiet standing and then during walking, and the minimum vibration frequency needed for walking was used throughout the experimental trials.

C. Study Participants

Four stroke survivors as detailed in Table I participated; community ambulation status for each participant is detailed as based upon [29].

The inclusion criteria for this study were: 1) at least 6 months post-stroke, 2) age 18–85 years, 3) able to walk without support with a preferred walking speed ≥ 0.4 m/s for at least 6 minutes, and 4) have adequate cognitive level with a Mini-Mental State Examination score$\geq$ 17. The exclusion criteria of this study were: 1) any medical issues that can significantly influence gait such as cardiopulmonary or respiratory disorders, 2) severe spasticity of the lower limb muscles (Modified Ashworth Scale (MAS) > 3), and 3) pre-existing neurological disorders other than stroke (e.g., Parkinson's disease or dementia). All participants provided written, informed consent under Georgia Institute of Technology Institutional Review Board protocol H18182.

D. Self-Paced Treadmill

The 'self-paced' treadmill utilized motion capture (Vicon Inc., Colorado, USA) and allowed for speed ranges between 80%–150% of the SSWS [30], [31]. The final 1 minute of treadmill walking in each condition was collected using the self-paced treadmill. Participants were instructed to find their "comfortable walking speed" when using the self-paced treadmill.

E. Robotic Ankle Exoskeleton and Tuning Procedure

The Dephy ExoBoot robotic ankle exoskeleton (Model 504, Dephy Inc., Maynard, MA, USA) was used for this experiment. The exoskeleton weighed a total of 4.7 kg, including two exoboots (1.4 kg for each boot) and one waist-mounted electronics pack. A custom four-point spline assistance profile controller as detailed in [32] was used to provide plantarflexion torque (up to 30 Nm) during late stance bilaterally. The exoskeleton controller and delivered assistance were independent of the biofeedback system. However, the use of the biofeedback enabled the limb to be positioned more favorably to receive the assistance from the robotic ankle exoskeleton.

After the baseline gait condition and before the Exo-only condition, the robotic exoskeleton was individually tuned and fitted to each participant. Because actuated dorsiflexion assistance is not available on the Dephy exoskeleton, a spring was necessary anteriorly to reduce foot-drop, and an estimation of the passive dorsiflexion torque was added to the plantarflexion assistance on the paretic limb to ensure proper assistance was provided. Adjustments were made to both magnitude and timing of assistance as well as the spring-based passive dorsiflexion assistance based on the presence or lack thereof of gait deviations and reported participant comfort. A representative assistance profile (P02) is shown in Fig. 1(c). The same assistance profile was used for the Exo-only and Exo+BF conditions. Practice on the treadmill was given before the Exo+BF condition to allow for re-acclimation to the paradigm.

F. Determination of Zero Position and Target TLA

The zero position of the IMUs was determined during quiet, erect standing.

A one-minute walking trial was used to determine the average baseline peak TLA on both legs of the participant. Goal target TLA values for biofeedback were determined for each individual through percentage increases from their baseline TLA. See (2) where n = 0, 0.2, 0.4, etc. Minimum/maximum peak TLA was determined by each limb's minimum/maximum measured TLA during the one minute of walking. Through both clinical and measured TLA assessment, the targeted side was determined. Providing biofeedback to the paretic limb was preferred to test the hypothesis that biofeedback can increase paretic propulsion. If the non-paretic TLA was consistently and visibly lower than the paretic TLA, the non-paretic limb was targeted for biofeedback as to not worsen the TLA asymmetry. As such, two participants were provided paretic TLA biofeedback (P02 and P04), and two participants were provided non-paretic TLA biofeedback (P01 and P03).

$$Goal\,TLA = TLA_{\min} + n\left(TLA_{\max} - TLA_{\min}\right),\; n \in [0, 2] \tag{2}$$

Goal TLAs were determined during the testing and tuning phase. Instructions to increase TLA were provided by the study clinician and tailored to each participant. No instructions were provided to the participants during the experimental trials on how to increase their TLA.

G. Data Analysis

The primary outcome measures of this experiment were paretic propulsive impulse and SSWS [15], [16], [17]. The propulsive impulse is the time integral of the anterior component of the anterior-posterior ground reaction force (AGRF) [20], which is typically reduced on the paretic side in stroke survivors [33]. The secondary outcome measures include the non-paretic propulsive impulse and step length symmetry.

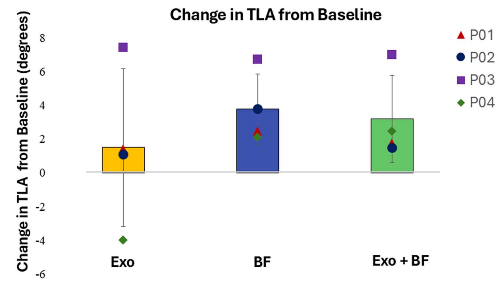

Fig. 2. Change in TLA from baseline.

The propulsive impulse was averaged across twenty gait cycles during the two-minute treadmill walking trial. The SSWS was calculated by averaging 30 seconds of the one-minute self-paced treadmill walking trial. Step length symmetry was calculated as the average paretic step length divided by the average non-paretic step length during overground walking.

A step length symmetry of 1 is indicative of perfect symmetry. We used the minimum detectable change (MDC) to assess the immediate changes in gait variables [34] under different conditions within an individual and thus present each participant's data separately in lieu of aggregate statistics. Given the heterogeneity often present within stroke survivors [35] and our low sample size, the individual analyses presented herein provides a more detailed understanding of the impacts of the experimental interventions. We defined 0.24% BW^*s and 0.47% BW^*s [34] as the MDC for the paretic and non-paretic propulsive impulses, therefore calculated as a 19.96% and 17.74% change from baseline based on our data, respectively. We adopted an MDC of 0.033 for step length ratio [34]. For assessing changes in SSWS, a minimal clinically important difference (MCID) of 0.1 m/s was used as suggested in [36] for stroke survivors.

III. Results

A. Trailing Limb Angle

The average changes from baseline of the TLA on the targeted limb were greater than the MDC threshold of 1° [34] across all conditions (Fig. 2). During the BF-only condition, all four participants were able to reach the set goal TLA and showed changes greater than the MDC when compared to baseline. In the Exo+BF condition, all participants showed greater change than the MDC compared to baseline, and all except for one participant (P02) were able to reach the set goal TLA.

B. Paretic and Non-Paretic Propulsive Impulse

AGRF for both paretic and non-paretic sides from a representative participant (P02) under all conditions are shown in Fig. 3(a) and (b). The delayed propulsion around 50% of gait cycle seen in baseline and BF conditions on the paretic limb was mitigated in Exo-only and Exo+BF conditions through a more consistent increase in propulsion through stance phase (Fig. 3(a)). For the paretic limb, we observed a propulsive impulse greater than the MDC for the BF and Exo+BF conditions compared to baseline (Fig. 3(c)). In conditions including

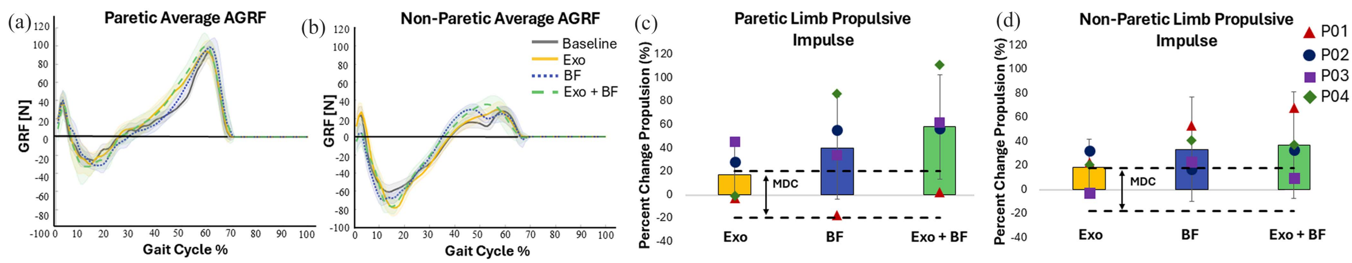

Fig. 3. (a) and (b). Representative paretic and non-paretic AGRF across conditions from a representative participant (P02). The shaded envelopes represent one standard deviation from the mean value. (c) and (d). Percent change of paretic (c) and non-paretic (d) propulsive impulse compared to baseline under all experimental. Error bars represent ± 1 std. The MDC with respect to baseline is shown as dashed lines.

the robotic exoskeleton, average paretic propulsive impulse increased by 34% and exceeded the MDC when biofeedback was provided (in the Exo+BF condition). For the non-paretic side, all conditions showed consistent propulsive force increases (∼50% gait cycle) before the peak propulsion was observed (Fig. 3(b)). Similar to the results shown for the paretic side, participants exhibited non-paretic propulsive impulse greater than the MDC under the BF-only and Exo+BF conditions when compared to baseline (Fig. 3(d)).

C. Self-Selected Walking Speed

Average percent changes in SSWS with respect to baseline from the self-paced treadmill trials are shown in Fig. 4(a). The average baseline SSWS across all participants was 1.03 ± 0.15 m/s. On average, participants exceeded the MCID during the BF-only condition compared to baseline. Three out of four participants (P01, P02, and P04) increased SSWS beyond the MCID when transitioning from the Exo to Exo+BF condition. Regression analysis was performed to examine the correlation between SSWS and the AGRF of both limbs with correlation coefficients of 0.3097 ($p = 0.0252$) and 0.1775 ($p = 0.1042$), respectively for the Non-Paretic and Paretic limbs (Fig. 4(b) and (c)) with greater magnitudes of Non-paretic AGRF and lower magnitude of paretic AGRF correlated with slower walking speeds.

D. Step Length Symmetry

Previous work demonstrates spatiotemporal gait symmetry for non-disabled individuals ranges from 0.9 to 1.1 [37]. The baseline step length symmetry ratio fell within the normal range for all participants except P02 (Fig. 5). While we observed changes beyond the MDC [34] for P01, P03 and P04, their step symmetry ratios remained within the normal range across conditions with the exception of the Exo-only condition for P04 in which the symmetry worsened beyond the MDC and outside of the normal range. P02 improved symmetry beyond the MDC for every condition compared to baseline with greatest improvement seen for the Exo+BF condition.

IV. Discussion

This feasibility study is the first to combine an autonomous robotic ankle exoskeleton with gait biofeedback using a novel, wearable system that provides real-time, vibrotactile, and auditory feedback during walking in stroke survivors. We examined the effects of robotic exoskeleton assistance and biofeedback on propulsive impulse, SSWS, and step length symmetry. We rationalized that intervention in the form of either biofeedback

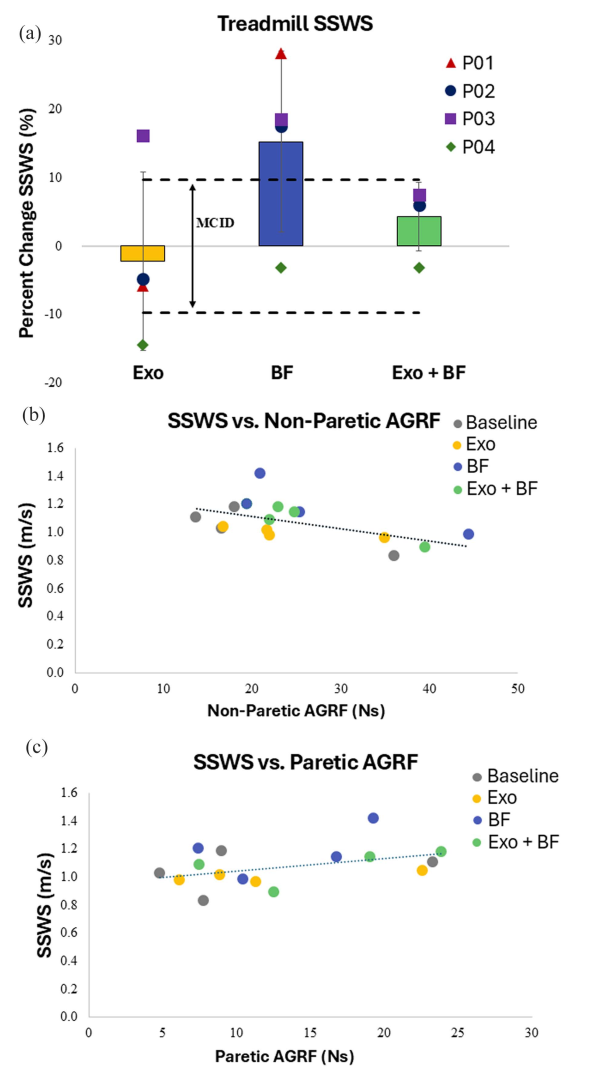

Fig. 4. (a) Percent change of SSWS compared to baseline across all experimental conditions. Error bars represent ± 1 std. The percent change of MCID from baseline is shown as dashed lines. (b) and (c). The relationship of SSWS vs. non-paretic and paretic AGRF across all conditions, respectively.

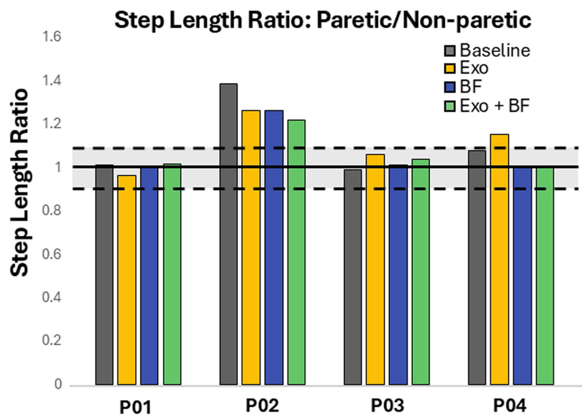

Fig. 5. Step length ratio across all conditions for all participants. Perfectly symmetric step lengths correspond to a step length ratio of one, shown in the plot as a black line. The normal range of step length ratio values for non-disabled individuals can be seen as a light grey box outlined by dashed black lines.

or exoskeleton assistance would lead to improved outcomes (Hypothesis 1), but the two combined would be better than either alone (Hypothesis 2).

We partially accept Hypothesis 1 as we saw improvements in bilateral propulsive impulse *and* SSWS beyond the MDC for the biofeedback-only condition compared to baseline. We saw improvements in these same metrics with the Exo-only condition compared to the baseline condition, but they were not beyond the MDC. We also partially accept Hypothesis 2 as when the exoskeleton and biofeedback were combined, we saw greater improvements in bilateral propulsive impulse compared to the Exo-only, biofeedback-only and baseline conditions which were beyond the MDC. However, SSWS did not improve beyond the MDC in the combined condition compared to baseline; while SSWS was faster in the combined condition than the Exo-only condition, it was slower than the biofeedback-only condition. While we observed changes beyond the MDC for step length ratio across conditions (independently and combined) for most participants, our study cohort was already largely symmetrical in their baseline walking. The changes that occurred secondary to the varying study conditions did not cause step length symmetry to move outside the typical range of symmetry for non-disabled individuals making the differences between conditions less clinically important for this metric. We did observe one participant with an asymmetric gait at baseline who improved step length symmetry beyond the MDC across all conditions with greatest improvement in the combined condition, and one participant who worsened beyond the MDC and outside of the typical range for the Exo-only condition.

Despite our small sample size in this feasibility study, we can still use the results herein to improve implementation of the proposed technology and thus outcomes for stroke survivors. The addition of biofeedback independently and in combination with the robotic ankle exoskeleton showed clear benefits for propulsive impulse and SSWS beyond the baseline condition. Promisingly, our study cohort was largely successful in achieving the targeted trailing limb angle provided by our wearable biofeedback system indicating this system is feasible for retraining gait patterns in stroke survivors. This is in line with previous work [18] indicating positive gait outcomes in stroke survivors using biofeedback. This study adds to the literature given the novelty of our wearable biofeedback system for use in clinical settings and other real-world environments without access to motion capture. Participants anecdotally reported feeling positive changes in their gait due to the biofeedback despite the short study period. In the future, this system could be used during community re-integration following stroke as an adjunct to physical therapy allowing for increased repetition earlier on in rehab which has shown significant benefit for improving long term outcomes [38].

While we did not see the improvements with the Exo-only condition as we had hypothesized, we did see meaningful improvements when it was combined with the biofeedback system as suggested in [39]. Particularly interesting is the improvement seen in the paretic limb propulsive impulse with the Exo+BF combined condition, which improved beyond the BF-only condition. This provides evidence that by increasing the TLA through biofeedback, a robotic ankle exoskeleton can usefully improve forward propulsion, which was our primary premise for the study. This is in line with previous results as reported in [4] suggesting that using an ankle exoskeleton is beneficial for retraining gait after a stroke. We also found that greater paretic limb contributions to the AGRF increased SSWS, while greater non-paretic limb contributions reduced SSWS, so the ability of an Exo+BF combined intervention to improve a patient's paretic limb AGRF may mitigate the need to compensate on the non-paretic limb for lost propulsion. This, in turn, may lead to improvements in SSWS. Future work should investigate the long-term benefits associated with improved bilateral symmetry in AGRF as well as patient-reported outcomes associated with these interventions to better assess clinical acceptability.

Variability is frequently common among clinical populations, and the smaller study cohort herein shows appreciable variation in age and time since stroke which likely influenced the results for each participant. One limitation was that the robotic control was hand-tuned for each participant; improvements to the tuning procedure may have yielded different results. Adaptive and explicit tuning of torque magnitude and timing based on the patient's current needs and walking pattern may have improved the results of the exoskeleton only condition as well as combined condition.

V. Conclusion

Our results demonstrate that the combination of biofeedback with robotic ankle exoskeleton assistance improves propulsive impulse and walking speed compared to the robotic exoskeleton-only condition. While the biofeedback-only condition tended to show greater improvements across outcomes, we observed mixed results across the robotic exoskeleton only condition with some participants improving beyond the MDC for some of the outcomes and not others. In summary, this feasibility study provides important insights to compel future work on the use of biofeedback in conjunction with advanced robotic exoskeletons to improve walking outcomes in stroke survivors.

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