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Changes in Center of Pressure after Robotic Exoskeleton Gait Training in Adults with Acquired Brain Injury

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***Abstract*— Acquired brain injury (ABI) resulting in hemiplegia, is one of the leading causes of gait and balance deficits in adults. Gait and balance deficits include reduced momentum for forward progression, reduced step length, increased spatial and temporal asymmetry, and decreased speed; resulting in reduced functional ambulation, activities of daily living, and quality of life. Wearable lower extremity robotic exoskeletons (REs) are becoming an effective method for gait neurorehabilitation in individuals with ABI. REs can provide high dose, consistent, goal-directed repetition of movements as well as balance & stability for individuals with ABI. The objective of this study is to understand the effect of RE gait training using center of pressure (COP) displacement, temporal & spatial parameters, and functional outcomes for individuals with ABI. The results from this investigation show improved anterior-posterior COP displacement & rate of progression, spatial symmetry, step length, walking speed, and decreased time during the gait cycle. These preliminary results suggest that high dose, repetitive gait training using robotic exoskeletons has the potential to induce recovery of function in adults diagnosed with ABI.**

I. Introduction

Hemiplegia due to acquired brain injury (ABI) is one of the leading causes of permanent disability in adults in the United States [1]. Hemiplegia causes stance phase deficits, resulting in difficulty controlling forward progression during gait [2]. Individuals with moderate or severe ABI with hemiplegia have motor impairments resulting in reduced functional ambulation [3]. Recovery of functional ambulation involves neurorehabilitation to induce adaptive plasticity through intensive, task specific, repetitive physical therapy. Conventional physical therapy is based on this theory, but often cannot provide enough consistent repetitive practice during rehabilitation, which results in variable recovery including residual gait deficits [4]. As a result of these residual motor deficits, patients diagnosed with ABI may have decreased functional ambulation [5], or develop compensation mechanisms such as hip hiking [6], toe walking [7], and prolonged weight transfer [3] in order to achieve ambulation.

Wearable lower extremity robotic exoskeletons (REs) offer additional rehabilitation modalities to restore gait and balance. They can provide high dose, consistent, goal-directed repetition of movements to induce adaptive plasticity, as well as a rigid support for balance & stability during ambulation for individuals with ABI [8][9]. REs are anthropomorphic electromechanical devices powered bilaterally at the knee and hip joints to provide assistance as needed to the user. This is essential for individuals with chronic ABI who require high dose, consistent therapy to induce cortical re-organization for functional recovery.

Center of pressure (COP) movement has been identified as a measure of neuromuscular control during gait [10]. It is defined as the centroid of all the external forces acting on the plantar surface of the foot [11]. COP displacement has been used to identify balance control, foot function, and treatment efficacy [11][12]. During the healthy stance phase, the COP moves anterior from heel to toe as body weight transitions over the support limb. This forward progression of the COP is frequently disrupted in post-ABI gait. Quantifying the changes in anterior/posterior (AP) COP during stance can provide precise information on the control of forward progression and gait symmetry post ABI, as well as on mechanistic changes after RE gait training [11].

The current investigation presents preliminary data on two individuals diagnosed with ABI who utilized an RE to provide high dose, consistent, repetitive gait training during the chronic phase of rehabilitation. The objective of the study was to evaluate the efficacy of RE training, using COP displacement, temporal & spatial parameters, and functional outcomes. This preliminary study provides initial evidence for the efficacy of using an RE as a therapeutic device for rehabilitation in adults with gait deficits with ABI.

II. Methods

A. Participants

Two individuals diagnosed with ABI and one reference healthy control (HC) participant were recruited for this pilot study. Demographics are presented in Table I. Inclusion criteria for the participants with ABI were that they: 1) be between the ages of 13 and 28; 2) have no orthopedic, neuromuscular, or severe neurological pathologies unrelated to their ABI that would interfere with their ability to ambulate; 3) be able to stand upright for 30 minutes with or without

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assistance; and 4) be able to physically fit into the RE. The inclusion criteria for the HC were that they: 1) be between the ages of 13 and 28; 2) should not have any neurological, neuromuscular, or orthopedic pathologies. All procedures performed in this investigation were approved by the Institutional Review Board at Kessler Foundation, and informed consent was obtained prior to study participation.

TABLE I. PARTICIPANTS' DEMOGRAPHICS

Condition	*Gender*	*Age at Consent*	*Years since Injury*	*Weight (kgs)*	*Height (m)*	*Affected Side*	*Number of RE Sessions*
BI01: Stroke	F	23	0.9	54.0	1.6	Left	12
BI02:TBI	F	27	5	62.6	1.63	Left	11
HC	M	26	n/a	77.1	1.57	n/a	0

B. Gait Training

Participants with brain injury received gait training with the FDA class 2 approved commercially available RE (Ekso GT™, Ekso Bionics Inc., Richmond, CA, USA) (Figure 1). Gait training was administered by a licensed physical therapist for up to 50 minutes per day, 2-3 days per week, for 4 weeks as outpatient rehabilitation. RE assistance was customized to participant impairment and progressively reduced by the physical therapist as the participant improved, or with the recovery of function. Participants continued their standard of care, if they had any ongoing therapy at the time of study enrollment. Gait training dosage information is presented in Table II for participants diagnosed with ABI. The HC did not undergo gait training.

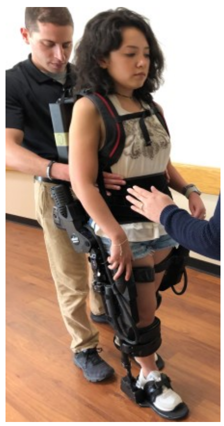

Figure1: Participant with ABI training with an RE

C. Data Collection

The participants with ABI completed two data collection sessions: 1) baseline (before RE gait training) and 2) follow-up (after 4 weeks of RE gait training). Participants with ABI did not utilize any other lower extremity assistive device or dorsiflexion wrap for assistance during data collection. The reference HC participated in one data collection session and data was collected while walking without the RE.

During each data collection session, participants performed about 6-7 trails of 10-12 meter walks at a self-selected speed on the Zeno™ walkway (ProtoKinetics, Havertown, PA, USA). All participants wore shoes for all walking assessments and were allowed to rest or take breaks at any time during testing to minimize the effects of fatigue.

D.Data Analysis

PKMAS (ProtoKinetics Havertown, PA, USA) and MATLAB (MathWorks, Natick, MA, USA) were used for data analysis, and the following characteristics were compared between the two conditions and between both sessions:

a) Center of Pressure (COP) displacement in the Anterior/ Posterior (A/P) Direction – The COP displacement during each gait cycle and an average of COP for all gait cycles were computed for both the legs without the RE at baseline and at follow-up. The average COP was normalized to 100% of the stance phase in each condition for comparison.

(i) *Linearity (Progression) of COP in the A/P direction*: During each session, a best fit line was computed for the average COP displacement with respect to the percentage of stance phase. This goodness of fit was determined to assess the error between the fitted line and the average COP displacement in the A/P direction for each subject in each session. R-square (R^2) was computed to quantify the linearity of COP displacement in the A/P direction. A higher R^2 value signifies increased progression or linearity of A/P COP.

(ii) *Rate and directionality of progression:* Slope indicates the rate and directionality of progression. Increased slope indicates an increased momentum during gait.

(iii) *Maximum COP displacement:* Maximum COP displacement in the A/P direction signifies the total progression from heel strike to toe-off. Maximum COP displacement is an indicator of progression symmetry, and is comparable bilaterally.

b) *Gait Speed* was computed from the stride length and time.

c) *Temporal Symmetry:* The swing and stance time of each foot during each gait cycle was computed, and the following ratios were used to compute temporal symmetry:

Temporal swing stance symmetry was computed for both affected and unaffected limbs.

$$Temporal\ swing\ stance\ symmetry = \frac{swing\ time}{Stance\ time} \quad \text{----- (1)}$$

$$Overall\ temporal\ symmetry = abs\left(\frac{affected\ swing\ stance\ symmetry}{unaffected\ swing\ stance\ symmetry}\right) \quad \text{----- (2)}$$

d) *Step Length* was calculated as the difference in the position along the x-direction of the contralateral and ipsilateral heels.

e) *Spatial Symmetry* ratio was calculated as follows:

$$\text{Spatial symmetry} = \left(\frac{unaffected\ step\ length}{affected\ step\ length}\right) \quad \text{----- (3)}$$

TABLE II. RE GAIT TRAINING DOSING INFORMATION

Session	*First Session*		*Last Session*		*All Sessions*	
	BI01	***BI02***	***BI01***	***BI02***	***BI01***	***BI02***
Total Number of Steps	916	552	1074	916	13600	8728
Total Distance (m)	290.8	182.3	341.1	279.2	4318.1	2725.6
Average Steps/Session	--	--	--	--	1133.3± 44.05	793.5± 51.5
Average Distance (m)	--	--	--	--	359.8± 13.99	227.1± 25.5
Total Walk Time (min)	29.7	21.5	31.5	36.5	424.1	323.3

III. RESULTS

A. Center of Pressure (COP)

The COP displacement was quantified using linearity, slope, and maximum COP displacement. These variables were all greater in the HC participant compared to individuals with ABI. In addition, the COP displacement was similar bilaterally for the HC.

At baseline, for both participants with ABI, linearity, rate, and maximum COP displacement of the affected side was lower than the unaffected side, as shown in Figure 2 & Table 3.

At follow-up, there was an increase in linearity and slope of COP displacement in the A/P direction for both participants (BI01 and BI02, Table 3) on the affected and unaffected sides. Overall, the A/P COP profile was more similar to the HC at follow-up compared to baseline.

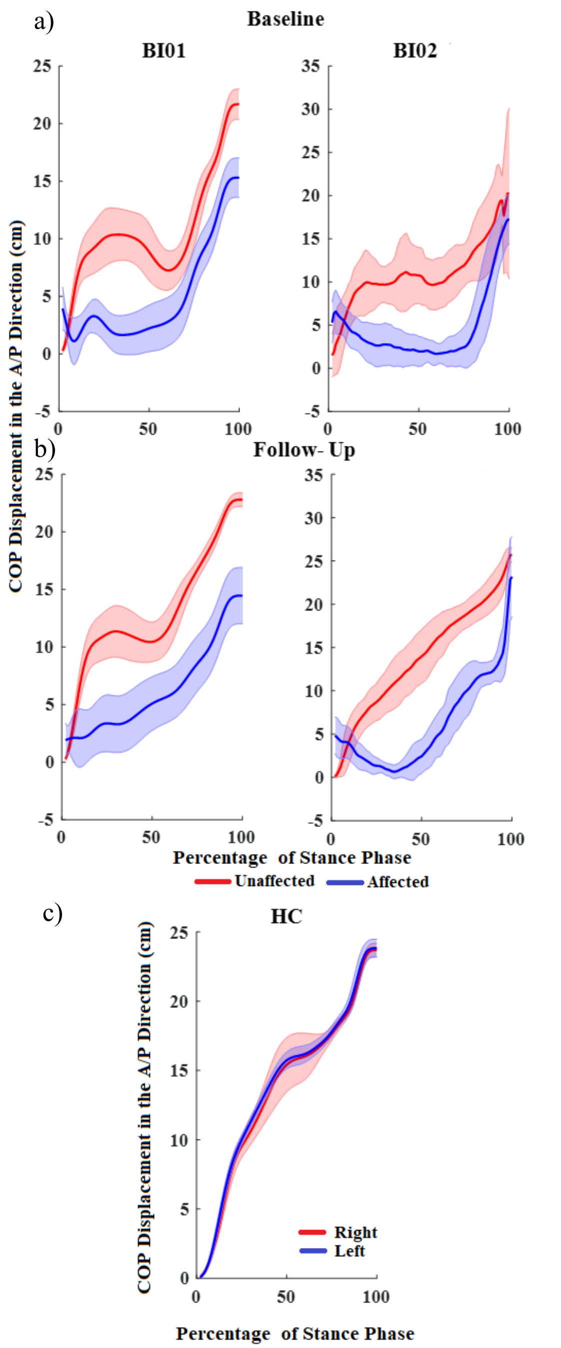

Figure 2: Mean ± std. deviation of the COP in the A/P direction of the affected and unaffected leg of two participants with ABI at a) baseline and b) follow-up without RE. c) Mean ± std. deviation of the COP in the A/P direction on the right and left leg of a reference HC.

B. Temporal and Spatial Characteristics

The temporal and spatial parameters are presented to understand the effect of RE gait training. Temporal and spatial symmetry closer to 1 signifies symmetrical gait. At baseline, both participants with ABI performed asymmetrical gait.

TABLE III. COP CHARACTERISTICS ON THE AFFECTED AND UNAFFECTED SIDE OF PARTICIPANTS WITH ABI AND HC

Metric	Progression of COP		Rate and Directionality		Max COP Displacement (cm)	
	Unaffected	*Affected*	*Unaffected*	*Affected*	*Unaffected*	*Affected*
BI01_BL	0.62	0.64	0.13	0.12	21.7±1.3	15.3±1.7
BI01_FU	0.86	0.89	0.17	0.13	22.8±0.6	14.5±2.4
BI02_BL	0.78	0.22	0.12	0.07	25.7±1.8	17.3±2.9
BI02_FU	0.98	0.67	0.22	0.15	25.7±0.8	23.2±4.6
	Right	*Left*	*Right*	*Left*	*Right*	*Left*
HC	0.94	0.93	0.22	0.21	23.7±0.5	23.9±0.7

In addition, the step length was low and the time required to complete the gait cycle was high, resulting in lower walking speeds compared to HC.

At follow-up, after 4 weeks of RE gait training, both participants (BI01 and BI02) improved their step length on the affected as well as the unaffected side (Table 4). The time

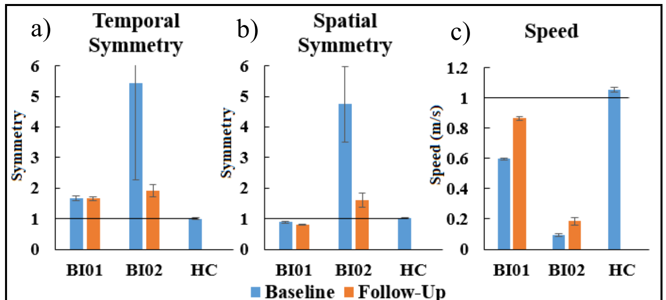

Figure 3: Mean ± std. error of a) temporal symmetry, b) spatial symmetry, and c) walking speed of two participants with brain injury at baseline and follow- up without RE, and a reference HC.

taken to complete the gait cycle also decreased at follow-up compared to baseline for both the participants (Table 4).

At follow-up, temporal symmetry improved in participant BI02 while no change was observed in participant BI01 (Figure 3). The spatial symmetry improved in both participants at follow-up. Both participants with ABI improved their mean walking speed after RE training, but the HC still walked faster than the individuals with ABI.

TABLE IV.TEMPORAL AND SPATIAL CHARACTERISTICS.

Metric	Step Length (cm)		Total Time
	Unaffected	**Affected**	
BI01_BL	39.8±0.9	45.1±0.5	1.4±0.01
BI01_FU	46.2±1.1	57.2±0.6	1.2±0.02
BI02_BL	41.9±1.8	12.6±1.9	6.0±0.5
BI02_FU	47.9±2.0	32.5±3.0	4.6±0.5
	Right	**Left**	
HC	65.9±0.6	65.1±0.8	1.2±0.02

IV. DISCUSSION

Individuals with moderate to severe ABI have gait deficits, and recovery may be slow during the chronic phase. During the chronic stages of acquired brain injury, high dose repetitive therapy is required to restore motor function. Table 1 shows the high dose RE gait therapy administered. It also shows that the participants with ABI increased the total distance, number of steps, and walk time during RE gait therapy, showing RE therapy progression over sessions. In this preliminary study, we evaluated the effect of RE gait training in adults with chronic ABI, using COP displacement & rate of progression in the A/P direction, temporal & spatial characteristics, and functional outcomes in order to quantify recovery.

COP movement has been identified as a measure of neuromuscular control during gait. The neural mechanisms of the ankle are reflected by the location of the COP. Increased activity in the plantar flexors results in the movement of the COP in the anterior direction. This suggests the tibia is rolling over the calcaneus (heel) and progressing towards toe-off. This mechanism preserves forward momentum for the next gait cycle. In the HC stance phase, the COP moves anterior from heel to toe (Figure 2). The A/P COP displacement in the HC also showed a linear increase with an increased rate of COP progression (Table 3) during the stance phase of the gait cycle. The maximum COP displacement was also similar bilaterally (Table 3). These results show that COP progression is consistent between limbs, leading to conservation of forward momentum during gait.

At baseline, in both participants with ABI during the stance phase, there was a nonlinear increase in displacement (Figure 2). In addition, linearity, rate of progression, and maximum COP displacement in the A/P direction on the affected side was lower than on the unaffected side. These variables were also lower than in the HC. This indicates that the participants were not progressing from heel-strike to toe-off, but were using compensatory mechanisms such as toe-walking or mid-heel strike etc. This also demonstrates the inefficient transfer of momentum for the next gait cycle [10].

After RE training, COP progression in the A/P direction improved. There was also an observed improvement in COP displacement during the stance phase (Figure 2). Changes in A/P COP displacement during the stance phase provides information on the control of forward progression. An increase in linearity and slope signifies improved speed & progression of COP, and therefore improved conservation and transfer of momentum during gait. In addition, COP progression was similar bilaterally at follow-up compared to baseline, demonstrating improved COP-displacement symmetry between limbs. Research has shown that improved COP progression leads to improved spatial and temporal symmetry.

After 4 weeks of RE gait training, the spatial symmetry and temporal symmetry improved. Studies have reported that temporal & spatial asymmetry is a significant predictor of hemiparetic ambulation performance, such as walking speed [13]. Improvements in step length as well as time duration were observed in conjunction with improved walking speed.

Improvement in the transfer of momentum during gait may have resulted in improved symmetry, step length and time to complete the gait cycle. These mechanistic changes may have also caused the improvement in the observed functional change of walking speed. Gait speed is a commonly used metric to assess the functional capacity of people with ABI to ambulate in the household or the community. Therefore, an increase in gait speed could potentially result in improved functional mobility and increased community ambulation & participation, leading to improved quality of life [14].

Future studies with a more controlled training environment (duration of training) and comparison to standard of care (control group) are required to further validate the efficacy of RE gait training.

V. Conclusion

Precise changes in the COP during gait can provide information about underlying control mechanisms of the neuromuscular system. The results from this preliminary study suggest that an improvement in COP progression, temporal & spatial characteristics, and functional outcomes can be achieved after 4 weeks of RE gait training in individuals with chronic ABI. Understanding the changes in underlying mechanistic control strategies and the corresponding functional ambulation recovery can help to guide RE rehabilitation strategies for gait therapy for individuals with ABI in the chronic stage of rehabilitation.

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