Evaluation of Gait Stability in Response to Exoskeleton Variations

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***Abstract*—Lower limb exoskeletons have been shown to reduce users' metabolic costs, but users need time to get acquainted with them. This adaptation period may be due to the instability these devices can cause. This study aimed to assess the effect of different variations in exoskeleton controllers on users' gait stability. For this assessment, the distance between the centre of mass (CoM) and centre of pressure (CoP) metric was used. The analysis is based on the previous work of Poggensee et al. The results indicated that different conditions affect the mean variability. However, no discernible recurring trend was observed in the data, possibly due to various assumptions made during the assessment.**

key words: exoskeleton, the centre of pressure (CoP), the centre of mass (CoM), gait-stability.

I. Introduction

Over the past decade, there has been much development in the realm of exoskeletons. The exoskeleton serves multiple purposes: aiding rehabilitation, assisting disabled individuals with movement, and enhancing healthy human performance while reducing metabolic costs [1]–[4]. Despite advancements in exoskeleton design, there is still much to understand about its benefits for humans. Various aspects need assessment regarding human response to exoskeletons [4], [5], particularly how individuals adapt to these devices. While some aspects of this adaptation are known [4], [5], there is still much room for discovery.

Individuals can regulate their muscle activity to control the device, potentially reaching a lower level of exertion over time. Research suggests that variable training might yield results [6]. Studies vary widely in estimating the time needed to achieve a steady-state minimum energy cost, but longer exposure seems to offer greater benefits [7]–[14].

Expanding upon the current knowledge gaps, the research by Poggensee et al. demonstrated that different types of control strategies and duration of exposure to exoskeleton influence the performance of both fixed and personalized exoskeletons [3]. This results in reduced metabolic costs. However, to get completely acquainted with the exoskeleton, participants needed longer exposure to the exoskeleton compared to other studies. This can be associated with gait stability, as exposure to the exoskeleton and using different control techniques might initially make the user unstable, and they may require some adjustment period.

This paper aims to assess how variations in the exoskeleton affect gait stability. Gait stability is best evaluated through the description of the motion of the body's centre of mass (CoM) and centre of pressure (CoP), which is calculated using ground reaction force (GRF) data. Many studies have used the relative distance between the CoM and CoP to examine gait stability [15], [16]. When the distance between the CoP and CoM is larger, the moment arm for the ground reaction forces increases, leading to greater momentum generation. This means that leaning too far, which causes excessive separation between the CoM and CoP, requires more active postural control and energy to counteract the increased moment to maintain balance [17]. However, these measures can be influenced by the subject's stature [18]. Another method for assessing gait stability using CoM and CoP metrics involves evaluating the inclination angle (IA) of the line connecting the CoM and CoP in both the sagittal and frontal planes, as well as the rate of change of IA (RCIA) [19], [20]. This method is not influenced by the variation in individual stature. However, it requires the vertical coordinate of the CoM, which is difficult to process from the GRF data. For this reason, the prior method was employed in this research for assessment, and the data were normalized to remove the impact of individual stature [17], [21].

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II. Methods

1) Subject and Data Collection: In this paper, data from six out of fifteen participants sourced from [3] were utilized for further analysis. Each group consists of three participants, two males and one female, categorized as shown in Table I

TABLE I
Characteristics of study participants

Group	Mass (kg)	Height (m)	Age (yrs)
Continued Optimization	73.6 ± 1.24	1.71 ± 0.06	23 ± 1.24
Static Training	71 ± 15.12	1.7 ± 0.08	24.3 ± 3.68
Reoptimization	78 ± 10.6	1.77 ± 0.05	26 ± 0.47

In the original experiment by Poggensee et al., all participants in each group underwent a six-day experiment. They began with the first day as a pretest, during which all participants walked without the exoskeleton, with the exoskeleton set to zero torque, and with the exoskeleton providing assistive torque, with two trials for each condition. For the remaining five non-consecutive days, each participant started with 72 minutes of adaptation followed by 6 minutes of validation, including trials from the pretest repeated twice in a double-reversal order. Participants were equipped with tethered bilateral ankle exoskeletons, and the control loop operated at 1000 Hz on a real-time computer (Speedgoat, Liebefeld, Switzerland). All walking experiments were conducted on an instrumented split-belt treadmill (Bertec, Columbus, OH, USA), which also recorded ground reaction forces (N) and moments (Nm) [3].

2) Data Analysis: Using ground reaction data, the Centre of Pressure (CoP) and Centre of Mass (CoM) coordinates were calculated in meters. Each of the two independent force-measuring belts measures 1.75 metres in length and 0.5 metres in width [22]. To calculate the combined belt's origin, it was set at the midpoint of the belt combined, as illustrated in Figure 1. Each belt's local origin was adjusted by 0.25 metres in the mediolateral direction and zero offset for the anteroposterior position.

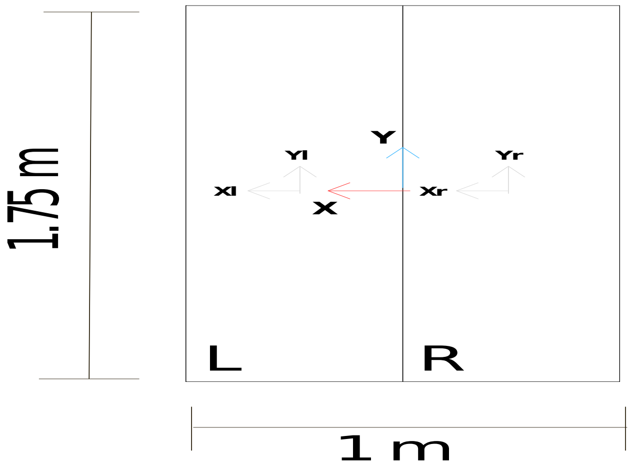

Fig. 1. Schematic view of split-belt treadmill belt

The mediolateral range of motion is described relative to the line of progression that bisects the medial/lateral range of motion during a gait cycle, and the anteroposterior position is parallel to the direction of the progression.

Centre of Pressure (CoP) was calculated using the moment equation i.e a vector cross-product of distance and force component as follows:

When the leg is in the swing phase then,

$$CoP_x = \frac{-M_y}{F_z} \pm X_0 \tag{1}$$

and

$$CoP_y = \frac{M_x}{F_z} \pm Y_0. \tag{2}$$

When both feet make contact with the ground, the weighted criteria were applied to process the GRF [23],

$$\mathrm{CoP}_i = \mathrm{CoP}_l \cdot \frac{F_{zl}}{F_{zl} + F_{zr}} + \mathrm{CoP}_r \cdot \frac{F_{zr}}{F_{zl} + F_{zr}}. \tag{3}$$

Where M_i (for $i = x, y$) is the moment, F_i is the reaction force, and x and y are the mediolateral and anteroposterior directions, respectively. X_0 and Y_0 are the offsets from the origin of the force belt and the subscript l and r represent the left and right directions.

The Center of mass (CoM) is calculated based on ground reaction force (GRF) data that was obtained from the force plate through simple dynamic equilibrium based on Newton's Second law.

$$CoM_i = \int_t \int \frac{F_i}{m} \cdot dt. \tag{4}$$

Where F_i (for $i = x, y$) is the ith component of the GRF, m is the total body mass (kg), and t is time (sec), and the initial positions were calculated from CoP data by taking the median value of the CoP when both feet are in contact with the ground.

After processing the CoP and CoM, the distance between CoM and CoP was calculated by the Euclidean distance method. Furthermore, these data were normalized by each participant's leg length [17] which was assumed to be $0.530H$ [24], where H is the total height of the participant. All data in this paper were analyzed using MATLAB R2023B (MathWorks Inc., Natick, MA).

3) Statistical Analysis: To evaluate the impact of the exoskeleton and its variations on gait stability, the total distance between the Center of Mass (CoM) and the Center of Pressure (CoP) across different conditions was compared. These conditions included: Normal Walking without the exoskeleton (NW), walking with the exoskeleton with zero torque (ZT), and walking with the exoskeleton with generic assistance (GA) on Day 1. In addition to these, walking with the exoskeleton with optimal assistance (OP) during the training period.

Since the goal of this study is to assess how subjects respond to exoskeleton variations, data from the training period only from Day 2 were analyzed. This choice was made because participants were first exposed to optimal assistance on Day 2. Additionally, to ensure observation of the effect of variation in the exoskeleton, only the first 120 seconds of each condition were analyzed. This approach aims to observe participants' responses to the utilization of exoskeletons and their variations.

A one-way ANOVA was used to analyze the data, assessing differences between various exoskeleton variations for the combined group. Additionally, a paired t-test was employed to compare two groups, with a significance level (p-value) of 0.05.

III. Results

Table II presents the mean and standard deviation for the displacement between the Center of Mass (CoM) and Center of Pressure (CoP) of subject groups under various conditions across two days, while Figure 2 illustrates the same data. For the different conditions, the Reoptimization (RO) group shows a significant difference in mean variability compared to the Continued Optimization (CO) and Static Training (ST) groups on both days ($p < 0.05$), as determined by a paired t-test.

Figure 3 illustrates the mean variability of displacement for various exoskeleton variations on Day 1, combining all groups, with the results analyzed using a one-way ANOVA, showing no significant differences ($p > 0.05$). In contrast, Figure 4 compares the mean variability of displacement on Day 2, including the optimal assistance condition, and the one-way ANOVA indicates significant differences ($p < 0.05$).

IV. Discussion

The purpose of this paper was to assess the effect of different exoskeleton variations on gait stability. Although the table II shows that different conditions affect displacement, there is no discernible recurring trend in the data. For Day 1 in the continued optimization (CO) group, the mean distance

TABLE II
THE MEAN AND VARIABILITY MEASURES OF THREE GROUPS ACROSS VARIOUS CONDITIONS ON BOTH DAY 1 AND DAY 2.

	CO ($n = 3$)	**ST** ($n = 3$)	**RO** ($n = 3$)
Day 1			
NW	0.166 $\pm$ 0.082	0.139 $\pm$ 0.069	0.289 $\pm$ 0.165
ZT	0.158 $\pm$ 0.083	0.152 $\pm$ 0.080	0.280 $\pm$ 0.146
GA	0.173 $\pm$ 0.120	0.153 $\pm$ 0.099	0.269 $\pm$ 0.133
Day 2			
NW	0.143 $\pm$ 0.071	0.166 $\pm$ 0.108	0.318 $\pm$ 0.162
ZT	0.156 $\pm$ 0.085	0.146 $\pm$ 0.071	0.273 $\pm$ 0.133
GA	0.165 $\pm$ 0.112	0.158 $\pm$ 0.095	0.252 $\pm$ 0.133
OP	0.157 $\pm$ 0.126	NA	0.271 $\pm$ 0.125

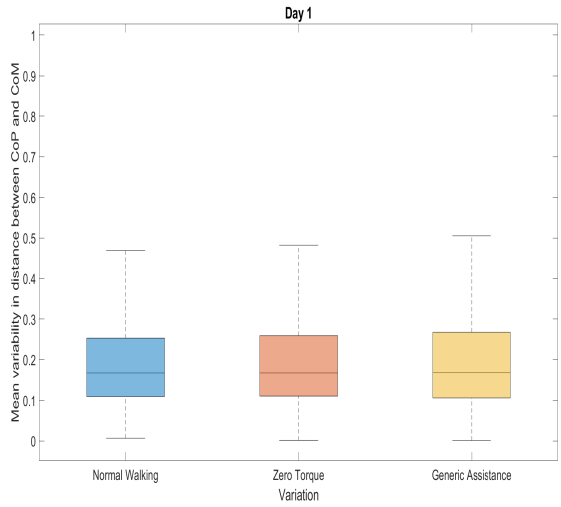

Fig. 3. Displacement variability attributed to the three conditions on Day 1.

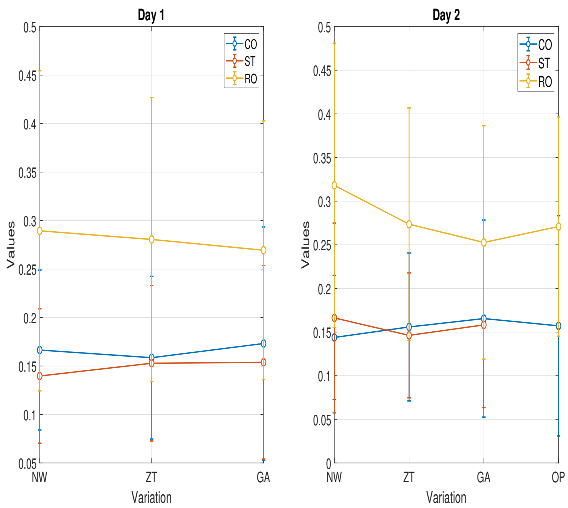

Fig. 2. Graphical representation of the data presented in Table II.

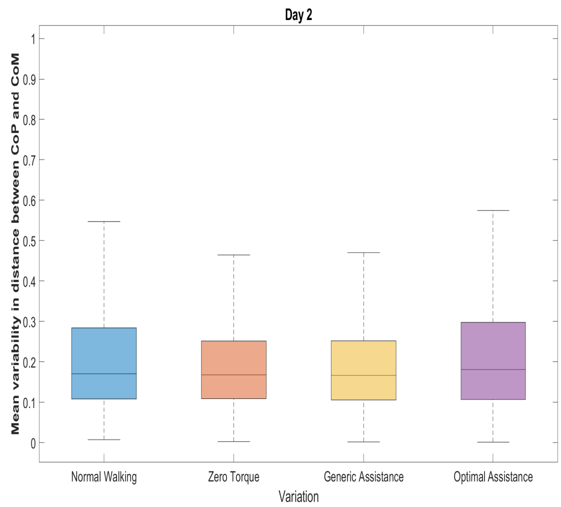

Fig. 4. Displacement variability attributed to the four conditions on Day 2.

between CoP and CoM decreases for the zero torque condition compared to normal walking. However, in the generic assistance condition, the mean distance increases, which was originally expected. In the static training (ST) group for Day 1, the mean distance increased for both the zero torque and generic assistance conditions, which was ideally expected. However, in the case of reoptimization (RO), the mean variation decreases after users walk with the exoskeleton, contradicting the results of the CO and ST groups. This discrepancy should not be the case since these tests were done on the first day of the experiment when no control optimizations were applied to the exoskeleton. Therefore, for all groups, the results should have followed the same trends, making these results unreliable for drawing any conclusions.

This inconsistency might be due to various assumptions made during data calculation. For example, the initial position for the Center of Mass (CoM) was determined using the median value of the Center of Pressure (CoP) when both feet were in contact. Additionally, instead of normalizing the data by accurate leg length, an approximation was used. Future studies should consider employing different evaluation techniques to obtain more plausible results. Assessing parameters such as varying displacement in the medial-lateral and anterior-posterior directions could help evaluate gait stability more effectively [17].

Moreover, this study only analyzed data from the first two days of the experiment, considering the initial 120 seconds of the test. Analyzing more extensive data over longer periods could yield more accurate results. Including a larger sample size and repeated measures across multiple days would provide more reliable insights into the effects of exoskeleton variations on gait stability.

V. CONCLUSION

This study attempted to investigate the effects of different exoskeleton variations on gait stability by analyzing the distance between the centre of mass (CoM) and the centre of pressure (CoP). The findings indicate that while different conditions do affect displacement, no consistent trend was observed. These inconsistencies suggest that the method for the assessment presented in this paper may not be reliable for drawing definitive conclusions about the impact of exoskeleton variations on gait stability.

The assessment for gait stability with exoskeletons requires more robust methodologies and comprehensive data. Future studies should incorporate additional parameters such as medial-lateral and anterior-posterior displacements, extend the duration of data collection, and include larger sample sizes. Addressing these factors might provide more reliable insights and contribute to the effective development and optimization of exoskeleton controllers for improved user stability. The code used in this paper is available at https://github.com/junglator/GaitStability_COP_COM.git.

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