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Lateral Body Center of Mass Sway During Self-Paced Versus Fixed Speed Treadmill Walking

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Lateral Body Center of Mass Sway During Self-Paced Versus Fixed Speed Treadmill Walking

by

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Abstract

Lateral Body Center of Mass Sway During Self-Paced Versus Fixed Speed Treadmill Walking

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Treadmill walking has been commonly used for gait training and is a safe and effective approach to assist older adults to improve balance and mobility outcomes. Recent development of self-paced treadmill controllers allow for variations in walking speed and offers the opportunity to better emulate overground walking while on a treadmill. However, how self-paced treadmill condition affects lateral balance stability during walking remains unclear. The primary purposes of this study were to (1) determine whether lateral body center of mass (COM) sway was different between self-paced and fixed speed treadmill conditions in older adults, and (2) identify potential sagittal and frontal plane gait characteristics that predict changes in body lateral sway across treadmill conditions. Seventeen healthy older adults walked at their preferred walking speeds on the fixed speed (FS) treadmill condition and the self-paced (SP) treadmill condition. Our results showed that older adults increased lateral COM sway

during the SP condition compared to the FS condition ($p < 0.01$). In addition, this increase in the lateral COM sway was predicted by changes in medial ground reaction force ($\beta = 0.57$), step width ($\beta = 0.39$), and anterior-posterior center of mass sway ($\beta = 0.3$). These results indicated that walking with adaptive belt speed treadmill affected frontal plane stepping biomechanics that were associated with lateral stability. Findings may provide important information for gait rehabilitation strategy designs that consider adopting self-paced treadmill training for older adults.

Table of Contents

List of Tables

List of Figures

1. Introduction

Older adults pose a higher risk for falling (Hegeman et al., 2007; Tinetti et al., 1988) and decreased mobility (Gunter et al., 2000; Shumway-Cook et al., 2005) compared to younger adults. 30% to 60% of community-dwelling older adults fall each year (Berg et al., 1997; Campbell et al., 1990; Granacher et al., 2012; Luukinen et al., 1994; Maki et al., 1994; Tinetti et al., 1988). Intrinsic factors, such as walking and balance disorders, have been identified as major causes of falls in older adults (Rubenstein & Josephson, 2002). Fall-related injuries reduce mobility and functionality in older adults (Granacher et al., 2012). Thus, fall prevention and rehabilitation are important for older adults.

Talbot and colleagues reported that 28% of falls occur during walking (Talbot et al., 2005). This is likely related to the continuous shift in body center of mass (COM) motion that is required during walking. To maintain balance stability, an individual has to regulate the body COM position relative to the base of support (Woollacott & Tang, 1997). While the dynamics of bipedal walking is passively stable in the sagittal plane, lateral motion stability requires active control (Donelan et al., 2004); yet older adults are particularly vulnerable to lateral instability (Hilliard et al., 2008). Because deterioration of mediolateral balance regulation is associated with an increased number of falls in older adults (Mille et al., 2013; Robinovitch et al., 2013), considering lateral balance control is important when developing gait rehabilitation approaches for older adults.

Treadmill walking has been commonly used for gait training and is a safe and effective approach to assist older adults with improving balance and mobility outcomes (Gerards et al., 2017). However, treadmill gait training typically imposes a constant speed that constrains movement (Terrier & Dériaz, 2011), and therefore does not resemble the speed variations commonly seen in overground walking. Thus, gait training gains from treadmill walking often do not completely transfer to overground walking. For example, following 6 months of treadmill gait training, individuals with chronic stroke showed improvements in gait symmetry that were only observed during treadmill walking, and not overground (Patterson et al., 2008). Recent development of self-paced treadmill controllers allow for variations in walking speed and can emulate overground walking while on a treadmill (Hedrick et al., 2021). During this self-paced condition, increases in preferred walking speeds were observed compared to a fixed-speed condition in older adults (Hedrick et al., 2021), indicating altered forward progression characteristics with the self-paced condition. However, how self-paced treadmill condition affects lateral balance stability during walking remains unclear.

Previous studies have shown that humans modulate step width and medial ground reaction force to regulate lateral stability (Bruijn & van Dieën, 2018; Vistamehr et al., 2016). Gait characteristics in the sagittal and the frontal plane can affect each other. For example, voluntarily modifying step length also altered the medial-lateral stability of the trunk during walking in healthy young adults (McAndrew Young & Dingwell, 2012). Such evidence indicates that the anterior-posterior (AP) gait characteristics altered by the self-paced treadmill could induce changes in lateral stability during walking. Identifying the frontal and sagittal plane biomechanical characteristics, that couple with changes in lateral stability across treadmill conditions, could generate important information to identify factors that contribute to lateral stability regulation during walking with different treadmill conditions.

Accordingly, the primary purposes of this study were to (1) determine whether lateral body center of mass (COM) sway, as characterized by the variance of body mediolateral center of mass acceleration ($\mathrm{COM}_{\mathrm{acc}}$), would be different between self-paced and fixed speed treadmill conditions in older adults despite the effects of differences in speed between conditions, and (2) identify potential sagittal and frontal plane gait characteristics that predict changes in lateral balance regulation across treadmill conditions. Because increased walking speed was observed during self-paced treadmill walking compared to fixed-speed walking (Hedrick et al., 2021; Parker et al., 2021), and mediolateral body COM displacement decreased with increased walking speed (Orendurff et al., 2004), we hypothesized that participants would show decreased COM sway during self-paced treadmill walking compared to a comfortable walking fixed-speed condition. In addition, we hypothesized that changes in medial ground reaction force, step width, and stride length across conditions would be primary predictors for changes in mediolateral COM sway.

2. Methods

2.1 Participants

Eighteen healthy older adults participated in this study. Due to equipment malfunctions for one participant, data for seventeen participants were analyzed (age 70.24 ± 5.25 yrs., body weight 73.68 ± 12.52 kg, body height 1.64 ± 0.09 m, 16 female). The inclusion criteria was age between 60 and 85 years. Exclusion criteria included a diagnosis of osteoporosis, and/or a diagnosis of a neurological disorders including but not limited to stroke, traumatic brain injury, Alzheimer's, and dementia. Informed consent was collected from all participants and the study was approved by the University of Nebraska Medical Center Institutional Review Board.

2.2 Protocol

Participants completed two treadmill walking conditions: fixed speed (FS) walking and self-paced (SP) walking, in a randomized order. For the FS walking condition, participants walked at their preferred walking speed for three minutes. To determine the participant's preferred walking speed, the treadmill was initially set to 0.5 m/s and increased by 0.1 m/s every ten seconds until the participant verbally indicated they were walking at a comfortable speed (Gault et al., 2013; Mannering et al., 2017). Participants were instructed to perform the preferred walking speed as closely to their natural walking speed as possible. The participant proceeded to walk at their comfortable speed for thirty seconds for acclimatization. Following the acclimatization, the treadmill was restarted for the three minute trial at the preferred speed.

For the SP treadmill walking condition, the treadmill initially started at 1 m/s (Zeni Jr. & Higginson, 2009) and belts' speed were adjusted in response to the impulse of the instantaneous anterior inertial force, step length and duration, position of the participant relative to the center of the treadmill, foot placement on the treadmill, and walking phase. Real-time calculations were made concurrently for both limbs concerning foot placement on the treadmill and walking phase in D-Flow (Motek Medical, Norwell, MA, USA) with a 300Hz sampling rate. Previous work has described the treadmill controller and the protocol in detail (Hedrick et al., 2021; Parker et al., 2021; Ray et al., 2018). A two-minute acclimation period was performed on the SP treadmill, and more time was given if needed (Lee & Hidler, 2008). Following the acclimation period, participants were instructed to walk at a comfortable pace "like walking in the park" for three minutes and were encouraged to not use the handrails for either treadmill condition unless needed for safety.

2.3 Data Recording

Kinematics and kinetics were collected using a 14-camera motion capture system (Vicon, Oxford, UK) with a 100 Hz capture rate and an instrumented split-belt treadmill (Bertec, Columbus OH, USA) with a 1000 Hz sampling rate, respectively. Motion capture markers were placed using a custom marker set with markers placed on the sternum, cervical spine 7, thoracic spine 8, and bilaterally at the feet, ankles, knees, greater trochanters, pelvis, and acromion process. Marker shells were placed bilaterally at the thigh and shank segments.

2.4 Data Analysis

Kinematic and kinetic data were processed using Nexus (VICON, Oxford, UK) and calculations for all variables were performed in Visual 3D software (C-Motion, Inc., Germantown, MD, USA) and MATLAB (Mathworks, Natick, MA, USA). Force and marker data were filtered at 6 Hz using a low pass Butterworth filter. Center of mass acceleration was filtered using a lowpass Fast Fourier Transform (freq. cutoff = 6 Hz) (Hatze, 1981).

Mediolateral and anterior-posterior body COM sway was defined as the standard deviation of whole body center of mass accelerations averaged across each gait cycle in each direction (Wang et al., 2019; Yu et al., 2008). Mean peak medial GRF was defined as the average of the maximum medial ground reaction force of each gait cycle. Cadence was defined as the number of steps per minute and was averaged between legs. Stride length was defined as the sum of averages of left and right step length at heel strike. Step width was defined as the distance between left and right heel markers at heel strike averaged across the trial. For all variables, changes across conditions were calculated by subtracting the values during the FS condition from that of the SP condition for each individual, and only data after the first 30 seconds of walking was used to insure no effect from the acclimation period of SP walking condition.

2.5 Statistical Analysis

One-way repeated measures ANOVA was used to determine the differences in the variance of COM lateral sway, as well as changes in step width, medial GRF, walking speed, cadence, stride length, and variance of AP COM sway, between the SP and FS conditions. Also, one-way repeated measures ANOVA was run on changes in the variance of COM lateral sway, step width, medial GRF, cadence, stride length, and variance of AP COM sway, once normalized for walking speed, to identify if changes in these variables are related to the previously identified change in speed between conditions. Stepwise linear regression analysis was used to identify predictors for changes in COM lateral sway between conditions. Potential predictors include changes in step width, medial GRF, walking speed, cadence, stride length, and AP COM sway across conditions (Alamoudi & Alamoudi, 2020; Arvin et al., 2016; Bakshi et al., 2014; Bruijn & van Dieën, 2018; Hak et al., 2013; McAndrew Young & Dingwell, 2012). Finally, Pearson's correlation coefficient was used to determine the relationships between the selected predictors and changes in COM lateral sway across treadmill conditions. The significance level was set at an alpha of 0.05 with statistical analyses performed in IBM SPSS Statistics (28.0.0, IBM Corp.).

3. Results

Compared to the FS condition, COM lateral sway increased by 11.38 ± 17.19% during the SP condition (FS: 0.554 ± 0.11 m/s^2; SP: 0.614 ± 0.14 m/s^2; p=0.01, Fig. 1).

On average, peak medial GRF increased 14.59% (FS: 0.076 ± 0.01 N; SP: 0.086 ± 0.02 N; p>0.05), step width increased 11.18% (FS: 0.116 ± 0.03 m; SP: 0.127 ± 0.04 m; p> 0.05), speed increased 22.53% (FS: 0.971 ± 0.2 m/s; SP: 1.17 ± 0.29 m/s; p<0.01), mean stride length increased 10.55% (FS: 1.01 ± 0.17 m; SP: 1.11 ± 0.21 m; p<0.05), AP COM sway increased 22.1% (FS: 0.653 ± 0.14 m/s^2; SP: 0.78 ± 0.23 m/s^2; p<0.05), and mean cadence decreased 3.94% (FS: 33.031 ± 3.86 steps/min; SP: 31.654 ± 4.64 steps/min; p> 0.05) from the FS to the SP condition. Interestingly, when these variables are normalized for speed, only stride length (p<0.01) and cadence (p<0.05) show differences between conditions. Stepwise linear regression model revealed that the changes in peak medial GRF (β=0.569, Fig. 2A), step width (β=0.391, Fig. 2B), and AP COM sway (β=0.3, Fig. 2C) were the primary predictors for changes in COM lateral sway (Table 1), while speed, stride length, and cadence were removed from the model (Table 2). Adjusted R-square shows that these primary predictors explained 87.2% of the variance in changes in lateral COM sway.

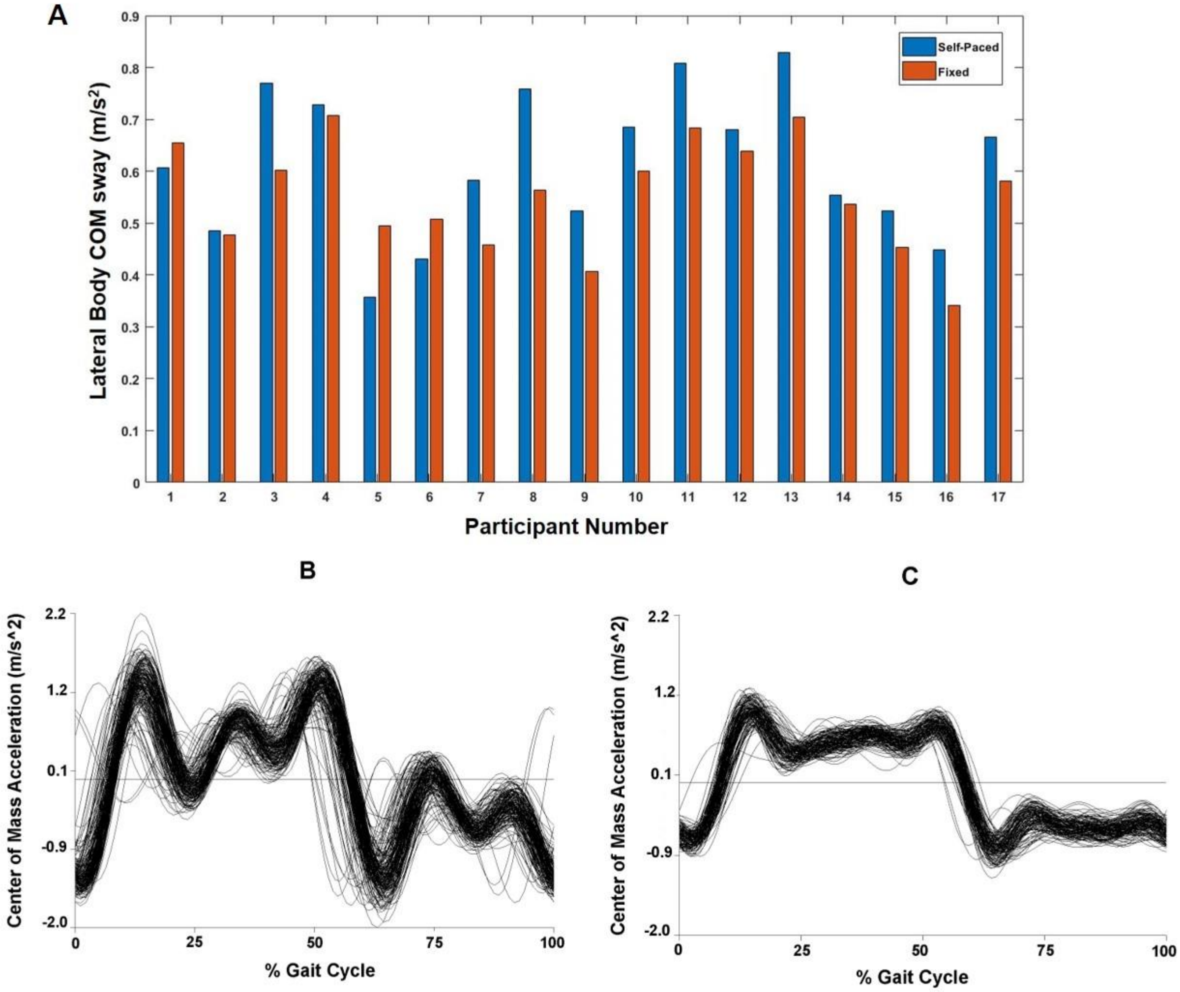

Figure 1. **(A)** Body center of mass (COM) lateral sway during Fixed speed and Self-paced conditions across all participants ($p<0.01$). **(B)** Body center of mass position from a representative participant (subject #3) during self-paced and **(C)** fixed speed condition. Red markers represent the instant of Left Heel Strike.

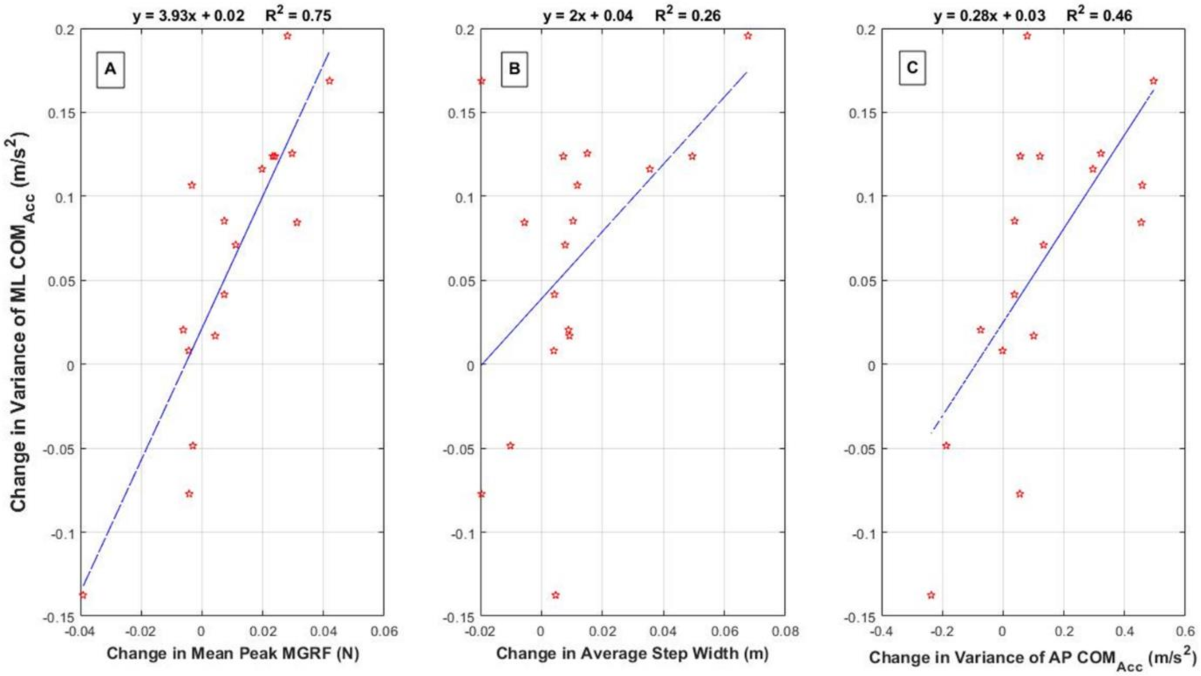

Figure 2. (A) Relationship between changes in body center of mass (COM) lateral sway and changes in the mean peak medial ground reaction force (MGRF) ($p<0.01$). **(B)** Relationship between changes in COM lateral sway and changes in mean step width ($p<0.05$). **(C)** Relationship between changes in COM lateral sway and the changes in COM anterior-posterior (AP) sway ($p<0.01$).

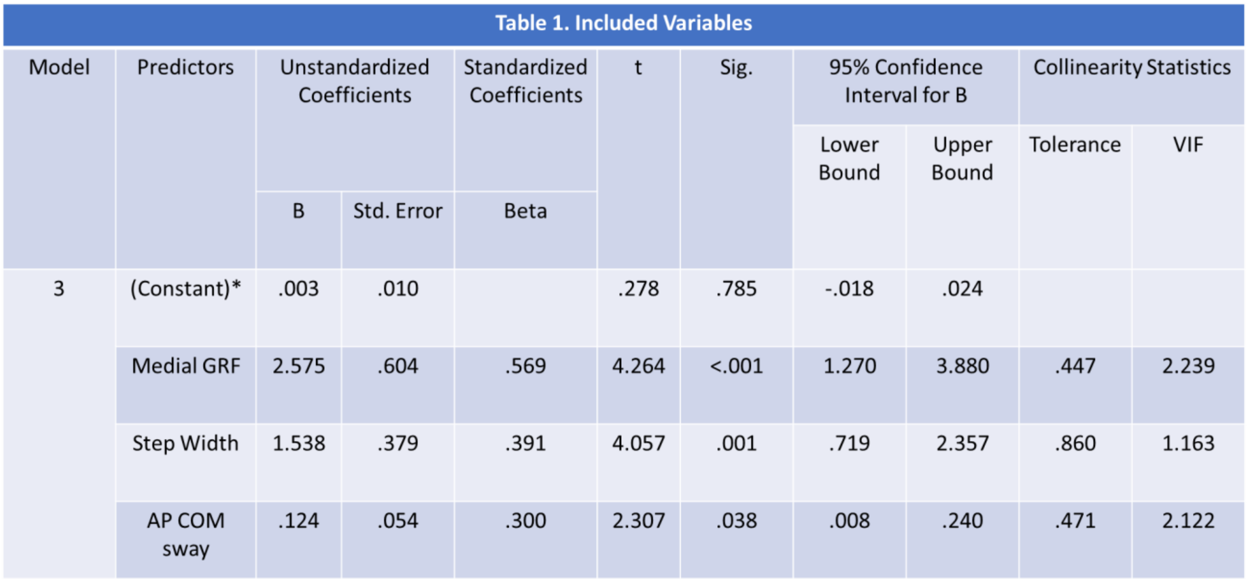

Table 1. Included Variables

Model	Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
3	(Constant)*	.003	.010		.278	.785	-.018	.024		
	Medial GRF	2.575	.604	.569	4.264	<.001	1.270	3.880	.447	2.239
	Step Width	1.538	.379	.391	4.057	.001	.719	2.357	.860	1.163
	AP COM sway	.124	.054	.300	2.307	.038	.008	.240	.471	2.122

Table 1. Coefficients for primary predictors of the final stepwise regression model. * Represents Mediolateral COM sway.

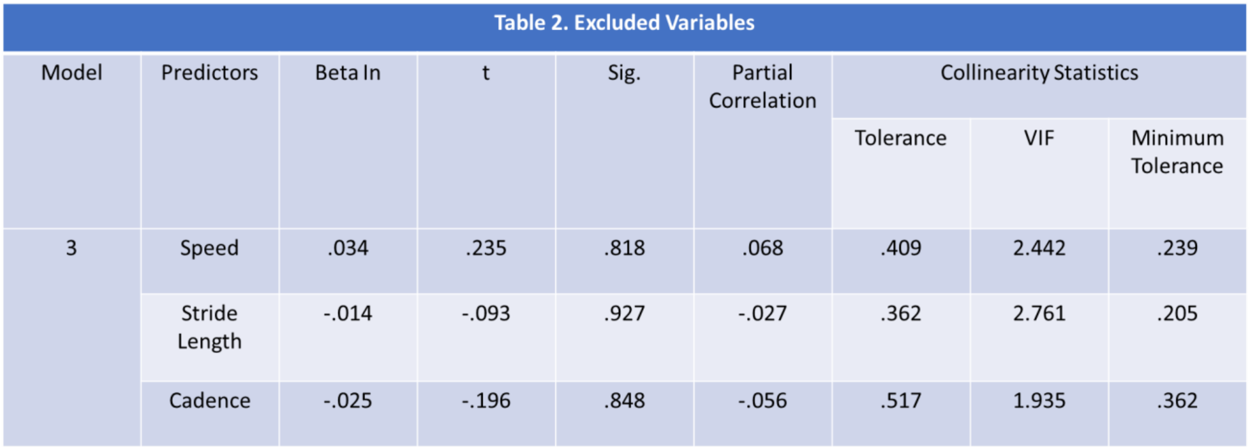

Table 2. Excluded Variables

Model	Predictors	Beta In	t	Sig.	Partial Correlation	Collinearity Statistics		
						Tolerance	VIF	Minimum Tolerance
3	Speed	.034	.235	.818	.068	.409	2.442	.239
	Stride Length	-.014	-.093	.927	-.027	.362	2.761	.205
	Cadence	-.025	-.196	.848	-.056	.517	1.935	.362

Table 2. Coefficients of the variables excluded from the final stepwise regression model.

4. Discussion

This study determined the effect of a SP treadmill condition on body lateral COM sway in older adults. In addition, biomechanical factors that predicted changes in body lateral COM sway across treadmill conditions were identified. Our results showed that older adults increased lateral COM sway in the SP condition compared to the FS condition, and that this increase in the lateral COM sway was predicted by changes in medial GRF, step width, and AP center of mass sway. We also identified that this change in ML COM sway between conditions may be related to the changes between conditions of walking speed that has been supported by previous studies. These results may provide important information for gait rehabilitation strategy designs that consider adopting self-paced treadmill training for older adults.

Contrary to our hypothesis, older adults increased both walking speed and lateral sway during the SP condition compared to FS condition. This increase in walking speed during SP condition supports the notion that FS treadmill may constrain walking speed (Hedrick et al., 2021; Terrier & Dériaz, 2011). A Previous FS treadmill gait study reported that body lateral displacement typically decreases with increased walking velocity (Tesio & Rota, 2019). Our results showed that this observation may not be applicable to the SP treadmill condition. A potential explanation could be that greater variations in walking speed was allowed during the SP condition compared to the FS condition. As such, participants might walk with less consistent foot placement compared to the FS treadmill and, therefore, increased the variation of body movement. Compared to overground gait, walking on a FS treadmill appeared to increase medial GRF (Watt et al., 2010). In the present study, we found that step width and medial GRF were further increased during SP walking. Thus, our results may suggest that SP walking likely induced greater challenge in lateral stability compared to FS and overground gait. Because challenging body lateral sway may be appropriate or beneficial for some, but not all, clinical populations, further research that identifies suitable populations that will be most likely to benefit from such walking condition is warranted.

Our results showed that SP treadmill walking induced changes in body movements in both the sagittal and frontal planes. This finding appeared to agree with previous studies that demonstrated the relationship between sagittal and frontal plane body movements during walking (Buurke et al., 2020; Cruz et al., 2009). Similarly, interactions between AP and mediolateral (ML) gait characteristics have been observed when voluntarily changing step length and step width on a treadmill (McAndrew Young & Dingwell, 2012). Our findings expand these previous results by demonstrating that altering treadmill constraints in the AP direction (i.e. adaptive belt speed) affected ML stepping biomechanics (i.e. step width, medial GRF) that were associated with lateral stability. Interestingly, Tesio & Rota reported that walking speed affects the lateral displacement of the body; however, our results showed that changes in treadmill speed did not independently predict changes in ML COM sway across conditions. Instead, we found that changes in COM sway in the AP direction provided unique information that predicted changes in COM lateral sway. Taken together, these results may suggest that the variation, rather than the average, of AP gait characteristics are more strongly coupled with changes in ML COM sway. These results support previous findings that the mechanisms for controlling dynamic stability were multi-planar (Ramanujam et al., 2020). Thus, careful consideration both of AP and lateral stability are needed when applying SP as an assessment and/or intervention tool.

Our results partially supported our hypothesis and agreed with previous studies that showed positive relationships between step width, ML GRF, and lateral stability (King et al., 2012; McAndrew Young & Dingwell, 2012). From a biomechanical standpoint, increased step width and medial GRF likely reflected increased body lateral instability (Hatze, 1980). Because the belt speed was continuously adjusted according to the participants' gait characteristics during the SP condition, changes in belt speed may trigger participants' response to modify their step width to increase the base of support.

This modification of stepping strategy may be related to the intensity of the belt speed change that could vary between different SP treadmill controller algorithms. Thus, the effect of SP walking on frontal plane biomechanics associated with lateral COM sway may be different between different algorithms used. Indeed, previous studies reported inconsistent results in changes in step width between FS and SP conditions (Kao & Pierro, 2021; Sloot et al., 2014). Kao & Pierro found no difference in step width between conditions, while Sloot et al. determined that step width was increased in SP walking. The controllers described by Kao & Pierro regulates treadmill belts' acceleration by monitoring the instantaneous position and speed of the participant (Kao & Pierro, 2021). In contrast, our controller adjusts the belt speed based on anterior GRF, step length, and step duration. Thus, it is possible that by adjusting key parameters of the SP controller, stepping strategy and lateral stability regulation reactions could be modified during gait. Future research that determines how altering controller parameters affects stepping strategy may further enhance the potential application for self-paced treadmills.

There were several limitations among this study. First, three subjects used the handrail during walking. Additional handrail support may affect lateral stability and walking mechanics. However, data from these participants were not outliers in any of the variables analyzed in this study and showed similar trends with data from other participants. Second, overground gait data was not collected in this study and therefore limited our ability to directly compare SP gait with overground gait. Lastly, the majority of participants were females. Thus, the results may be biased toward female gait characteristics.

4.1 Conclusion

In summary, the SP walking condition induced increases in mediolateral COM sway compared to the FS walking condition. Changes in ML COM sway were coupled with changes in MGRF, step width, and AP COM sway across treadmill conditions. These results highlighted the importance of considering lateral stability during gait training with SP treadmills.

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Vita

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