2023

Gait Strategies While Walking with Discrete Perturbations on a Self-Paced Treadmill

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GAIT STRATEGIES WHILE WALKING WITH DISCRETE PERTURBATIONS ON A SELF-PACED TREADMILL

by

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M.S. University of Central Florida, 2019
B.S. University of Central Florida 2017

A dissertation submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy
in the Department of Mechanical and Aerospace Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Spring Term
2023

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ABSTRACT

Introducing perturbations on a self-paced treadmill allows participants to experience uncertain environments without restricting their ability to continuously change their walking speed and kinematics. In this dissertation, I evaluated how different self-paced treadmill controller sensitivities affected gait parameters and variability on decline, level, and incline slopes. I also investigated how healthy young and older adults adjust their gait strategies when responding to perturbations of varying unpredictability and whether the changes in gait strategies remained once the perturbations were no longer present. Lastly, I evaluated how differences in gait kinematics when responding to visual and mechanical perturbations at varying frequencies. I found that detrending gait kinematics could be used as a tool to compare gait kinematics when participants walk with varying walking speeds. Higher controller sensitivities lead to greater speed fluctuations and longer steps for decline, level, and incline slopes. When introducing mediolateral perturbations as participants walked on a self-paced treadmill, I found that young and older adults walked faster, not slower, when responding to the perturbations compared to walking with no perturbations. Additionally, I found that after removing mediolateral perturbations faster walking speeds are carry over and are not rapidly washed out. Our findings suggest that separating gait variability into speed-trend and detrended variability could be beneficial for interpreting gait variability among multiple self-paced treadmill studies and when comparing self- paced walking with fixed speed walking. Additionally, these findings are of interest to

populations with slow walking speeds such as patients in rehabilitation because using perturbations such as discrete mediolateral treadmill shifts can potentially be designed to encourage participants to walk faster.

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CHAPTER 1 : INTRODUCTION

In uncertain environments and as people age humans begin to change their gait. Understanding differences in gait strategies used as people age could be examined with perturbations on a self-paced treadmill. Self-paced treadmills are becoming increasingly popular in evaluating gait biomechanics because participants can continuously adjust their walking speed. Another advantage of self-paced treadmills is that participants are no longer limited to short (10-20 meter) ramps or available outdoor terrains (Silverman et al. 2012; McIntosh et al. 2006; Prentice et al. 2004; Sun et al. 1996). Therefore, we can now leverage self-paced treadmills to gain a better understanding on how humans adjust their gait in uncertain environments as they age.

Changes in gait are associated with cognitive, sensorimotor, and biomechanical factors. Cognitive refers to the executive function and attention to internal and environmental cues (Yogev-Seligmann, Hausdorff, and Giladi 2008). Studies that evaluated short-term and long-term decreases in cognitive or executive function found an increase in fall risk (Muir, Gopaul, and Montero Odasso 2012; Amboni, Barone, and Hausdorff 2013). Sensorimotor refers to the mechanism the body uses for anticipatory and reactive support, control of balance, and postural stability. More specifically, motor commands act on the musculoskeletal system from sensory feedback through visual, vestibular, and somatosensory systems which contribute to changes in postural stability and locomotion (Bronstein 2016; MacKinnon 2018). Lastly, biomechanical, refers to changes in kinematics and kinetics. Walking at different speeds change kinematics such as step length, step frequency, and joint kinematics, as well as kinetics such as ground reaction forces and joint moments (Bovi et al. 2011; Bohnsack-McLagan, Cusumano, and Dingwell 2016).

First of all, we wanted to understand how self-paced treadmills work and if they forced participants to change their gait by the parameters that were set in the self-paced controller. Thus, we evaluated differences in self-paced treadmill controller sensitivities and how they affect gait parameters and variability on decline, level, and incline slopes. Then, we wanted to gain an understanding on how different environments would affect gait as humans age. We investigated changes in gait strategies between healthy young and older adults when responding to perturbations of varying unpredictability and whether the changes in gait strategies remained once the perturbations were no longer present. Lastly, we evaluated how differences in gait kinematics when responding to visual and mechanical perturbations at varying frequencies.

Our findings provide people using self-paced treadmills a better understanding on how they affect gait kinematics, which is crucial for biomechanical research. Additionally, these findings would be of interest to populations with slow walking speeds (i.e. patients in rehabilitation) because using perturbations such as discrete mediolateral treadmill shifts can potentially be designed to encourage participants to change their walking patterns.

CHAPTER 2 : SELF-PACED TREADMILL WALKING HAS SPEED-RELATED GAIT VARIABILITY THAT INCREASES WITH MORE SENSITIVE SELF-PACED CONTROLLERS

Abstract

Self-paced treadmills are being used more and more to study humans walking with their self-selected gaits on a range of slopes. Self-paced treadmills often use customized controllers, which raises questions about how different self-paced controller parameters affect self-paced walking biomechanics. We sought to determine how self-paced treadmill controller sensitivity (i.e. responsiveness to changes in speed) and mode (self-paced versus fixed speed) affect spatiotemporal gait parameters on different slopes. Our primary hypothesis was that the self-paced mode and more sensitive self-paced controllers would produce greater speed fluctuations, step length variability, and step width variability on each slope. Ten young adults walked on a self-paced treadmill using three self-paced controller sensitivities (low, medium, and high) and fixed speeds at three slopes (decline, -10°; level, 0°; incline, +10°). Within each slope, average walking speeds and spatiotemporal gait parameters were similar regardless of self-paced controller sensitivity. With higher controller sensitivities on each slope, speed fluctuations, speed variance, and step length variance increased whereas step frequency variance and step width variance were unaffected. Detrending speed from step length revealed that detrended step length variances were unaffected while speed-trend step length variances increased with more sensitive controllers. Further, detrended step length variances were similar for fixed speed and self-paced modes,

whereas the self-paced mode added substantial speed-trend step length variance not present in the fixed speed mode. These findings indicate that self-paced controller sensitivity can alter gait variability and that separating gait variability into speed-trend and detrended components could be beneficial when interpreting self-paced walking variability.

Introduction

Self-pace treadmills (also known as user-driven treadmills, active treadmills, and adaptive speed treadmills) are typically motorized treadmills that modulate belt speeds to match the subject's walking speed and are becoming more prevalent in gait laboratories. Self-pace control algorithms can use ground reaction forces, marker locations, and gait parameters, among other real-time measures, to determine when and how much to speed up or slow down the treadmill belts. Often, the intent for using self-pace treadmills is to match overground walking speeds and allow for less constrained gait (Minetti et al. 2003; Ray, Knarr, and Higginson 2018; Souman et al. 2011). As such, subjects can walk at their self-selected walking speed for several minutes and hundreds of strides while preserving natural gait fluctuations on self-pace treadmills (Plotnik et al. 2015; Choi et al. 2017; Sloot, van der Krogt, and Harlaar 2014). Self-pace treadmills can also be set at incline and decline slopes to study self-selected uphill and downhill gaits (Kimel-Naor, Gottlieb, and Plotnik 2017), overcoming limitations of overground sloped walking studies that are often constrained to short (10-20 meter) ramps or available outdoor terrains (Silverman et al. 2012; McIntosh et al. 2006; Prentice et al. 2004; Sun et al. 1996).

Several studies have investigated differences between self-paced treadmill walking and fixed speed treadmill walking where the treadmill speed is constant, requiring the subject to match the treadmill speed. Studies showed that stride variabilities, muscle activities, and walking speed during self-paced treadmill walking were more similar to overground walking than fixed speed treadmill walking (Sloot, van der Krogt, and Harlaar 2014; Ibala, Coupaud, and Kerr 2019; Ray, Knarr, and Higginson 2018). Peak anterior ground reaction forces also increased on a user-driven treadmill compared to a fixed speed treadmill (Ray, Knarr, and Higginson 2018). On an active (self-paced) treadmill, the sensorimotor cortex was more engaged compared to passively walking on the (fixed speed) treadmill (Bulea et al. 2014). Additionally, self-pace treadmills have helped demonstrate that exoskeletons, visual feedback, and mechanical perturbations can shift a subject's preferred walking speed (Song, Choi, and Collins 2019; O'Connor and Donelan 2012; Farrens, Lilley, and Sergi 2020).

As more groups incorporate self-pace walking into their studies, more customized self-pace controllers are being developed and implemented on treadmills already in a laboratory space or on new treadmills that do not have a self-pace mode option (Feasel et al. 2011; J. Kim et al. 2012; Minetti et al. 2003; Ray, Knarr, and Higginson 2018; Song, Choi, and Collins 2019; Yoon, Park, and Damiano 2012; O'Connor and Kuo 2009). Some treadmill companies (ex. Motekforce Link, used in this study) provide a built-in self-pace mode. A previous study showed that different control algorithms and parameters can generate different speed fluctuations when walking on a self-pace treadmill at a level slope (Sloot, van der Krogt, and Harlaar 2014). This multitude of self-pace treadmill controllers and parameters that can generate a range of speed dynamics may affect gait analyses, making comparing and interpreting findings across multiple self-pace walking studies difficult. Determining how to analyze spatiotemporal gait parameters while accounting for differences in speed fluctuations and responsiveness for multiple self-pace controllers is necessary for understanding differences in gait when using self-pace treadmills.

Gait parameters, particularly those with a strong relationship with speed such as step length (Grieve and Gear 1966), are likely to be sensitive to differences in self-selected gaits and speed fluctuations. Gait parameters have both long-range correlations over hundreds of steps (Terrier, Turner, and Schutz 2005) and short-range dependencies on preceding strides (J. M. Hausdorff et al. 1995), which may modulate walking speed over short distances (Riley et al. 2007). By removing the speed relationship from step length during overground walking, step length variability can be separated into speed-related (speed-trend) and speed-independent (detrended) components. These components may represent long-term and short-term active balance control (Collins and Kuo 2013). Other overground gait studies have also removed speed-related trends to analyze detrended gait variability to avoid speed-related effects (Jonathan B. Dingwell, Bohnsack-McLagan, and Cusumano 2018; Ojeda et al. 2015). To our knowledge, studies examining gait variability during self-pace walking on any slope have not detrended speed relationships from gait variability. As such, any likely speed-related effects have not been accounted for in self-pace treadmill walking findings.

The primary purpose of this study was to investigate how self-pace treadmill controller sensitivity and mode (self-pace versus fixed speed) affect self-pace walking speed and spatiotemporal gait parameters on different slopes (decline, level, and incline). We hypothesized that using the self-pace mode compared to the fixed speed mode and increasing self-pace controller sensitivity would increase speed fluctuations, step length variability, and step width variability within each slope. We also hypothesized that detrended gait variability would be similar across sensitivities within a slope as potential speed-related contributions to gait variability would no longer be present. Because studies often use a single sensitivity (or set of controller parameters) for all conditions, a secondary purpose was to investigate the effect of slopes on self-paced treadmill walking speed and spatiotemporal gait parameters with each sensitivity. We hypothesized that walking speed would be fastest and gait variability would be smallest on the level slope compared to decline and incline slopes with each sensitivity.

Materials and Methods

Ten healthy young adults (22.6±3.5 years; 4 females) with no musculoskeletal or neurological conditions participated in this study and provided informed written consent.

The University of Central Florida Institutional Review Board approved the protocol and consent form.

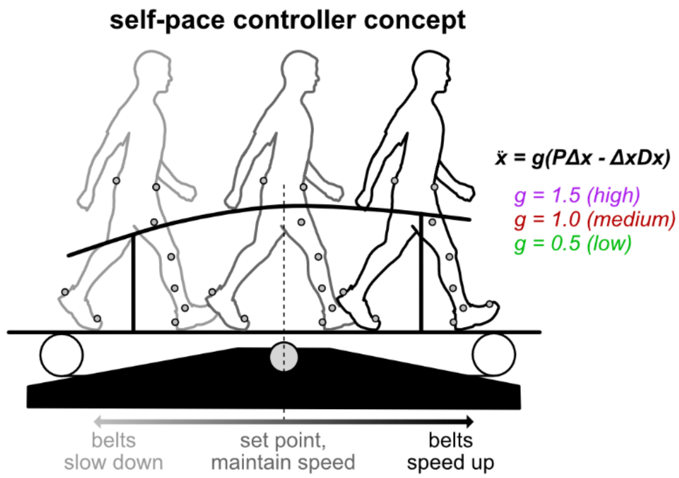

Figure 2-1: Schematic illustrating the self-pace controller concept and equation. The equation parameters are described in Eq. 1, and gains of 0.5, 1.0, and 1.5 yield the low (green), medium (red), and high (purple) controller sensitivities. When the subject moves in front of the set point, the treadmill belts speed up. When the subject moves behind the set point, the treadmill belts slow down. When the subject remains near the set point, the belt speed does not change.

Subjects walked on a self-pace instrumented treadmill (M-Gait System and D-Flow software version 3.28, Motekforce Link, Amsterdam, Netherlands) as motion capture data using the 16-marker OptiTrack “Conventional Lower Body” marker set was recorded (22 cameras, Prime 13 and 13W, OptiTrack NaturalPoint Inc., Corvallis, Oregon). The self-pace controller uses a proportional-derivative controller to adjust belt speed, $\ddot{x_b}$ based on the subject’s speed, $\dot{x}$ and relative position of their approximate center-of-mass (average of the pelvis markers’ positions) on the treadmill relative to the middle set point, Δx (Sloot, van der Krogt, and Harlaar 2014)(Eq. 1, Fig. 1).

$$\ddot{x_b} = \mathrm{g}(\mathrm{P}\Delta\mathrm{x} - \Delta\mathrm{x}\mathrm{D}\dot{x}) \tag{1}$$

The controller parameters are the sensitivity gain, g, proportional constant, P, and derivative constant, D. The low, medium, and high sensitivity controllers corresponded to gains of 0.5, 1.0, and 1.5, respectively.

Experimental Protocol

Subjects first walked on the treadmill with a range of fixed speeds and self-pace controller sensitivities during a brief familiarization period. They also completed a 10-meter walk test to identify their level overground walking speed. Subjects then completed nine 5-minute self-pace treadmill walking conditions, which were the combinations of controller sensitivities (low, medium, high) and slopes (decline, -10°; level, 0°; incline, +10°) in a randomized order with brief 1-2 minute rest periods between conditions. Subjects then completed 3 subject-specific fixed speed conditions, one for each slope. We calculated the average walking speed (calculated from the last 2.5 minutes of a condition) for the 3 controller sensitivities on a slope for each subject.

Data Analysis

Using custom MATLAB (Mathworks, Inc., Natick, Massachusetts) scripts, we first resampled the treadmill belt speed data from 333 Hz to 240Hz to match the motion capture system. We applied a low-pass filter (zero-lag fourth-order Butterworth filter at 6 Hz) to these data. We identified heel strikes as the most anterior position of the calcaneus markers and toe-offs as the most posterior position of the second metatarsal head markers for each foot (Zeni, Richards, and Higginson 2008).

We excluded the first 45 seconds for all analyses and used the last 255 seconds, which we considered to be at “steady-state” speeds (Plotnik et al. 2015). Walking speed was the sum of the treadmill belt speed and speed of the approximate center-of-mass. To characterize speed fluctuations, we computed the power spectral density of the walking speeds between 0.01-0.2 Hz frequencies. Step length was the anterior-posterior distance between heel markers, and step width was the mediolateral distance between heel markers for each step (heel strike to contralateral heel strike). Step frequency was the number of steps per second.

To quantify gait variability, we computed the variances for speed, step frequency, step length, and step width. We also separated the step length and step width variances into speed-dependent (speed-trend) and speed-independent (detrended) components (Collins and Kuo 2013). For each self-pace condition, we fitted the speed and step length data with Eq. 2 based on Grieve & Gear, 1966.

$$step\ length = \propto x\ v^{\beta} \tag{2}$$

where v is walking speed and α and β are constants and fitted the speed and step width data with Eq. 3 based on Collins and Kuo, 2013.

$$step\ width = \ (\gamma\ \times\ v) + \delta \tag{3}$$

where v is walking speed and γ and δ are constants. For each fixed speed condition, we combined data from the three self-pace sensitivities for a slope before performing the fits to identify a single set of parameters (α, β and γ, δ). We calculated step lengths and step widths using the fits and subtracted them from the actual step lengths and step widths, respectively, to obtain the detrended component (Collins and Kuo 2013). The speed-trend variance was the difference between the total and detrended variances because uncorrelated speed-trend and detrended variances sum linearly to equal the total variance.

Statistics

To test our first hypothesis and determine if controller sensitivity was a main effect within a given slope, we applied general linear models with repeated-measures independently for each spatiotemporal gait parameter. The assumptions of a repeated measures ANOVA (normality, homoscedasticity, and sphericity) were validated using a Shapiro-Wilk Test, Bartlett's test, and Mauchly's test. Outliers based on the default methods (Hi leverage, Cook's distance, and DFITS) used in Minitab (version 19.2020.1, Minitab, LLC, State College, Pennsylvania) were excluded. Because gait experiments typically use a single sensitivity, we applied the same statistical approach with each sensitivity to determine if slope (decline, level, and incline) was a main effect for a given sensitivity. Whenever sensitivity or slope was a main effect, we used post-hoc pair-wise Tukey's Honest Significant Difference (HSD) tests adjusted for multiple comparisons (Dunn-Bonferroni correction) to identify which sensitivities were significantly different within a given slope and which slopes were significantly different for a given sensitivity. We set the significance level to 0.05 and only report Tukey HSD p-values when either sensitivity or slope was a main effect for their respective statistical models. Due to an error saving the fixed speed data, only five subjects had fixed speed datasets, and we chose not to perform statistics to compare fixed speed and self-pace modes. We used SPSS (version 25, IBM Corporation, Armonk, NY, USA) for Mauchly's sphericity test and Minitab (version 19.2020.1, Minitab, LLC, State College, Pennsylvania) for all other statistical analyses.

Results

Speed Fluctuations

In all slopes, self-paced walking speeds had evident fluctuations over time, unlike fixed speeds (Fig. 2.2A). Speed fluctuations were distributed across more frequencies and had greater power at higher frequencies as self-pace controller sensitivities increased within each slope (Fig. 2.2B). The spectral powers for the fixed speed mode (not plotted in Fig. 2.2B) were 2 orders of magnitude less than the self-pace mode.

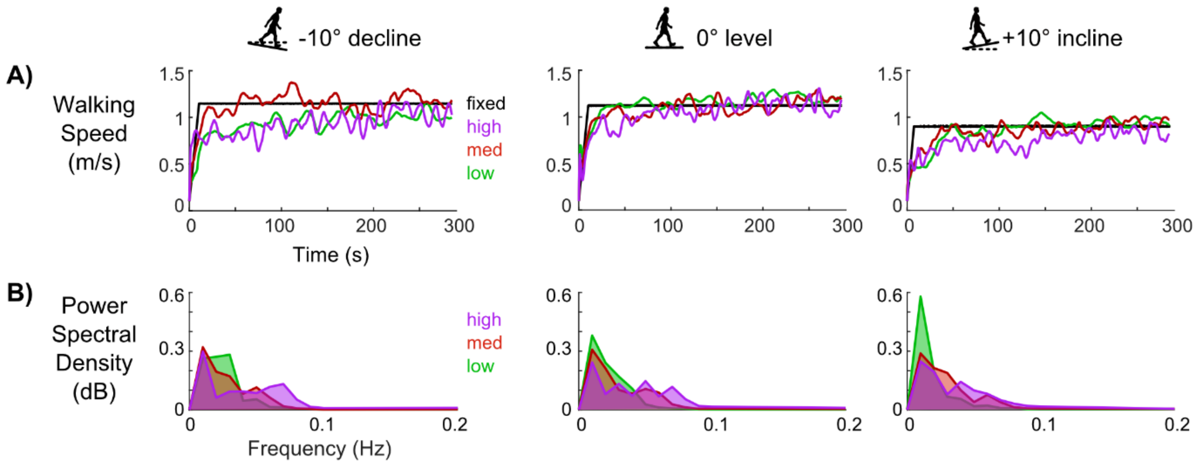

*Figure 2-2. **A)** Walking speed fluctuations over the duration of each condition (green = low; red = medium; purple = high; black = fixed speed) at each slope for a representative subject. Fixed speed conditions had nearly no fluctuations compared to the self-pace conditions. **B)** The group (n = 10) averaged power spectral density of walking speed was distributed across more frequencies with higher sensitivities.*

Average Speed and Spatiotemporal Gait Parameters

For the level slope, the walking speeds (mean±standard deviation) were 1.24±0.28 m/s, 1.23±0.26 m/s, and 1.22±0.28 m/s for low, medium, and high sensitivities, respectively, which were similar to the 10-meter walk speeds, 1.27±0.11 m/s.

Within each slope, increasing self-pace controller sensitivity did not affect average speed, step frequency, step length, or step width (Fig. 2.3).

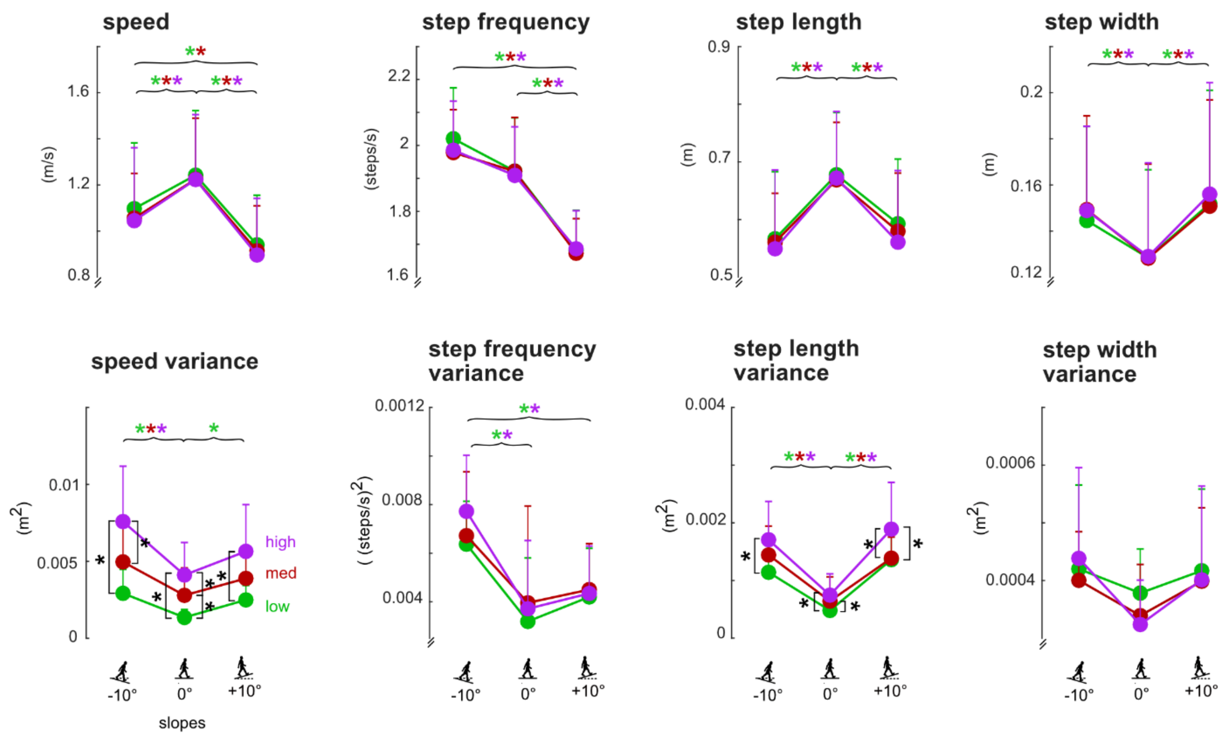

Figure 2-3: Group averaged walking speed, step frequency, step length, and step width (top row) and corresponding variances (bottom row) for each controller sensitivity for each slope. For all gait parameters, n=10 except for speed variance and step length variance where n=9, due to statistical outliers. Single sided error bars are shown and indicate standard deviations. Square brackets with black asterisks indicate significant differences between sensitivities within a slope (Tukey HSD, $p<0.05$). The brackets in these plots show that controller sensitivity only resulted in significant increases for speed variance and step length variance. Curly braces indicate significant differences between slopes within a single sensitivity indicated by the color-coded asterisks (Tukey HSD, $p<0.05$). The curly braces in these plots show that A) walking speed was fastest and speed variance was lowest on the level slope; B) step frequency was slowest on the incline while step frequency variance was highest on the decline; C) step lengths were longest and had the least variance on the level slope; and D) step width was smallest on the level slope while step width variances were not significantly different among slopes.

Each sensitivity showed that subjects walked the fastest with the longest step lengths and narrowest step widths on the level slope compared to the decline and incline slopes (Fig. 3, colored asterisks, p's<0.05). Additionally, the slowest step frequencies were on the decline compared to level and incline slopes (p’s<0.05). With the low or medium sensitivity, subjects walked faster on the decline compared to the incline (p’s<0.05).

Gait Variability

Within each slope, increasing self-pace controller sensitivity did not affect step frequency variance and step width variance (Fig. 2.3). Only speed variance and step length variance showed significant increases with higher sensitivities within each slope (Fig. 2.3, black asterisks, p’s<0.05).

Each sensitivity showed that step length variance was smallest on the level slope compared to the incline and decline slopes (Fig. 2.3, colored asterisks, p’s<0.05), and there were no significant differences in step width variance among slopes (Fig. 2.3). Each sensitivity also showed that speed variance on the decline was larger than level (p’s<0.05). Speed variance on the incline was larger than level with just the low sensitivity. With the low or high sensitivity, step frequency variance on the decline slope was larger than level and incline slopes (p’s<0.05).

Detrended and Speed-trend Step Length Variances

Speed-trend step length variances accounted for 34%, 47%, and 52% of the total variances for low, medium, and high sensitivities, respectively, on the decline (Fig. 2.4A). Similar percentages were observed on level (35%, 57%, 50%) and incline (41%, 46%, 58%).

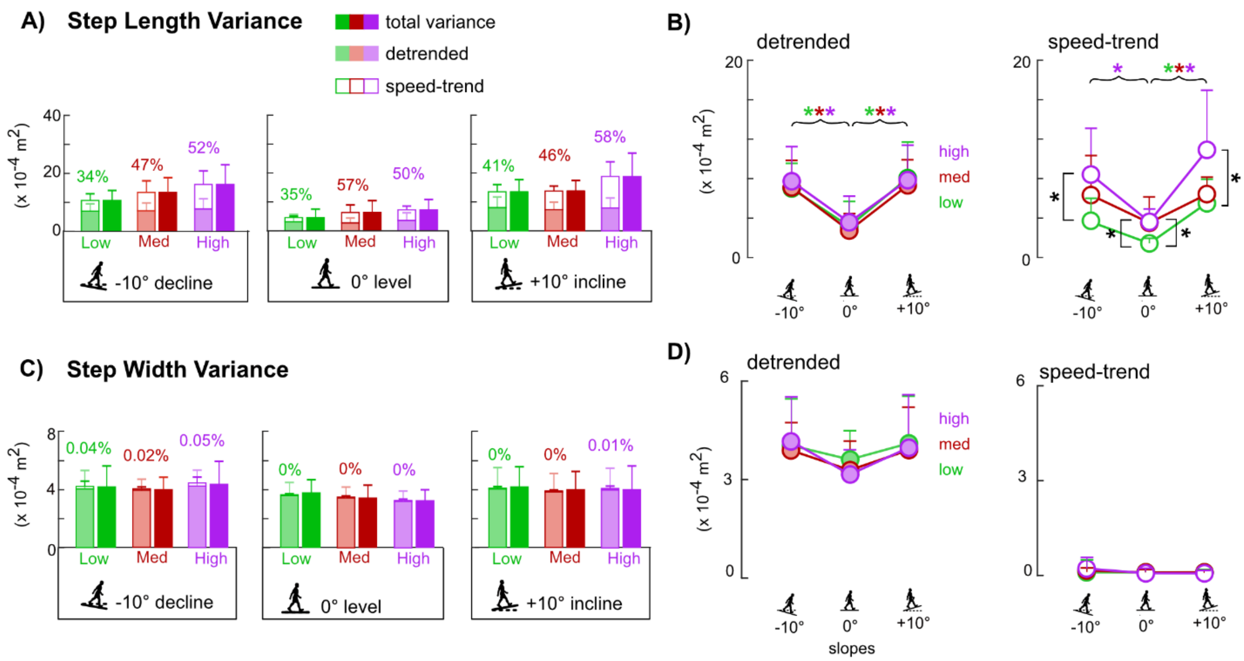

Figure 2-4: Step length variances and step width variances on decline, level, and incline slopes for low, medium, and high controller sensitivities (n=9, due to statistical outliers). Error bars are standard deviations. Solid colored bars are the total variance. Stacked bars show the summation of the detrended (faded colored bar) and speed-trend (open bar) components. Percentage values above the stacked bars report the percentage of the speed-trend component. A) As controller sensitivity increased, the speed-trend component in total step length variance also increased within each slope. B) Controller sensitivity did not affect detrended step length variances within a given slope, but as controller sensitivity increased, speed-trend step length variance also increased within a given slope, as indicated with square brackets and black asterisks (Tukey HSD, $p<0.05$). When comparing across slopes within a given sensitivity, detrended and speed-trend step length variances were smallest on level compared to incline and decline, as indicated by the curly braces with color-coded asterisks of the specific sensitivities (green = low; red = medium; purple = high) (Tukey HSD, $p<0.05$). C) Step width variances had minimal, near zero speed-trend components within each slope. D) Detrended and speed-trend step width variances were not different across sensitivities within a given slope nor across slopes within a sensitivity.

Within each slope, detrended step length variances were not significantly different among sensitivities, while speed-trend step length variances were largest with the high sensitivity compared to the low sensitivity (Fig. 2.4B, black asterisks, p's<0.05).

Speed-trend step length variances were also larger with the medium sensitivity than the low sensitivity on the level slope ($p<0.05$).

Each sensitivity revealed that detrended step length variance was lowest on the level slope compared to decline and incline (Fig. 2.4B, colored asterisks, p's<0.05) and that step length variance was not significantly different between decline and incline (Fig. 2.4B). Each sensitivity also showed that speed-trend step length variance was larger on the incline than level (p's<0.05). Speed-trend step length variance was larger on the decline compared to level only with the high sensitivity ($p<0.05$).

Detrended and Speed-trend Step Width Variances

Unlike speed-trend step length variances, speed-trend step width variances only accounted for 0.04%, 0.02%, and 0.05% of the total variances for low, medium, and high sensitivities, respectively, on the decline (Fig. 2.4C). On level and incline, speed-trend step width variances were negligible (<0.01%) compared to the total variance in all sensitivities.

Within each slope, detrended and step-trend step width variances were not significantly different among sensitivities (main effect p's>0.05, Fig. 2.4D).

Within each sensitivity, there were also no significant differences in detrended and speed-trend step width variances among slopes (main effect p's>0.05, Fig. 2.4D).

Fixed Speed Mode Versus Self-Pace Mode

Total step length variance was the smallest for the fixed speed mode compared to any self-pace sensitivity (Fig. 2.5). Detrended step length variances for the fixed speed mode were within the range for the self-pace sensitivities, while speed-trend step length variances for the fixed speed mode were negligible < 1×10^{-7} m^2 (Fig. 2.5).

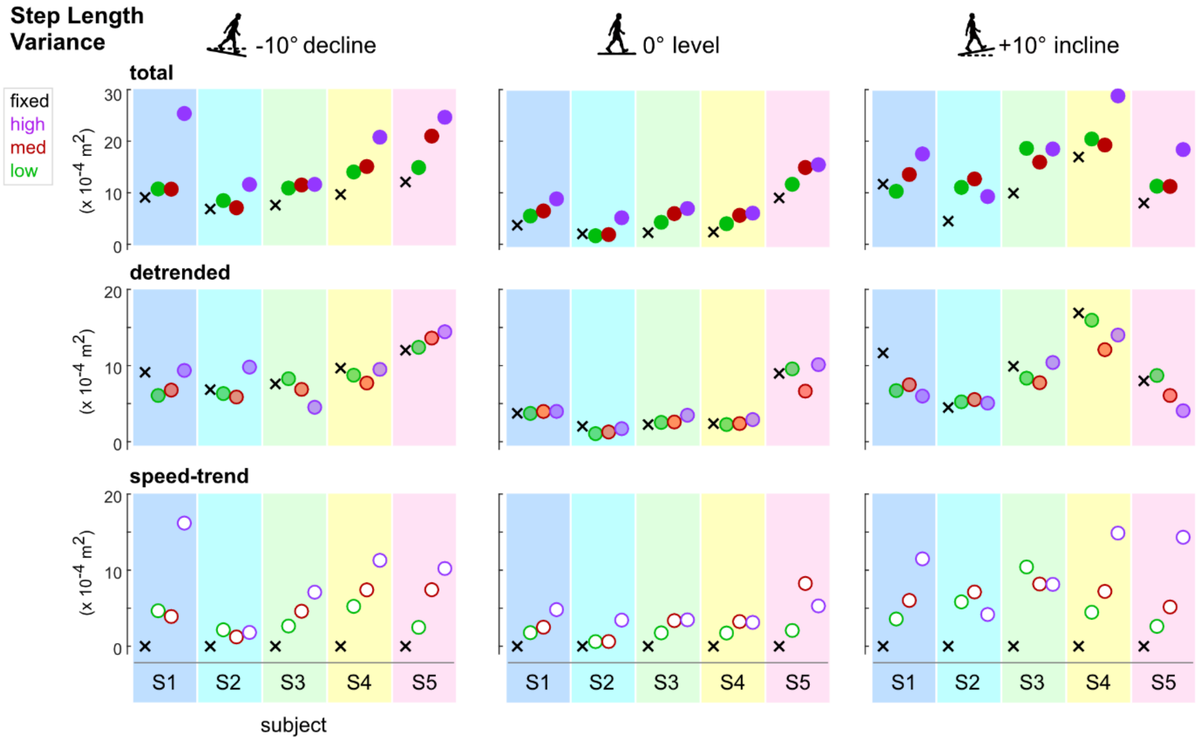

Figure 2-5: Total (solid circles), detrended (faded circles), and speed-trend (open circles) step length variances for the fixed speed mode (black x's) and low (green), medium (red), and high (purple) sensitivity self-pace controllers for 5 subjects (multi-colored shaded rectangles). Detrended step length variances were similar among the fixed speed and three self-pace controller sensitivities for each slope (middle row). Speed-trend step length variances were near zero for the fixed speed mode (bottom row). Total step length variances were lowest for fixed speeds compared to the self-paced conditions (top row) as a result of the near zero speed-trend step length variances for fixed speeds (bottom row).

Discussion

We sought to determine how self-pace treadmill controller sensitivity and mode (self-pace vs. fixed speed) affect spatiotemporal gait parameters on different slopes. Within each slope, increasing self-pace controller sensitivity did not affect average walking speeds or spatiotemporal gait parameters. However, more sensitive self-pace controllers resulted in greater speed variance and step length variance but had no significant effects on step frequency variance or step width variance. Altogether, these results partially supported our main hypothesis that increasing controller sensitivity would increase speed fluctuations, step length variability, and step width variability. Importantly, all detrended variances were not affected by controller sensitivity, as hypothesized, whereas speed-trend step length variance increased with more sensitive controllers. Further, substantial speed-trend step length variance was evident during self-pace treadmill walking, which contributed to increased total step length variance whereas speed-trend step length variance was negligible during fixed speed treadmill walking. We also compared speed and gait parameters among slopes with a single sensitivity as a typical study would do. As hypothesized, walking speed was fastest and gait parameter variances were smallest on the level slope compared to decline and incline slopes with each sensitivity. Overall, our study highlights that speed-related components of step length variability and potentially other gait parameters with strong relationships with speed, may affect the interpretation of gait variability during self-pace treadmill walking.

An important finding was that self-pace treadmill walking had speed-related step length variability components that were negligible during fixed speed treadmill walking but increased with more sensitive self-pace controllers for all slopes. Differences in gait variability between our fixed speed and self-paced conditions were not due to differences in walking speed because we matched the fixed speed to the average self-pace walking speed for individual subjects on each slope. The nearly non-existent speed-trend step length variance during fixed speed treadmill walking could explain why total speed length variance for the fixed speed mode will most likely always be less than the self-pace mode. Additionally, the speed-trend step length variance component and its percentage of the total step length variance increased with more sensitive self-pace controllers. Differences in gait variability between the fixed speed and self-pace modes would then be exacerbated with more sensitive self-pace controllers. However, detrended step length variances for the fixed speed condition and the three self-pace conditions were similar, with no systematic trends.

These results raise a question of how to interpret differences in step length variability for self-paced treadmill walking conditions. Generally, increased gait variability is interpreted as being less stable (J. B. Dingwell et al. 2001; Jonathan B. Dingwell, John, and Cusumano 2010; J. M. Hausdorff et al. 1997; O'Connor, Xu, and Kuo 2012) or involving greater active control (O'Connor and Kuo 2009). Based on total step length variance or speed-trend step length variance, walking on a self-pace treadmill with higher sensitivities was less stable and required more active control.

However, based on detrended step length variance, there were no apparent differences in stability or active control between fixed speed and self-pace treadmill walking, for any sensitivity. Alternatively, speed-trend step length variability may reflect active control needed to manage speed fluctuations and unstable dynamics of self-paced treadmill walking (Qian et al. 2019) Detrended step length variability may reflect active control intrinsic for steady-state walking, which was similar for both modes and all sensitivities. The negligible contributions of speed-trend step width variance was expected, as lateral foot placement has little relation to speed (Collins and Kuo 2013). Comparisons of step width variability across fixed speed and self-pace treadmills are likely to be less affected by any potential differences among modes or controller sensitivities. Thus, increases in total or detrended step width variability for different treatment groups or external destabilization/stabilization manipulations on any self-pace treadmills would represent differences in mediolateral stability (O'Connor, Xu, and Kuo 2012).

Our results suggest that self-pace walking on a decline was the most balance demanding while walking on level was most efficient. When walking conditions are less stable, subjects walk slowly with short and wide steps (Menant et al. 2009; Huijben et al. 2018; Mak et al. 2020; Kimel-Naor, Gottlieb, and Plotnik 2017), which we observed on the decline and incline. The increased detrended step length variance on the decline and incline also suggests gaits were less stable compared to level because increased step length variance corresponds with greater gait instability (Jeffrey M. Hausdorff 2007; Jonathan B. Dingwell, John, and Cusumano 2010). Step frequency variance on the decline was significantly larger than incline, suggesting that decline walking was more unstable than incline walking (Bohnsack-McLagan, Cusumano, and Dingwell 2016; Hunter, Hendrix, and Dean 2010; Beauchet et al. 2009; Jeffrey M. Hausdorff 2007). Finally, self-paced treadmill walking on the level slope had the fastest speeds, longest steps, and lowest detrended step length variance compared to decline and incline. This could be partly due to level walking being more stable and energetically favorable compared to walking on ±10° slopes (Hunter, Hendrix, and Dean 2010; Jeffers, Auyang, and Grabowski 2015).

Similar to other studies, we found that the self-pace walking speeds matched overground walking speed (Ray, Knarr, and Higginson 2018; Plotnik et al. 2015). The average difference between a subject's self-paced treadmill speed and overground speed was ~0.04 m/s, regardless of controller sensitivity. Our average self-pace walking speed was ~1.23 m/s on the level treadmill, which is at the lower end of the range of speeds (1.23-1.61 m/s) of other level self-pace treadmill studies (Plotnik et al. 2015; Choi et al. 2017; Song, Choi, and Collins 2019; Kimel-Naor, Gottlieb, and Plotnik 2017; Sloot, van der Krogt, and Harlaar 2014; Ray, Knarr, and Higginson 2018). Differences in speed among self-pace treadmill walking studies are likely due to other self-pace controller parameters instead of sensitivity or the sample of subjects, since we showed that average walking speed was indifferent to controller sensitivity, also seen in (Sloot, van der Krogt, and Harlaar 2014). Differences in speeds could be related to experiment protocols such as using visual optic flow, which resulted in faster walking speeds than without optic flow (Plotnik et al. 2015).

Limitations of this study include potential learning effects of walking on a self-pace treadmill and testing a small subset of sensitivities and slopes. Participants with no experience walking on a self-pace treadmill or sloped treadmill could experience a learning effect over the nine self-pace mode conditions. Another limitation is that we only used the maximum slope angle possible, ±10° and did not test shallower slopes. Similarly, we did not test sensitivities that spanned the full range, which could have revealed additional significant effects of sensitivity.

In summary, self-pace controller sensitivity had non-significant effects on average walking speed and spatiotemporal gait parameters on decline, level, and incline slopes. Self-pace treadmill walking includes speed-dependent gait variability components that increased with higher sensitivity self-pace controllers. Separating gait variability into speed-trend and detrended components is one approach to account for speed-dependent components of gait variability when interpreting gait variability during self-pace treadmill walking.

CHAPTER 3 : SPEEDING UP: DISCRETE MEDIOLATERAL PERTURBATIONS INCREASED SELF-PACED WALKING SPEED IN YOUNG AND OLDER ADULTS

Introduction

People tend to walk with a more cautious gait in uncertain environments and with increasing age. Typical features of a cautious gait include decreasing walking speed and increasing step width. People tend to walk slower and take wider steps when walking in unstable or uncertain environments such as a slippery floor surface (Reimann, Fettrow, and Jeka 2018) or with treadmill perturbations (Menant et al. 2009). Older adults without any impairments also tend to have slower walking speeds, shorter step lengths, and faster step frequencies compared to young adults (Richard W. Bohannon and Williams Andrews 2011), reflective of a more cautious gait.

A common approach for studying gait is to add perturbations during walking. There are a variety of perturbations which include visual perturbations using virtual reality (Shelton et al. 2022; Terry et al. 2012) and mechanical perturbations such as changing overground walking surfaces (Lockhart, Spaulding, and Park 2007), pulling a person side-to-side (Hof and Duysens 2018), using a force-field to create foot placement error (Nyberg et al. 2017), and shifting a treadmill platform side-to-side (Madehkhaksar et al. 2018; Li and Huang 2022). Introducing perturbations on a treadmill allows participants to experience uncertain environments within a controlled setting without limiting the number of gait cycles (Plotnik et al. 2015). Additionally, treadmills can apply mechanical perturbations in different directions (anterior-posterior or mediolateral). Perturbations can be implemented continuously or discretely at instances throughout a condition (Afschrift et al. 2019). Continuous perturbations constantly apply the perturbation for the entire condition, for example when a treadmill platform oscillates side-to-side following sinusoidal functions (Hak, van Dieën, et al. 2013). Discrete perturbations are applied at specific instances throughout the gait cycle. An example of a discrete perturbation is a sudden shift of the treadmill surface at a gait event (Afschrift et al. 2019).

Since walking in the real-world has an element of unpredictability, adding gait perturbations with a spectrum of unpredictability could provide further insights about gait strategies. Changing the timing and/or magnitude would vary the unpredictability of discrete and continuous perturbations. Predictable perturbations could have the same timing and magnitude, while unpredictable perturbations could vary both timing and magnitude. Previous studies have used discrete and continuous perturbations to create unpredictability and found that participants walk with a wider step width, faster cadence, and a shorter stride length (Madehkhaksar et al. 2018; Li and Huang 2022; Terry et al. 2012). However, these studies were performed on fixed-speed treadmills which did not allow for changes in walking speed or gait kinematics. As such, participants did not have the option to change their walking speed, which is a component of gait and balance control strategies.

Perturbations applied on self-paced treadmills could reveal whether changing walking speed is a key component of gait strategies for responding to perturbations.

Implementing perturbations on a self-paced treadmill allows participants to continuously adjust their walking speed (Plotnik et al. 2015; Sloot, van der Krogt, and Harlaar 2014). Self-paced treadmill studies with continuous mediolateral perturbations generated by shifting the treadmill platform side-to-side found that participants maintained a similar walking speed but increased step width and stride time while decreasing stride length compared to walking without perturbations (Hak, van Dieën, et al. 2013; Hak et al. 2012). Another self-paced walking study using similar continuous mediolateral perturbations found that stride length and stride time did not change during perturbed walking compared to unperturbed walking (Sinitski et al. 2015). However, no studies, to our knowledge, have evaluated how people respond to discrete perturbations while allowing them to continuously adjust their walking speed.

The purpose of this study was to investigate how healthy young and older adults adjust their gait strategies when responding to discrete mediolateral perturbations of varying unpredictability. We hypothesized that more unpredictable perturbations would produce more cautious gait strategies and would be more pronounced in older adults than young adults. As such, we expected decreases in self-paced walking speed, step length, and an increase in step frequency and step width with the addition of perturbations and as unpredictability increased. We also expected that older adults would have larger changes in walking speed and step kinematics compared to young adults.

Methods

Ten young adults (23±4.2 years; 5 females; 5 males) and nine older adults (70±6.6 years; 4 females; 5 males) with no musculoskeletal or neurological conditions participated in this study and provided informed written consent. We used a phone screening survey of self-reported conditions, short physical performance battery test score ≥ 9 (Freire et al. 2012), and a mini-mental test score ≥ 24 (Arevalo-Rodriguez et al. 2015) to confirm eligibility, with values reported in Table 1 and Table 2. The University of Central Florida Institutional Review Board approved the protocol and consent form.

Table 1: Short Physical Performance Battery (SPPB), Mini Mental Status Exam (MMSE), 10m over ground walking speed, and No perturbation walking speed for young adults. The gray boxes show the average value for the corresponding metric in the column.

Young adults (n=10)				
Subject #	SPPB	MMSE	Over ground walking speed (m/s)	No perturbation walking speed (m/s)
1	12	28	1.37	1.48
2	12	27	1.41	1.33
3	12	30	1.4	1.11
4	12	29	1.13	1.34
5	12	30	1.2	1.12
6	12	30	1.48	1.31
7	12	30	1.3	1.37
8	12	30	1.36	1.16
9	12	30	1.43	1.17
10	12	27	1.29	1.3
Average	12±0	29.1±1.12	1.34±0.11	1.27±0.13

Table 2: Short Physical Performance Battery (SPPB), Mini Mental Status Exam (MMSE), 10m over ground walking speed, and No perturbation walking speed for older adults. The gray boxes show the average value for the corresponding metric in the column.:

Older adults (n=9)				
Subject #	SPPB	MMSE	Over ground walking speed (m/s)	No perturbation walking speed (m/s)
1	12	27	1.24	1.53
2	11	30	1.12	1.51
3	10	30	1.16	1.17
4	12	30	1.46	1.4
5	12	29	1.32	1.38
6	12	30	1.4	1.37
7	12	29	1.18	1.63
8	12	28	1.24	1.7
9	12	30	1.32	1.33
Average	11.67±0.71	29.22±1.1(	1.27±0.11	1.45±0.16

We recorded lower limb movements using motion capture (OptiTrack NaturalPoint Inc.; OptiTrack “Conventional Lower Body” marker set) as participants walked with safety harness on a self-paced instrumented treadmill (M-Gait System, D-Flow v3.28, Motek Medical B.V). We used D-flow’s self-paced controller with parameters: sensitivity of 1.0, new algorithm, and used the center of the treadmill as the baseline position (Castano and Huang 2021; Mokhtarzzadeh, Richards, and Geijtenbeek 2022). The self-paced algorithm uses the relative difference between the participant’s center of mass, calculated as the average 4 pelvis marker positions, and the center of the treadmill to adjust the treadmill’s belts speeds (Fig. 3.1A).

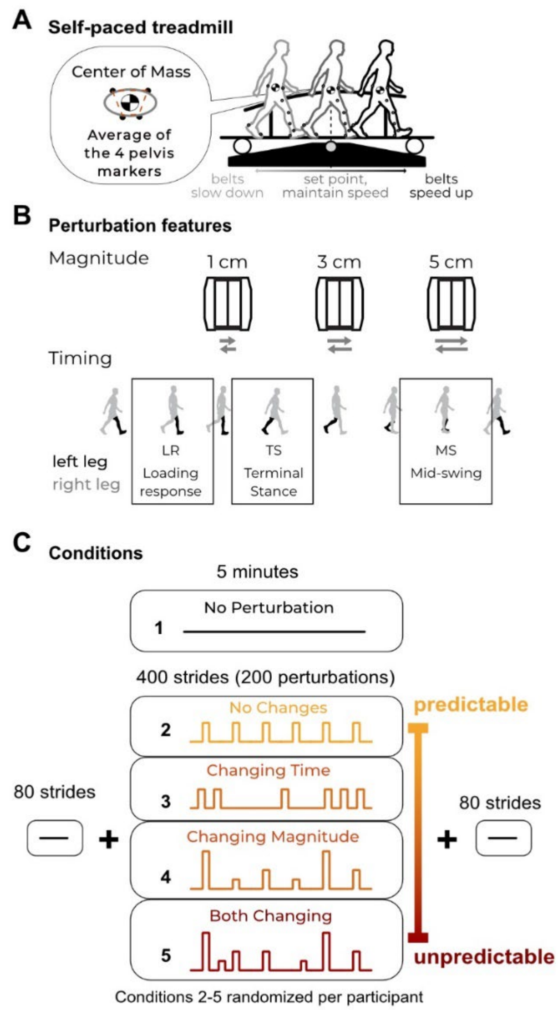

Figure 3-1: Schematic of the study protocol and perturbation unpredictability spectrum. A) Self-paced treadmill controller concept. B) Perturbation features of the different magnitudes (1 cm, 3 cm, 5 cm) and gait cycle timings (loading response, terminal stance, mid-swing) used for the perturbation conditions. C) The five conditions used in this study, 1) No Perturbation – baseline condition of 5 minutes of self-paced walking, 2) No Changes – Same timing and magnitude (most predictable), 3) Changing Time – Same magnitude (3 cm) with the 3 different timings, 4) Changing Magnitude – 3 magnitudes with the same timing (loading response), 5) Both Changing – 3 magnitudes with 3 timings (most unpredictable). For the perturbation conditions, participants walked for 80 strides to reach a steady-state walking speed with no perturbations followed by 200 perturbations at every other stride then finished with 80 strides with no perturbations. The perturbation conditions, conditions 2-5, were randomized per participant.

Protocol

Participants first completed a 10-meter walk test to identify their overground walking speed. Then, participants walked with the treadmill's self-paced mode and experienced mediolateral perturbations until they displayed a steady gait pattern without external support. Participants experienced perturbations in the familiarization period because pilot data suggested the first few absolute perturbations resulted in extreme responses in the step kinematics, which would skew responses in the first condition compared to the perturbed conditions.

There were 5 conditions: 1) a baseline condition of 5 minutes of self-paced walking (No Perturbation) and 4 perturbation conditions of different unpredictability levels. We changed the discrete mediolateral treadmill shift magnitudes and/or times within the gait cycle to create a spectrum of unpredictable perturbations (Fig. 3.1B): **2**) No Changes (3cm shift; left leg loading response; least unpredictable), **3**) Changing Time (loading response, terminal stance, and mid-swing; 3cm shift), **4**) Changing

Magnitude (1cm, 3cm, or 5cm shifts; left leg loading response), and **5**) Both Changing (1cm, 3cm, or 5cm treadmill shifts; loading response, terminal stance, and mid-swing; most unpredictable). A perturbation condition had 400 strides where a discrete perturbation occurred every other stride (200 perturbations total per condition) and began and concluded with 80 strides of self-paced walking with no perturbations (Fig. 3.3.1C). The first condition was the No Perturbation baseline condition followed by the perturbation conditions. The order of the four perturbation conditions were randomized for each participant.

Analysis

We analyzed the data with a custom MATLAB (Mathworks, Inc.) script. First, we resampled the treadmill data from 333 Hz to 240Hz to match the motion capture data. We applied a low-pass filter (zero-lag fourth-order Butterworth filter at 6 Hz) to the treadmill and motion capture data. We identified heel strikes as the most anterior position of the calcaneus markers and toe-offs as the most posterior position of the second metatarsal head markers for each foot (Zeni, Richards, and Higginson 2008). We calculated walking speed as the sum of treadmill belt speed and the approximate center of mass velocity, which was the derivative of the average of the four pelvis markers. Step length was the anterior-posterior distance between heel markers, and step width was the mediolateral distance between left and right heel markers at heel strike for each step. To examine step length and step width variability, we detrended walking speed from step length and step width to account for walking speed fluctuations

(Castano and Huang 2021). One older adult did not complete all conditions and was excluded from analysis.

Statistics

We used general linear models with repeated measures (SPSS; IBM Corporation) for all metrics to determine if unpredictable perturbations produced a more cautious gait. We performed a 2x5 repeated measures ANOVA with age (young and older) as our between-subjects factor and conditions (No Perturbations, No Changes, Changing Time, Changing Magnitude, and Both Changing) as our within-subjects variables. A Shapiro-Wilk test and Mauchly's test validated the assumptions of the repeated measures ANOVA. If condition or condition*age had a statistically significant main effect ($p<0.05$), then post-hoc pair-wise Tukey's Honest Significant Difference tests adjusted for multiple comparisons (Dunn-Bonferroni correction) were conducted to identify which conditions were significantly different ($p<0.05$). To test if older adults had significantly different step kinematics compared to young adults, we used independent t-tests with $\alpha = 0.05$.

Results

Condition was a main effect in all repeated measures ANOVAs (F's≥3.18; p's≤0.02, $\eta_p^2 \geq 0.158$) except for speed-trend step length variance, indicating there were significant differences among conditions for all metrics except speed-trend step length variance. There was no interaction effect for condition*age for all metrics (p's>0.09), indicating that there was no significant difference between the trends of the two age groups. Full statistical results are reported in supplementary table 1.

Walking speed increased for the 4 perturbation conditions compared to No Perturbation (p's<0.05; Fig. 3.2A). In the No Perturbation and Changing Times condition, average walking speed was significantly greater in older adults compared to young adults (p<0.05; Fig. 3.2). Walking speed variance significantly increased in the most unpredictable condition, Both Changing, compared to No Perturbation (p=0.038; Fig. 3.2B).

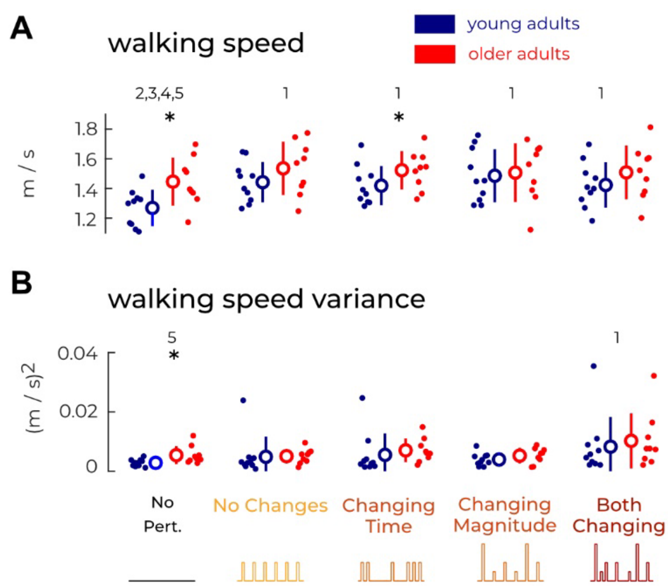

Figure 3-2: Walking speed average and variance for young (n=10, blue) and older (n=9, red) adults during (1) No Perturbation, (2) No Changes (most predictable), (3) Changing Time, (4) Changing Magnitude, and (5) Both Changing (most unpredictable) conditions. Solid circles are individual participants values, and the open circle is the group average. Vertical lines are +/- the standard deviation. Numbers above each condition indicate a significant difference between conditions. Black asterisks indicate a significant difference between young adults compared to older adults. **A)** Average walking speed increased for all perturbation conditions compared to No Perturbation, but conditions with more unpredictable perturbations did not affect walking speed. Older adults had greater walking speeds for all conditions compared to young adults **B)** Walking speed variance increased for the most unpredictable condition compared to No Perturbation.

Average step length, frequency, and width increased in conditions with discrete perturbations (Fig. 3.3). Step length and step frequency increased for all perturbation conditions compared to No Perturbation (p's≤0.05; Fig. 3.3A & 3B). Step width increased for the Changing Time, Changing Magnitude, and Both Changing conditions compared to No Perturbation (p's≤0.003, Fig. 3.3C). With respect to unpredictability, step lengths were greater for the most predictable condition (No Changes) compared to the most unpredictable condition (Both Changing) (p=0.011; Fig. 3.3A), and step width also increased as perturbation unpredictability increased (p's≤0.011; Fig. 3.3C). Step frequency was not different among perturbation conditions. With respect to age, step lengths were not significantly different between young and older adults (p's>0.05, Fig. 3.3A). Step frequency was greater in older adults compared to young adults for the No Perturbation, No Changes, and Changing Time conditions (p's<0.05; Fig. 3.3B) while step width was greater in older adults compared to young adults for the No Changes (t_{17}=-1.739, p=0.05; Fig. 3.3C) and Changing Magnitude conditions (t_{17}=-1.771, p=0.047; Fig. 3.3C).

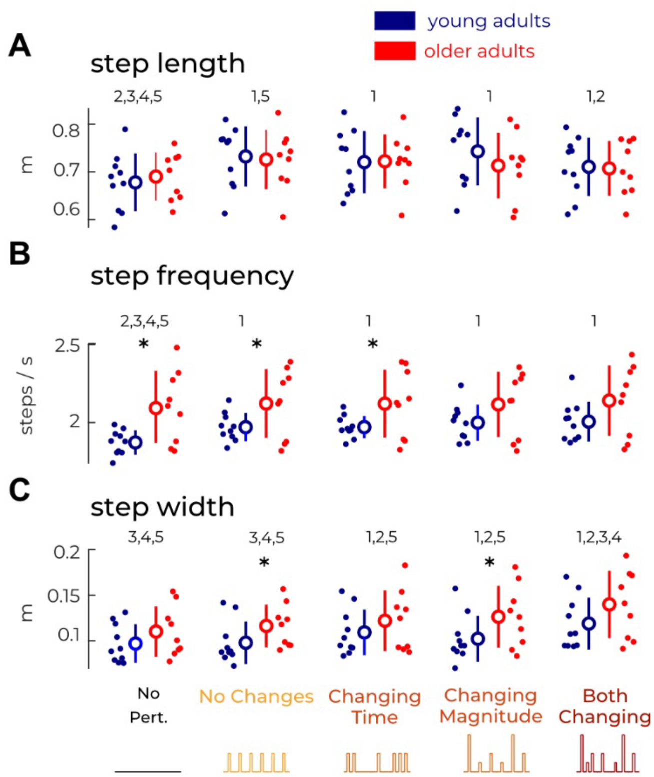

Figure 3-3: Average step length, step frequency and step width for young (n=10, blue) and older (n=9, red) adults during (1) No Perturbation, (2) No Changes (most predictable), (3) Changing Time, (4) Changing Magnitude, and (5) Both Changing (most unpredictable) conditions. Solid circles are individual participants values, and the open circle is the group average. Vertical lines are +/- the standard deviation. Numbers above each condition indicate a significant difference between conditions. Black asterisks indicate a significant difference between the younger adult group compared to the older adults. **A)** Step length increased with perturbation conditions compared to the No Perturbation condition. Step length decreased in the most unpredictable condition (5) compared to the most predictable condition (2). **B)** Step frequency increased with perturbation conditions compared to the No Perturbation condition. Older adults had greater step frequencies for all conditions. **C)** Step width increased as perturbation unpredictability increased and was greater for older adults than young adults.

Step kinematic variances generally increased as perturbation unpredictability increased (Fig. 3.4). The variances of step length, step frequency, and step width were significantly greater for the Changing Magnitude and Both Changing conditions compared to No Perturbation (p’s<0.05; Fig. 3.4). Variance of all step kinematics were greatest for the most unpredictable condition, Both Changing (p’s<0.05; Fig. 3.4A). With respect to age, step frequency variances were greater in older adults than young adults for the No Perturbation (t_{17}=-2.274, p=0.018) and Changing Magnitude (t_{17}=-1.743, p=0.05) conditions (Fig. 3.4B). Additionally, step width variances were greater in older adults than young adults for the No Perturbation ($t_{9.63}$=-1.943, p=0.041), No Changes ($t_{12.54}$=-2.197, p=0.024), and Changing Magnitude ($t_{10.80}$=-2.205, p=0.025) conditions (Fig. 3.4C).

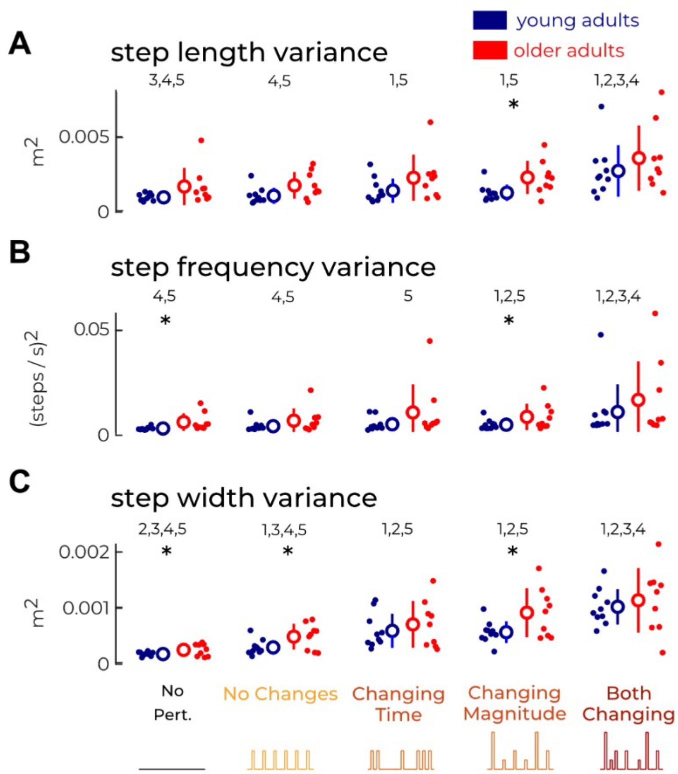

Figure 3-4: Step length, step frequency and step width variances for young (n=10, blue) and older (n=9, red) adults during (1) No Perturbation, (2) No Changes (most predictable), (3) Changing Time, (4) Changing Magnitude, and (5) Both Changing (most unpredictable) conditions. Solid circles are individual participants values, and the open circle is the group average. Vertical lines are +/- the standard deviation. Numbers above each condition indicate a significant difference between conditions. Black asterisks indicate a significant difference between the younger adult group compared to the older adults. **A)** Step length variance was greatest for the most unpredictable condition. **B)** Step frequency variance increased as perturbation unpredictability increased. **C)** Step width variance increased as perturbation unpredictability increased. Older adults also had greater step width variances compared to young adults for all conditions.

Total step length variance had clear speed fluctuation-related components (Fig. 3.5A). Detrended step length variance increased for the perturbation conditions compared to No Perturbations, except for No Changes (p's<0.05; Fig. 3.5B). Older adults had greater detrended step length variance for the No Changes (t_{17}=-1.78, p=0.047), Changing Time (t_{17}=-1.86, p=0.040), and Changing Magnitude (t_{17} =-3.228, p=0.002) conditions (Fig. 3.5B). For speed-trend step length variance, condition did not have a main effect ($F_{1.6,27.0}$=1.636, p=0.215, Fig. 3.5B). Older adults had greater speed-trend step length variance than young adults for the No Perturbation (t_{17}=-1.87, p=0.039, Changing Magnitude (t_{17}=-2.35, p=0.016), and Both Changing (t_{17}=-1.73, p=0.05) conditions.

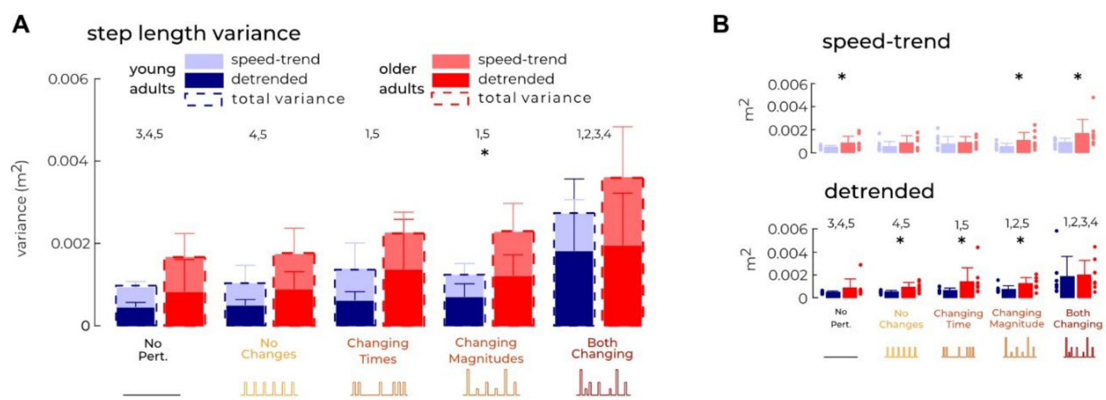

Figure 3-5: Detrended step length variance for young (n=10, blue) and older (n=9, red) adults during (1) No Perturbation, (2) No Changes (most predictable), (3) Changing Time, (4) Changing Magnitude, and (5) Both Changing (most unpredictable) conditions. Error bars are standard deviations. Darker colors represent detrended step length variance (dark blue-young adults; dark red-older adults) while lighter colors represent speed-trend variance (light blue-young adults; light red-older adults). The dashed box shows the total step length variance (dark blue-young adults; dark red-older adults). A) Total step length variance split into speed-trend and detrended components where speed-trend is stacked on top of the detrended step length variance. The numbers and asterisks above each condition represent significant differences between total step length variances. B) Speed-trend step length variance was greater for older adults in the condition without perturbations and for the Changing Magnitude and Both Changing perturbation conditions compared to young adults. Detrended step length variances for older adults were greater than young adults in all perturbation conditions except for the most unpredictable condition. Numbers above each condition indicate a significant difference of the variance metric between conditions while the black asterisks indicate a significant difference of the variance metric between young adults compared to older adults.

Discussion

We investigated how young and older adults adjust walking speed and step kinematics when responding to discrete predictable/unpredictable mediolateral perturbations on a self-paced treadmill. We hypothesized that participants would walk with a more cautious gait in the perturbed conditions and as unpredictability increased. As such, we expected participants to walk slower and take shorter, quicker, and wider steps. Participants walked faster and took longer, quicker, and wider steps, which partially agrees with our hypothesis. Even though average walking speed, step length, and step frequency did not follow a trend with our unpredictability spectrum, step width and step kinematic variability did increase as unpredictability increased. We also hypothesized that older adults would have a more pronounced cautious gait and expected that older adults would have larger changes in walking speed and step kinematics compared to young adults. Surprisingly, older adults walked faster and took quicker and wider steps with greater step kinematic variability compared to young adults, partially agreeing with our hypothesis. Overall, our study highlights that young and older adults preferred to walk faster as a strategy to adjust for unpredictable mediolateral perturbations. These findings suggest that perturbations can be designed to incentivize participants to adopt certain gait strategies.

An important and perhaps surprising finding was that participants walked faster, not slower, with discrete mediolateral perturbations. Previous studies that used continuous mediolateral perturbations found that self-paced treadmill walking speed decreased (Shelton et al. 2022) or remained similar (Hak, van Dieën, et al. 2013; Hak et al. 2012) compared to walking without perturbations. In our study, however, self-paced walking speed increased. A potential explanation for the contrasting results is the perturbation characteristics used in the studies. For the study where participants walked slower, the perturbation was continuous and visual, involving a virtual hallway oscillating side-to-side (Shelton et al. 2022). For the studies where walking speed did not change, the perturbation was mechanical and continuous, involving the treadmill platform shifting side-to-side continuously (Hak, van Dieën, et al. 2013; Hak et al. 2012). In our study where participants walked faster, we used discrete mediolateral treadmill shifts applied to every other stride. Participants may have walked faster with a lower foot clearance, possibly as a strategy to shorten reaction times and to be able to immediately increase their base of support to unexpected perturbations, which overground walking studies with unexpected perturbations have shown (Krasovsky et al. 2014; J. J. Eng, Winter, and Patla 1994). Interestingly, the unpredictability of the perturbations did not influence average walking speed as there were no significant differences among perturbation conditions. Based on our results and emerging results in the field, perturbation characteristics can influence self-selected walking speeds, which could potentially be tuned to alter walking speed purposefully.

Another interesting finding is that participants took longer quicker steps, not shorter quicker steps, when responding to discrete gait perturbations. Taking shorter steps (Lockhart, Spaulding, and Park 2007; Winter et al. 1990; Judge, Davis, and

Ounpuu 1996; R. W. Bohannon 1997) and quicker steps (i.e. increasing step frequency [5,6]) are often reflective of a cautious gait. In our study, participants took longer steps instead of shorter steps. Even though shorter steps often improve gait stability, taking longer and quicker steps can also enhance balance recovery based on studies where participants were released from different forward leaning angles while standing (Wojcik et al. 1999; Hemmatpour et al., n.d.). However, to our knowledge, taking longer steps has not been reported to improve balance while walking. As expected, participants took quicker steps for perturbation conditions compared to without perturbations, suggesting a more cautious gait strategy. Additionally, our participants seem to have used a more cautious gait for more unpredictable perturbations by taking shorter steps compared to the most predictable condition (Fig. 3.3). Overall, our results suggest that taking longer and quicker steps could be a strategy to enhance stability.

Increasing unpredictability increased balance demands as it led to greater step width and step kinematic variability. People tend to modulate step width to actively control balance (O’Connor and Kuo 2009) and often increase their step width for demanding balance tasks (Hak et al. 2012). Similarly, our participants took wider steps with more unpredictable perturbations perhaps as a strategy to increase gait stability. Step kinematic variability also tends to increase when gait stability is challenged (Bohnsack-McLagan, Cusumano, and Dingwell 2016; O’Connor and Kuo 2009). Our results showed greater variances for step width, step frequency, and step length as perturbation unpredictability increased, which suggests that gait stability was progressively challenged as unpredictability increased. Overall, more unpredictable perturbations appeared to have led to greater balance demands.

When we examined differences between age groups, we found that older adults surprisingly walked faster than young adults and had greater step kinematic variability. Previous fixed speed treadmill and overground studies showed that older adults tend to have a slower preferred walking speed than young adults (Richard W. Bohannon and Williams Andrews 2011; R. W. Bohannon 1997). In our study, older adults walked faster, not slower, than young adults in all conditions, even in the condition without perturbations. The differences in walking speed are likely related to differences in step length and step frequency since people can walk faster by increasing step length, increasing step frequency, or increasing both step length and frequency. While young and older adults had similar step lengths and relative increases in step lengths across conditions, older adults had higher step frequencies in all conditions compared to young adults, which explains the faster walking speed in older adults. In uncertain environments, people tend to take quicker steps [31], which appears to be a strategy older adults used to potentially increase stability. Our results also showed that older adults had greater overall gait variability compared to young adults. Step width variance had the most pronounced difference compared to step length and step frequency variances. Mediolateral balance often requires more active control (Dean, Alexander, and Kuo 2007), which may explain why older adults had greater step width variability.

Detrending step length variance revealed differences between young and older adults that were not apparent in the total step length variance. Detrending variance has been used in previous studies to account for fluctuations in walking speeds by separating variance into speed-related (speed-trended) and non-speed-related (detrended) components (Castano and Huang 2021; Collins and Kuo 2013). Our results showed that detrended variances for older adults were greater than young adults in conditions with perturbations. The increased detrended variances for older adults suggest that the perturbations exacerbated intrinsic balance demands in older adults. This difference between young and older adults was not evident in the total step length variance (Fig. 3.5). Detrending step length variance provided further evidence that older adults had less balance control when walking with perturbations.

Main limitations of this study were related to the protocol. One limitation is that walking on a self-paced treadmill is novel where participants need to explore and become familiar with how the treadmill matches their own walking speed. Additionally, participants were instructed to walk at a comfortable walking speed, which might have been perceived differently between participants. Lastly, the maximum treadmill shift was 5 cm which did not allow us to explore larger and possibly more destabilizing perturbations.

In summary, discrete mediolateral treadmill perturbations led to faster walking speeds and longer, quicker, and wider steps. Surprisingly, older adults walked faster than young adults in all conditions. Perturbation unpredictability primarily affected step width and step kinematic variability. Older adults had greater kinematic variability than young adults, and detrended step length variance further highlighted this difference between age groups. Overall, our findings suggest that gait perturbations could be designed to incentivize participants to adopt specific gait strategies.

CHAPTER 4 : FASTER WALKING SPEEDS ARE RETAINED AFTER EXPERIENCING DISCRETE MEDIOLATERAL PERTURBATIONS

Introduction

Humans adapt their gait depending on the environment around them. When walking in environments with perturbations, people adapt their gait to correct for these disturbances (Li and Huang 2022; Torres-Oviedo et al. 2011). In the real-word, people can take shorter/longer steps, quicker/slower steps, wider/narrower steps, and walk faster/slower to adjust to perturbations. However, changes in gait are not only driven by the environment but can also change due to age (J. M. Hausdorff et al. 1997; Winter et al. 1990; Tinetti, Speechley, and Ginter 1988). Evaluating how gait kinematics change after experiencing perturbations can further our understanding on balance control strategies and create new rehabilitation techniques for people with gait impairments. This is important because falls are a leading cause of injury and can significantly reduce the quality of life in order adults (Rubenstein 2006; Hartholt et al. 2011).

Perturbations can be introduced by disturbing the visual flow, waist pulling, changing belt speeds, shifting platforms side-to-side, etc., and have different levels of unpredictability. On a treadmill, perturbations can be applied at specific instances throughout a condition (discrete perturbations) or without stopping (continuous perturbation) (Afschrift et al. 2019). A treadmill with discrete perturbations can have the treadmill platform shift side-to-side or treadmill belts speed up or slow down at specific instances throughout the gait cycle. A treadmill with continuous perturbations can also have the treadmill platform shift side-to-side or treadmill belts speed up or slow down, but the perturbation does not stop. Discrete and continuous perturbations could also vary in timing and/or magnitude, making the perturbation predictable or unpredictable. On a treadmill, predictable perturbations would have the same timing and magnitude and unpredictable perturbations would vary in both timing and magnitude. (Rubenstein 2006; Hartholt et al. 2011)

Understanding how mechanical perturbations affect gait strategies may be helpful for improving mobility in older adults and other clinical populations because most falls typically occur due to mechanical perturbations during walking (Berg et al. 1997). Several studies implementing perturbation training approaches, by introducing anterior-posterior and mediolateral mechanical perturbations during static and dynamic tasks, have led to decreases in fall risk by increasing a participant's center of mass (Chien and Hsu 2018), improving pelvic motion (Gimmon et al. 2018), and increasing reaction times (Kurz et al. 2016). Perturbation training benefits are not only present immediately after training (Wang et al. 2019), but studies have also shown long-term benefits of up to 12-months post perturbation training (Okubo et al. 2019; Wang et al. 2019). More benefits also occur when multiple perturbation features are implemented (Gerards et al. 2017, 2021). Perturbation approaches that added features that simulate more realistic walking conditions have been shown to improve balance control strategies (Y-C Pai et al. 2003; Mansfield et al. 2015; Yi-Chung Pai et al. 2014). Motor learning paradigms using perturbations have demonstrated that the walking patterns that were adopted on a treadmill can be maintained when walking overground as well (Lee et al. 2020; Gimmon et al. 2018). Gaining a better understanding on how people respond to different perturbation features could lead to perturbation protocols that target specific biomechanical deficites in older adults, such as decrease step length (Mak et al. 2020; Menant et al. 2009), and result in faster walking speeds and mobility.(Shelton et al. 2022; Hak et al. 2012; Castano, Lee, and Huang 2022)

(Lee et al. 2020; Gimmon et al. 2018)A self-paced treadmill allows participants to experience uncertain environments without restricting their walking speed or kinematics. With a self-paced treadmill, studies can be performed to determine how treadmill perturbations affect walking strategies. Previous perturbation studies on a self-paced treadmill found that people may slow down (Shelton et al. 2022), maintain a similar walking speed (Hak et al. 2012), or walk faster (Castano, Lee, and Huang 2022) compared to walking without perturbations. In our previous study, we found that both young and older adults walk faster when experiencing discrete mediolateral perturbations compared to walking with no perturbations. However, we did not analyze if the faster walking speeds were retained after the perturbations were removed or whether those faster speeds carried over throughout the experiment. (Castano, Lee, and Huang 2022).

For this study, we performed follow-up analysis of our recent study where young and older adults walked faster after experiencing discrete mediolateral perturbations (Castano, Lee, and Huang 2022). In our study, a short period of no perturbations preceded (pre) and followed (post) each perturbation (pert) period, which would allow us to explore walking speeds before and after perturbations were removed. We also wanted to examine if the walking speed changed throughout the whole experiment, perhaps revealing a carryover effect from one condition to the next. We hypothesized that the perturbations would result in an increase in walking speed from the pre walking speed and that the post walking speed would remain higher than pre based on our previous findings. We also hypothesized that there would be a carryover effect, where the pre walking speed of the following condition would remain greater than the pre walking speeds of the previous condition.

Methods

All methods described, except the analysis, are the same as described in (Castano and Huang 2021). Ten young adults (23±4.2 years; 5 females; 5 males) and ten older adults (70±6.6 years; 4 females; 6 males) were used for analysis in this study and all provided written informed consent before participating. The written consent and protocol were approved by the University of Central Florida Institutional Review Board. Eligibility to participate was determined through a phone screening survey of self-reported conditions, a mini-mental test (Arevalo-Rodriguez et al. 2015), and a short physical performance battery test (Freire et al. 2012). The group average values for the mini-mental test for young adults is 29.1±1.12 and for older adults is 29.22±1.10. The group average values for the short physical performance batter test for young adults is 12±0 and for older adults is 11.67±0.71. The values for mini-mental test and physical performance battery test for individual subjects are reported in Chapter 3, Table 1 and Table 2.

The participants walked on a self-paced treadmill (M-Gait System, D Flow v3.28, Motek Medical B.V.) with the center of the treadmill as the baseline position, controller sensitivity of 1, and using the “new algorithm” (Castano and Huang 2021; Mokhtarzzadeh, Richards, and Geijtenbeek 2022). Motion capture (OptiTrack NaturalPoint Inc.; OptiTrack) with the “Conventional Lower Body” marker set was used to record lower limb movement along with calculating participants center of mass. The participants center of mass was found by taking the average of the four pelvis marker positions. The difference between the participants center of mass and the baseline position of the treadmill was used by the algorithm to adjust the treadmill's belts speed to allow for self-paced walking.

Protocol

The overground walking speed was identified by having participants complete a 10-meter walk. Then, participants were accustomed to the treadmill by going through a familiarization period to mitigate extreme responses. This familiarization period included a self-paced walking condition along with a perturbation condition, which was conducted until participants displayed steady gait patterns without external support.

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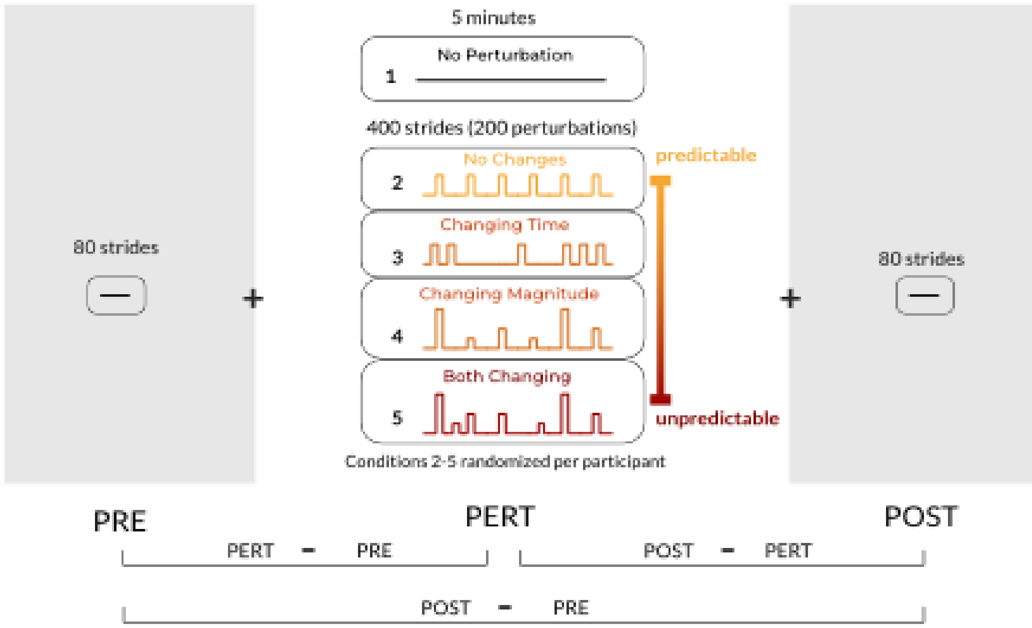

Figure 4-1: Schematic of the study protocol and perturbation unpredictability spectrum. The pre-perturbations (pre), perturbations (pert), and post-perturbations (post) periods have brackets to highlight the differences in walking speeds evaluated in this study.

There were a total of five conditions: **1**) No Perturbation, **2**) No Changes, **3**) Changing Time, **4**) Changing Magnitude, and **5**) Both Changing. For the No Perturbation condition (**1**), each participant walked for five minutes with self-paced mode to serve as a baseline. Following this condition there were four perturbation conditions that were randomized for each participant. Conditions **2-5** started with 80 strides of self-paced walking (**pre** period), followed by 400 strides with discrete perturbations that occurred every other stride (**perturbations/pert** period, a total of 200 perturbations per condition), and ended with 80 strides of self-paced walking (**post** period). These conditions varied in levels of unpredictability by changing the timing and magnitude of the perturbations. The No Changes condition (**2** – least unpredictable) consisted of 3cm treadmill shifts at left leg loading response. The Changing Time condition (**3**) had 3cm treadmill shifts at loading response, terminal stance, or mid-swing. The Changing Magnitude condition (**4**) had 1cm, 3cm, or 5cm shifts at left leg loading response. The Both Changing condition (**5** – most unpredictable) had 1cm, 3cm, or 5cm treadmill shifts at loading response, terminal stance, or mid-swing.

Analysis

In a previous study, we reported the average walking speed and step kinematics for the perturbation period of a condition only (Castano, Lee, and Huang 2022) whereas now we are looking at how participants changed their walking speed immediately before (pre) and after (post) experiencing perturbations within a condition. We are also looking at carryover from post to pre of the following condition.

We analyzed the data with a custom MATLAB (Mathworks, Inc.) script. First, we resampled the treadmill data from 333 Hz to 240Hz to match the motion capture data and applied a low-pass filter (zero-lag fourth-order Butterworth filter at 6 Hz) to both data sets. Left and right heel strikes were identified as the most anterior position of the calcaneus markers and left and right toe-offs as the most posterior position of the second metatarsal head markers (Zeni, Richards, and Higginson 2008). We calculated walking speed as the sum of the approximate center of mass velocity and treadmill belt speed. The approximate center of mass velocity was calculated as the derivative of the average position of the four pelvis markers. One older adult did not complete all conditions and was excluded from analysis.

Repeated measure ANOVAs (rmANOVA) (SPSS; IBM Corporation) were calculated for walking speeds for pre, pert, and post periods within a condition for young and older adults. We performed a 1x3 repeated measures ANOVA with period (pre, pert, and post) as our between-subjects factor. Another set of rmANOVA's were calculated, with a 1x4 design, to compare periods between conditions performed in chronological order. Shapiro-Wilk test and Mauchly's test validated the assumptions of the repeated measures ANOVA. If the rmANOVA had a statistically significant main effect ($p<0.05$), then post-hoc pair-wise Tukey's Honest Significant Difference tests adjusted for multiple comparisons (Dunn-Bonferroni correction) were used to identify which periods were significantly different ($p<0.05$). To test if older adults had significantly different changes in relative walking speed between periods compared to young adults, we used independent t-tests with $\alpha = 0.05$.

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Results

The rmANOVA for within-condition period comparisons were significantly different for all conditions for young adults whereas for older adults, the rmANOVAs had differences for all conditions except No changes. All significant differences reported have p-values of < 0.05.

For each perturbation condition, young adults walked faster with perturbations compared to pre-perturbations (Fig. 4-2). Once perturbations were removed, in the post-perturbations period of the conditions, young adults maintained similar walking speeds compared to the perturbation period, except for the Changing Magnitude condition. During the Changing Magnitude condition, young adults significantly decreased their walking speed compared to the perturbation period. Unlike young adults, older adults generally walked slower during perturbations compared to pre-perturbations (Fig. 4-2). During post-perturbation, older adults returned to the walking speeds during pre for No Changes and Both Changing. For Changing Time and Changing Magnitude, older adults walked the fastest during post-perturbations.

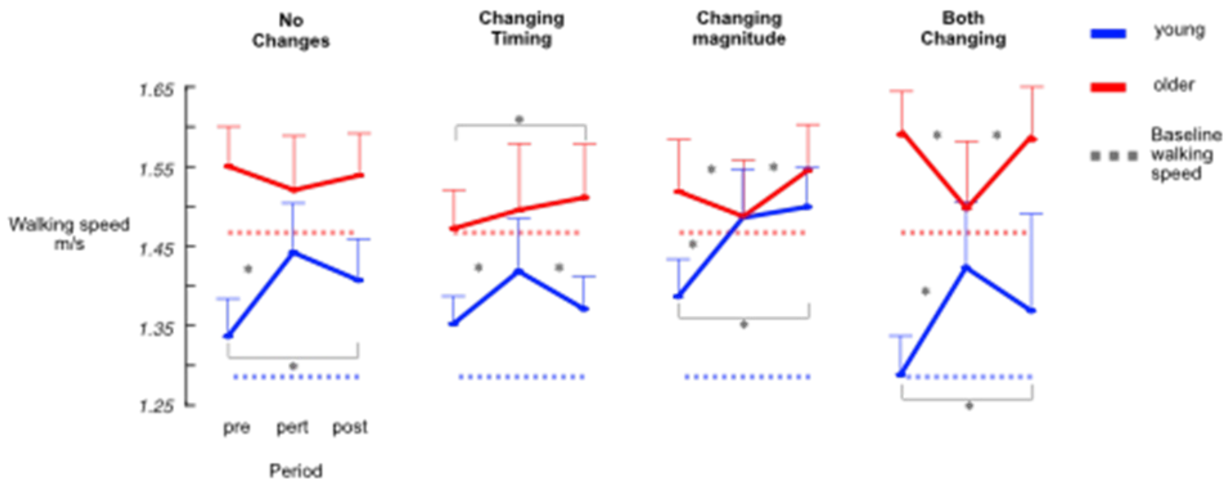

Figure 4-2: Average walking speeds for young (blue) and older (red) adults during pre-perturbations (pre), perturbations (pert), and post-perturbations (post) for No Changes (1), Changing Time (2), Changing Magnitude (3) and Both Changing (4) conditions. Single-sided error bars are shown and represent the standard deviation. The asterisks represent significant differences between paired (bracketed or connected) periods for young and older adults respectively. The average baseline walking speed is shown as a dotted line with the respective colors for young and older adults. Young adults walked faster with perturbations compared to pre-perturbations for all conditions, whereas older adults did not have a similar trend.

For young adults, the walking speeds for the pre-perturbation, perturbation, and post-perturbation periods generally increased in the order in which the conditions were performed (Fig. 4-3). Older adults had a similar increase in walking speed for all periods in line with the order performed, but only for the first three conditions (Fig. 4-3). However, both young and older adults had an increase in walking speed for pre-perturbation and post-perturbation when comparing the first condition performed to the fourth condition (Fig. 4-3).

Young adults significantly increased their walking compared to older adults when comparing the differences in the relative speed change during perturbation compared to pre-perturbation between young, for all conditions in chronological order (Fig. 4-4). Additionally, the differences in walking speeds during post-perturbations minus the perturbation period were significantly greater for young adults compared to older adults, for all conditions in chronological order (Fig. 4-5).

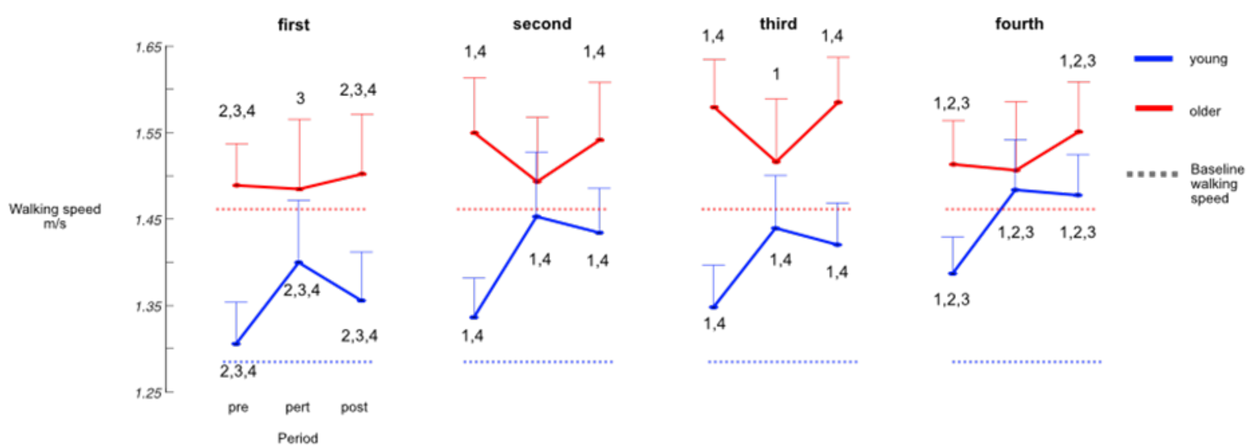

Figure 4-3: Average walking speeds for young (blue) and older (red) adults during pre-perturbations (pre), perturbations (pert), and post-perturbations (post) for conditions ordered in chronological order performed, first (1), second (2), three (3), four (4). The average baseline walking speed is shown as a dotted line with the respective colors for young and older adults. Single-sided error bars are shown and represent the standard deviation. The numbers above the periods in each condition represent significant differences between the periods of the following condition orders. Young and older adults had greater pre-perturbation and post-perturbation walking speeds for the fourth condition compared to the first condition.

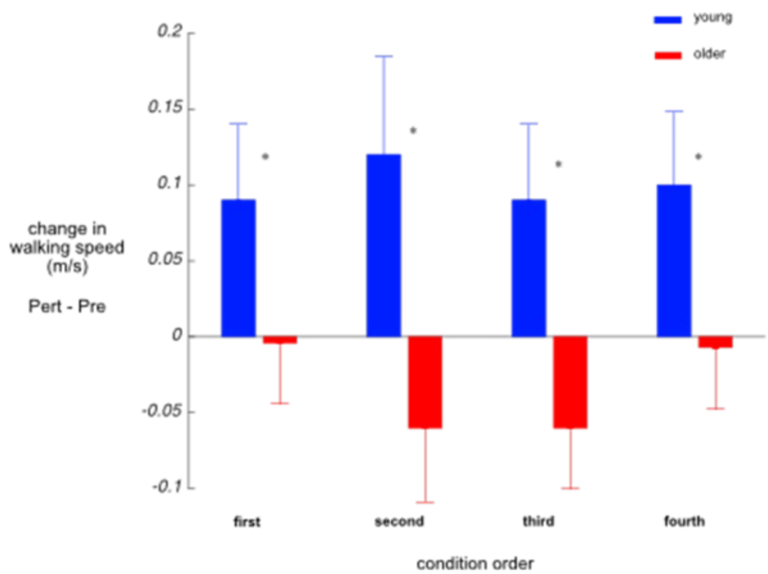

Figure 4-4: Group average changes in walking speed for perturbations – pre-perturbations for young (blue) and older (red) adults in the chronological order that the conditions were performed, first (1), second (2), three (3), four (4). Single-sided error bars are shown and represent the standard deviation. Positive changes indicate an increase in walking speed compared to pre while negative changes indicate a decrease in walking speed compared to pre. The asterisks above the condition order represent significant differences between young and older adults. Young adults had significantly faster walking speeds compared to older adults during the perturbations period compared to pre-perturbations.

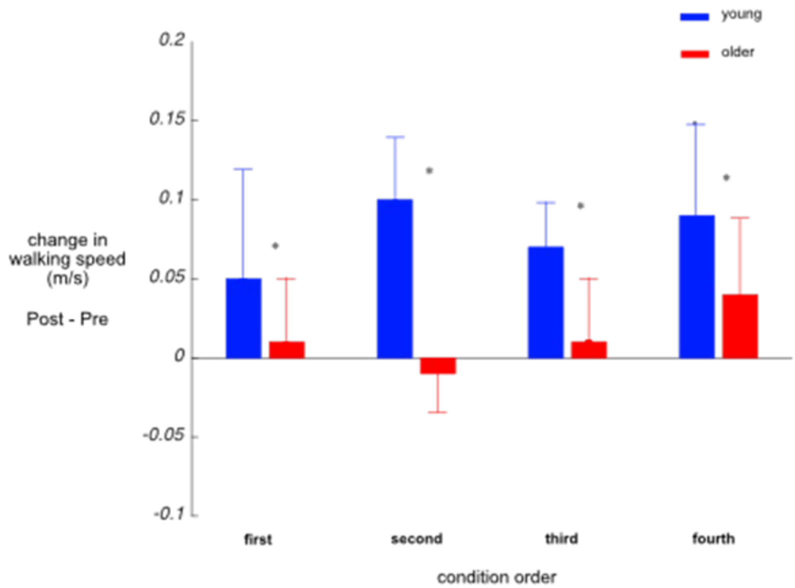

Figure 4-5: Group average changes in walking speed for post-perturbations – pre-perturbation for young (blue) and older (red) adults in the chronological order performed, first (1), second (2), three (3), four (4). Single-sided error bars are shown and represent the standard deviation. Positive changes indicate an increase in walking speed compared to pre while negative changes indicate a decrease in walking speed compared to pre. The asterisk above the condition order represents significant differences between young and older adults. Young adults had significantly faster walking speeds compared to older adults during the post-perturbations compared to pre-perturbations.

Discussion

We investigated walking speeds in young and older adults before and after introducing discrete mediolateral perturbations. We found that young adults walked faster with perturbations compared to pre-perturbations for all conditions. In contrast, older adults decreased their walking speed when experiencing the perturbations compared to pre-perturbations, revealing an age-related difference in gait strategy.. Additionally, young adults retained a similar walking speed post-perturbations compared to during the perturbations. We also sought to evaluate walking speeds after reordering the conditions to the chronological sequence performed to examine a possible carryover effect. We found progressively increasing pre-perturbation walking speeds from the first condition to the last condition for young adults and from the first condition to third condition for older adults. Our study demonstrates differences in gait strategies between young and older adults immediately before and after perturbations. These findings suggest that perturbations could be used to produce retained (carried over) increased walking speeds which would be useful for populations with slow walking speeds such as older adults and individuals with lower limb impairments.

One of the main findings is that faster walking speeds were retained for young and older adults, in that the post-perturbation walking speed were generally faster compared to the pre-perturbation walking speed (Fig. 4-4), which may be beneficial for improving mobility.(Barak, Wagenaar, and Holt 2006; Baker and Harvey 1985) Perturbation training is an error feedback protocol that often challenges gait stability and can be used to improve overground walking and prevent future falls (Yang and Pai 2013; Wang et al. 2019). Previous studies that implemented perturbation protocols have been able to improve balance control (Gimmon et al. 2018; Kurz et al. 2016), but there has not been a protocol that has increased walking speed. In our study, our perturbation protocol led to an increase in walking speed, where young and older adults maintained a faster walking speed after the perturbation was removed (post). Since perturbation training benefits can remain effective for several months (Yi-Chung Pai et al. 2010), our results suggest that introducing discrete mediolateral perturbations at every other stride could be an effective training method to increase walking speeds in the long-term.

Another interesting finding was that faster speeds carried over from one perturbation condition to the next during the course of the data collection session, which has potential implications on shifting gait strategies outside of the lab. Clinical studies have shown that perturbation training is an approach that can be taken to improve mobility in healthy older adults (Gillespie et al. 2012; Rieger et al. 2020), and older adults with Parkinson's (Steib et al. 2017) or post-stroke (Weerdesteyn et al. 2008). Reoccurring perturbations facilitate responses to similar random perturbations experienced later (Bierbaum et al. 2011; Y-C Pai et al. 2003), and the facilitated responses could be considered as a carryover effect. Here, young adults had an increase in walking speed for all pre periods that followed the chronological order of when the conditions were performed. In other words, as young adults had more exposure to mediolateral perturbations they walked even faster, possibly as a carryover effect from the first perturbation condition in an attempt to facilitate a response to the current and different perturbation. Similarly, after the first condition, older adults walked significantly faster in pre-perturbation and post-perturbation periods of the second, third, and fourth conditions, These findings align with other studies that worked with gait-impaired populations and found that treadmill-based rehabilitation training increased walking speeds, where more total time spent rehabilitating correlated highly with increased walking speeds based on a 5 or 10-meter walkway test (Thaut et al. 2007; Janice J. Eng and Tang 2007; C. L. Richards et al. 1993).

One of the most interesting findings was the clear age-related differences in gait strategies that emerged when comparing walking speed during the perturbation period compared to the pre-perturbation period (Fig. 4-4). Older adults walked slower with perturbations compared to their unperturbed pre-perturbation walking speed whereas young adults walked faster during the perturbation period compared to the pre-perturbation period. The older adult behavior aligns with our initial expectations that individuals would walk more slowly with perturbations. We expected that the instability and uncertainty from perturbations often result in a more cautious strategy of walking with shorter steps and slower speeds (Richard W. Bohannon and Williams Andrews 2011; Reimann, Fettrow, and Jeka 2018; Menant et al. 2009). Because mediolateral gait perturbations involve more balance demands, older adults may walk slower based on studies that suggest that decreased walking speeds is a mechanism older adults use to compensate for less muscle strength and greater cognitive demands when walking compared to young adults (Pijnappels et al. 2008; Lauretani et al. 2003; Stuart et al. 2019). An alternative explanation for older adults walking more slowly with the perturbations is that it could be that older adults walked unusually fast during the pre-perturbation period, perhaps due to a desire to perform well and walk like young adults. Typically, older adults walk slower than young adults in an unperturbed environment (Xie et al. 2017; Richard W. Bohannon and Williams Andrews 2011; Begg et al. 2014), which conflicts with our results in which older adults overall walked faster than our young adults. Some evidence that older adults just walked excessively fast is that by the fourth condition, older adults significantly decreased their pre-perturbation speed, perhaps from exhaustion from walking unusually fast (Fig. 4-2). Another factor that could contribute to the age-related differences is that when walking, older adults rely more on neural cognitive strategies for balance control whereas young adults use a more reactive strategy (Palmer et al. 2021; Maki and McIlroy 2007).

The increasing walking speed during the perturbation period compared to pre-perturbations observed in the young adult behavior is more aligned with the results comparing perturbation speeds with baseline, where perturbations led to faster walking speeds. It may be advantageous to walk faster in response to perturbations because faster walking speeds have reduced time in double support (McCrum et al. 2019; Wu et al. 2019), which would allow more time for changes in foot placement and base of support as an additional option for responding to the perturbations. During double support, control of the center of mass is the only option for responding to balance perturbations (Vielemeyer et al. 2021; Tesio and Rota 2019). Further, increasing step frequency results in faster reaction time (Baudendistel et al. 2021), which could be a strategy used to quickly adjust to the perturbations. If the step length remains the same or increases as step frequency increases, there would be an overall increase in walking speed.

In summary, we found that by examining walking speeds changes among the pre-perturbation, perturbation, and post-perturbation periods, young and older adults had different gait strategies .Young adults walked faster during the perturbation period compared to pre-perturbation while older adults walked slower during the perturbation period compared to the pre-perturbation period. Additionally, after reordering the conditions to the chronological sequence performed, both young and older adults progressively increased or maintained faster walking speeds at pre-perturbation after experiencing the first perturbation condition, demonstrating a carryover effect. These findings suggest that populations with slow walking speeds could use perturbations as a technique to generate and retain faster walking speeds.

CHAPTER 5 : PERTURBATION IMPLEMENTATION AND FREQUENCY AFFECTS SELF-PACED WALKING SPEEDS

Introduction

Typically, when the likelihood of falling increases, people tend to decrease their walking speed (England and Granata 2007; Jonathan B. Dingwell and Marin 2006). However, slower walking speeds are also related to people with increased fall risk, and locomotor activities such as walking usually lead to these falls (Curtze et al. 2011; Weerdesteyn et al. 2008; Tinetti, Speechley, and Ginter 1988). Gaining a better understanding of how people adjust their gait to disturbances in the environment could help develop rehabilitation strategies to prevent falls. Incorporating mechanical and visual perturbation in perturbation training has been a promising way to increase mobility in people with gait impairments and slow walking speeds who have a high fall-risk. However, a further understanding of how people respond to different perturbation features is needed.

As humans age, cognitive, sensorimotor, and biomechanical factors also change and locomotion becomes less autonomous (K.-M. Kim, Hart, and Hertel 2013; Alizadehsaravi et al. 2020). Previous studies have found that older adults typically walk slower, take shorter steps, and decrease foot clearance when walking on a level surface compared to older adults (Xie et al. 2017; Richard W. Bohannon and Williams Andrews 2011; Begg et al. 2014). Older adults experience age-related musculoskeletal changes such as sarcopenia, which is an age-related reduction of muscle mass and strength

(Pijnappels et al. 2008; Lauretani et al. 2003). The cross-sectional area of a muscle is correlated with muscle strength. With increasing age, muscle fibers begin to become fatty tissue and noncontractile elements which decreases the overall strength and activity of the muscles (Akima et al. 2001; Fiatarone et al. 1994). Cognitive processes are also required for locomotion and to collect sensory information from the body's movement through visual, proprioceptive, and vestibular systems (Fay B. Horak 2006; F. B. Horak and Nashner 1986). When evaluating cognitive differences with increasing age, studies have found an increase in cognitive activity, predominantly in the prefrontal cortex (Stuart et al. 2019; Mirelman et al. 2017; Chen et al. 2017). The decreases in muscle strength and greater cortical demands make, what is thought to be a simple task such as walking, a lot more demanding for older adults. Additionally, when walking in unstable environments, older adults have a more cognitive intensive control strategy compared to younger adults, who have a more reactive strategy (Palmer et al. 2021; Maki and McIlroy 2007). However, even with differences in adaptation strategies, perturbation-based training, where people are exposed to repeated unstable environments, is a method that can decrease fall risk in young and older adults (Y-C Pai et al. 2003; Kurz et al. 2016; Gimmon et al. 2018; Mansfield et al. 2015). Because of age-related changes, walking at a slower speed may be a compensatory mechanism to improve stability while walking.

Evaluating how people respond to different perturbation features can help create perturbation training methods targeted at changing a certain gait parameter for someone with a gait impairment. However, perturbations can have several features. Perturbation features include implementation, direction, structure, and unpredictability. Implementation is whether the perturbations are visual (moving a virtual reality scene) or surface (shifting a treadmill side to side). The direction can be anteroposterior (changing treadmill-belt speeds) or mediolateral (shifting the treadmill side to side). Structure pertains to continuous (constantly moving) or discrete (moving at certain instances). Lastly, unpredictability can range from predictable (the participant knows when a perturbation is coming) to unpredictable (random) perturbations. Focusing on perturbation features that can affect walking speed would be of interest for populations with high fall-risk.

Recent studies that had perturbations on a self-paced treadmill have found that changing features can affect walking speeds and gait kinematics. When people walk with continuous visual perturbations they decrease their walking speed (Shelton et al. 2022). Another study that continuously perturbed the treadmill surface, instead of a virtual scene, did not affect walking speed as people remained with similar walking speeds compared to walking without perturbations (Hak et al. 2012; Hak, van Dieën, et al. 2013). Introducing discrete surface perturbations, instead of continuous, increased walking speeds (Castano, Lee, and Huang 2022). However, no studies, to our knowledge have evaluated discrete visual perturbations or varying the frequency of discrete perturbations on a self-paced treadmill.

The purpose of this study is to investigate differences in walking speed when walking with visual/mechanical mediolateral perturbations and with perturbations introduced at different frequencies. We hypothesized that visual perturbations would result in a decrease in walking speed compared to mechanical perturbations. We also hypothesized that walking speed will decrease as perturbation frequency decreases, regardless of the perturbation feature (mechanical/visual).

Methods

Nine young adults (4 females and 5 males) were used for analysis in this study, and all provided written informed consent before participating. To participate in the study, participants had to pass a physical performance battery test and provide written consent. The written consent and protocol were approved by the University of Central Florida Institutional Review Board.

The participants walked on a self-paced treadmill (M-Gait System, D Flow v3.28, Motek Medical B.V.) with 16 motion capture (OptiTrack NaturalPoint Inc.; OptiTrack) markers following the “Conventional Lower Body” marker set. The self-paced treadmill has a self-paced controller that uses the center of mass location, found by taking the average of the four pelvis marker positions, with respect to the center of the treadmill to adjust the treadmill belt speeds, further details can be found in Motek Medical's paper (Mokhtarzzadeh, Richards, and Geijtenbeek 2022).

Protocol

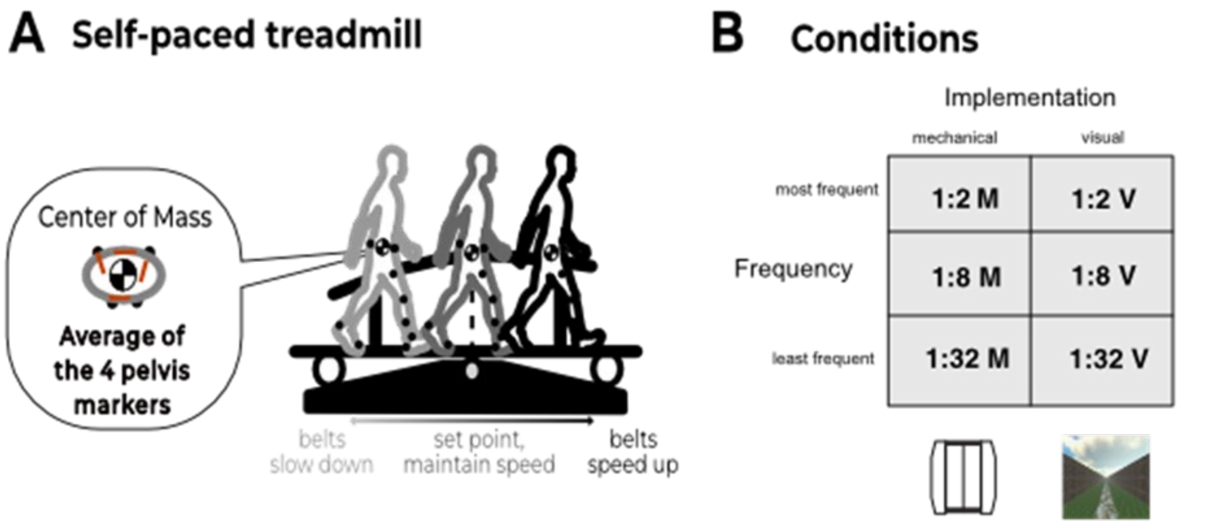

Figure 5-1: Schematic of the **(A)** self-paced treadmill controller concept and the **(B)** study conditions shown with the mechanical perturbation frequencies on the left column and visual perturbation frequencies on the right.

Participants completed a 10-meter walk test to collect their overground walking speed. Then, participants had a familiarization period which included a self-paced walking condition along with a mechanical and visual perturbations condition until participants displayed steady gait patterns without external support.

There were a total of six conditions that were the combinations of implementation (mechanical and visual) and frequency (at every 2, 8, or 32 strides) (Fig. 5-1B). For the mechanical perturbations, the treadmill shifted 0.3 cm side-to-side at loading response every 2, 8, or 32 strides, depending on the condition. To create a visual perturbation, we projected a visual scene of walking along a path on a projector placed in front of the participant (Fig. 5-1B). For the visual perturbations, the visual scene on the projector screen shifted 0.3 cm side-to-side at loading response every 2, 8, or 32 strides. The mechanical and visual perturbations took the same amount of time and shifted with the same velocity. All conditions started with 80 strides of self-paced walking with no perturbations (pre), followed by 400 strides during which the mechanical/visual perturbations were introduced at every 2, 8, or 32 strides (perturbation/pert), and ended with 80 strides of self-paced walking with no perturbations (post).

Analysis

We analyzed the data with a custom MATLAB (Mathworks, Inc.) script. First, we resampled the treadmill data from 333 Hz to 240Hz to match the motion capture data and applied a low-pass filter (zero-lag fourth-order Butterworth filter at 6 Hz) to both data sets. Left and right heel strikes were identified as the most anterior position of the calcaneus markers and left and right toe-offs as the most posterior position of the second metatarsal head markers. We calculated walking speed as the sum of the approximate center of mass velocity and treadmill belt speed. The approximate center of mass velocity was calculated as the derivative of the average position of the four pelvis markers.

Statistics

We used general linear models with repeated measures (SPSS; IBM Corporation) for all metrics to determine if walking with mechanical or visual perturbations results in differences in walking speed. We performed a 1x3 repeated measures ANOVA for mechanical and visual perturbations with conditions as our within-subjects variables. A Shapiro-Wilk test and Mauchly's test validated the assumptions of the repeated measures ANOVA. If there was a significant main effect ($p<0.05$), then post-hoc pair-wise Tukey's Honest Significant Difference tests adjusted for multiple comparisons (Dunn-Bonferroni correction) were conducted to identify which conditions were significantly different ($p<0.05$). To test if there was a difference between visual or mechanical perturbations, a t-test was calculated to compare each frequency for mechanical to visual with alpha set to < 0.05 for a significant difference.

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Results

All significant differences reported have repeated measures ANOVA or a t-test p-value of < 0.05.

Walking speeds during the perturbation period of the mechanical conditions had significantly greater walking speeds for 1:2 M and 1:8 M compared to 1:32 M (Fig. 5-2). After the perturbations were removed, during the post period, walking speeds remained slower for 1:32 M (Fig. 5-2). For all of the mechanical perturbation conditions, the relative change in speed between pre to pert significantly increased and the relative change between pert to post remained similar (Fig. 5-2).

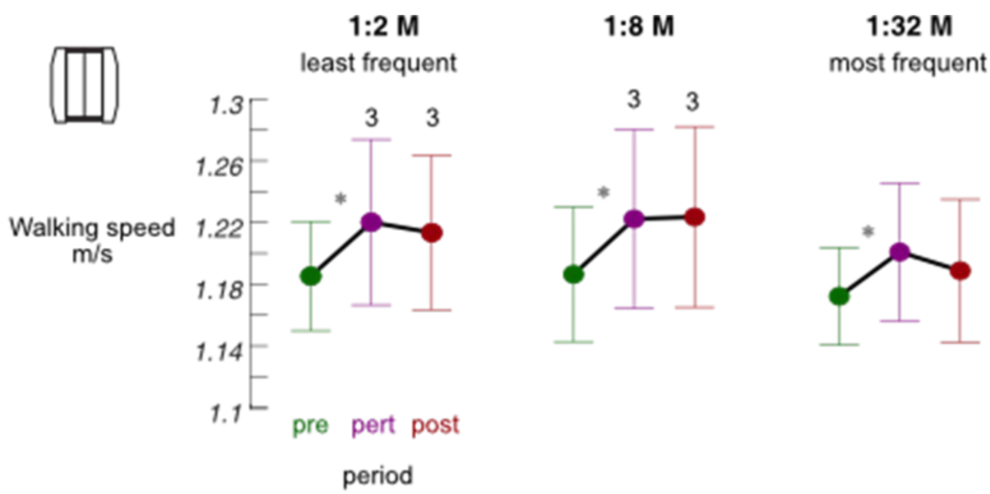

Figure 5-2: Average walking speeds for pre-perturbations (pre), perturbations (pert), and post-perturbations (post) phases during the mechanical perturbation conditions at every 2 (1:2 M), 8 (1:8 M), and 32 (1:32 M) strides. The numbers above the phases in each condition represent significant differences between conditions. The asterisks above the condition order represents significant differences between two phases of the same condition. Walking speeds during the perturbation (pert) phase of conditions 1:2 M and 1:8 M were greater than the perturbation (pert) walking speed of 1:32 M.

When walking with visual perturbations, participants maintained similar walking speeds for pre, pert, and post periods compared to each condition (Fig. 5-3). Within each condition, pre-perturbation walking speeds for all visual perturbation conditions were significantly slower compared to the perturbation period (Fig. 5-3). Comparing the perturbation period to the post-perturbation period, walking speeds remained similar once the perturbations were removed (Fig. 5-3).

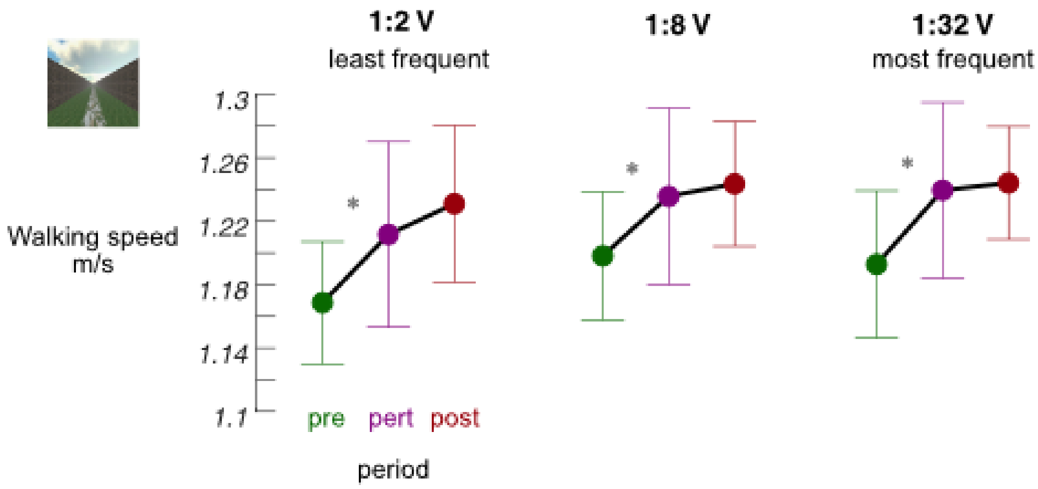

Figure 5-3: Average walking speeds for pre-perturbations (pre), perturbations (pert), and post-perturbations (post) phases during the visual perturbation conditions at every 2 (1:2 M), 8 (1:8 M), and 32 (1:32 M) strides. The asterisks above the condition order represents significant differences between two phases of the same condition. Walking speeds during the perturbation phase was significantly greater than the pre-perturbation phase.

Comparing walking with mechanical to visual perturbations, the 1:2 and 1:8 perturbation frequency conditions were similar for all periods (Fig. 5-4). The conditions with perturbations at every 32 strides, 1:32 M and 1:32 V, had differences in the perturbation and post-perturbation periods (Fig. 5-4). The perturbation period for the 1:32 mechanical condition was significantly slower than the 1:32 visual condition (Fig. 5-4). Once the perturbations were removed, in the post-perturbation period, the walking speed for the 1:32 mechanical perturbations remained significantly slower than the post-perturbation period for 1:32 visual perturbations condition (Fig. 5-4).

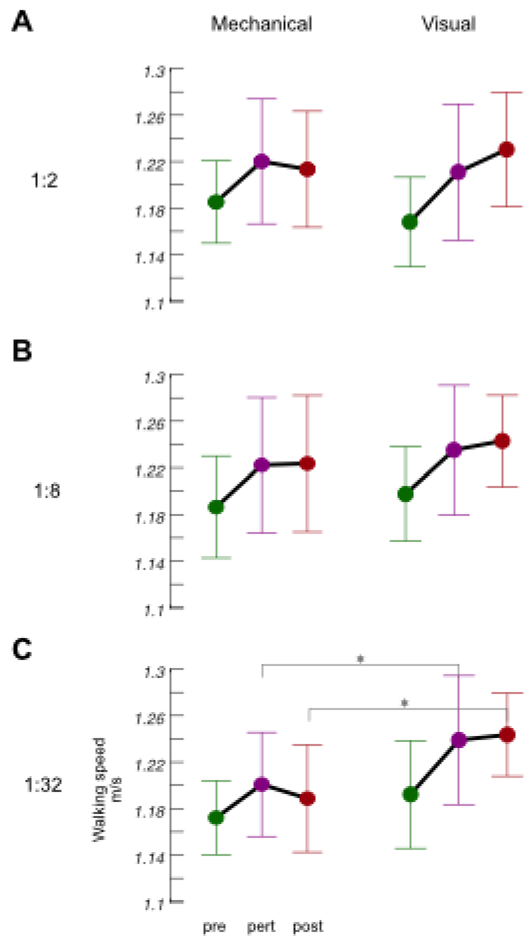

Figure 5-4: Average walking speeds for pre-perturbations (pre), perturbations (pert), and post-perturbations (post) phases during mechanical (left columb) and visual (right col perturbation conditions at **A)** 2 (1:2 M), **B)** 8 (1:8 M), and **C)** 32 (1:32 M) strides. The brackets with asterisks above the phases in each condition represent significant differences between mechanical and visual perturbation conditions at a specific frequency.

Discussion

We evaluated changes in walking speed when walking with visual and mechanical discrete mediolateral perturbations. We hypothesized that visual perturbations would result in a decrease in walking speed compared to mechanical perturbations. We found that walking speed actually increased when walking with visual discrete mediolateral perturbations at every 32 strides compared to mechanical perturbations, which challenges our hypothesis. We also hypothesized that walking speed will decrease as perturbation frequency decreases. We compared mechanical perturbations at different frequencies and found that participants walked slower with perturbations every 32 strides, compared at every 2 (1:2 M) and 8 (1:8 M) strides. For the visual perturbations, walking speeds remained similar for all frequencies, partially disagreeing with our hypothesis. Our study shows that changing perturbation implementation affects a participant's self-selected walking speed, but still increases their walking speed compared to pre-perturbations. These findings suggest that visual and mechanical perturbations could be used to increase walking speeds in populations with high fall-risk.

Participants walked faster when experiencing discrete mediolateral perturbations, regardless of implementation (visual/mechanical). People tend to rely on the visual field if their vestibular and proprioceptive senses are compromised, also known as visual field dependence. An increase in visual field dependence has been associated with aging, as well as, decreases in walking speed when disturbing their optical flow (Jönsson et al. 2004; Barr et al. 2016). Studies perturbating visual scenes on a self-paced treadmills have found a decrease (Shelton et al. 2022) and no changes (Hak et al. 2012; Hak, Houdijk, et al. 2013) in walking speed compared to walking with no perturbations. However, these studies had a continuous visual perturbation where the virtual scene moved throughout the entirety of the condition without stopping. In our study, we used discrete visual perturbations and found that walking speeds increased compared to per-perturbations, for all frequencies. These results suggest that for visual perturbations, implementation has a greater impact on a participants walking speed compared to changes in the frequency of the same perturbation.

Visual feedback is associated with maintaining walking speed and active foot placement while walking (Selgrade et al. 2020; Barton, Matthis, and Fajen 2019). The way people process the visual field and optic flow around them can be indicative of certain medical diseases such as multiple sclerosis, where people have balance deficits when navigating through different environments (Kujala et al. 1994), and a greater reliance on visual feedback has also been linked to increasing age (Franz et al. 2015). Yet, even young adults with no medical diseases rely on visual feedback and adjust their gait accordingly. People tend to modulate to the optic flow of an environment and match their walking speed to the velocity of the moving visual environment (Konczak 1994; Takamuku and Gomi 2021). When the optic flow is continuously changing speeds or rotating, known as optical flow perturbations or visual perturbations, people become more unstable (Franz et al. 2015; J. T. Richards et al. 2019;

Shelton et al. 2022). A study that allowed participants to change their walking speed in response to continuous visual perturbations found a decrease in walking speed (Shelton et al. 2022). Our study, which had discrete visual perturbations, resulted in participants walking faster compared to without perturbations. These findings suggest that people respond differently to changes in visual perturbation structure, with a continuous structure possibly being more destabilizing due to the decreases in walking speed.

Adding sensory feedback as people walk increases cognitive demands which could affect walking speeds. Studies that evaluated short-term and long-term decreases in cognitive or executive function found an increase in fall risk (Muir, Gopaul, and Montero Odasso 2012; Amboni, Barone, and Hausdorff 2013). Walking with random visual perturbations could have had greater cognitive demands compared to random mechanical perturbations, which could explain the slower walking speeds when comparing 1:32 mechanical to 1:32 visual.

Decreasing the frequency of mechanical discrete mediolateral perturbations slows walking speeds compared to more frequent perturbations. In our previous study, we found that participants had faster walking speeds when walking with discrete mediolateral perturbations at every other stride, regardless of unpredictability (Castano, Lee, and Huang 2022). For our unpredictability paradigm, we adjusted the magnitude and timing of the perturbation within a gait cycle, such as loading response and terminal stance. Here, the differences in timings between perturbations took longer. The difference in time during perturbations at every 2 strides and 8 strides is ~6 seconds, whereas experiencing perturbations at loading response instead of terminal stance is a ~0.3 second difference. Therefore, these results suggest that varying when in the gait cycle a discrete mediolateral perturbation is introduced does not impact walking speed compared to the amount of time elapsed since the previous perturbation.

In summary, visual discrete mediolateral perturbations at every 32 strides led to faster walking speeds compared to mechanical perturbations. All visual and mechanical perturbation conditions had faster walking speeds once the perturbations were introduced and remained similar once the perturbations were removed. Within the mechanical perturbation conditions, walking speed decreased when perturbations occurred every 32 strides compared to every 2 and 8 strides. Within the visual perturbation conditions, there were no differences in walking speeds between periods. Overall, our findings provide further insight into balance control strategies when controlling for implementation and frequency in disruptive environments. These results suggest that depending on the perturbation features, visual perturbations could not only be used to challenge gait stability and decrease walking speeds, but also as a method to increase walking speeds.

APPENDIX IRB APPROVAL

UCF

UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
FWA00000351
IRB00001138Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

APPROVAL

December 10, 2019

Dear Cesar Castano:

On 12/10/2019, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	Effects of Self-paced Treadmill Controllers on Walking Dynamics
Investigator:	Cesar Castano
IRB ID:	STUDY00001180
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	• 10 Meter Walking Test.pdf, Category: Test Instruments; • email_SP_Controllers.docx, Category: Recruitment Materials; • flyer_SP_Controllers.docx, Category: Recruitment Materials; • selfpaced_walking_IRB_Protocol_revision2.docx, Category: IRB Protocol; • selfpaced_walking_IRB-Consent_revision3.pdf, Category: Consent Form; • short_ad_SP_Controllers.docx, Category: Recruitment Materials; • subject_info, Category: Survey / Questionnaire;

The IRB approved the protocol from 12/10/2019.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Adrienne Showman
Designated Reviewer

Institutional Review Board
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IRB00001138, IRB00012110
Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

UNIVERSITY OF CENTRAL FLORIDA

APPROVAL

October 27, 2021

Dear Cesar Castano:

On 10/27/2021, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	How does the predictability of perturbations influence self-paced treadmill walking?
Investigator:	Cesar Castano
IRB ID:	STUDY00003485
Funding:	Name: National Institute on Aging (NIA)
Grant ID:	
IND, IDE, or HDE:	None
Documents Reviewed:	• HRP-251- FORM - Faculty Advisor Scientific-Scholarly Review fillable form.pdf, Category: Faculty Research Approval; • flyer, Category: Recruitment Materials; • hjhuang_R01_aims_research_strategy_biblio (1).pdf, Category: Sponsor Attachment; • mmse_SPP.pdf, Category: Test Instruments; • phone survey, Category: Survey / Questionnaire; • SPP Consent, Category: Consent Form; • SPP Protocol, Category: IRB Protocol; • SPP-contactinfo.docx, Category: Survey / Questionnaire; • SPP-sppb.doc, Category: Test Instruments; • SPP-subjectinfo.docx, Category: Test Instruments

The IRB approved the protocol from 10/27/2021.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in are detailed in the manual. When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Katie Kilgore

Katie Kilgore
Designated Reviewer

UNIVERSITY OF CENTRAL FLORIDA

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Orlando, FL 32826-3246

APPROVAL

February 8, 2023

Dear Cesar Castano:

On 2/8/2023, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	How do visual and mechanical perturbations influence self-paced walking?
Investigator:	Cesar Castano
IRB ID:	STUDY00004985
Funding:	Name: National Institutes of Health (NIH), Funding Source ID: 5R01AG054621-02
Grant ID:	
IND, IDE, or HDE:	None
Documents Reviewed:	• HRP-251- FORM - Faculty Advisor Scientific-Scholarly Review fillable form.pdf, Category: Faculty Research Approval; • flyer.jpg, Category: Recruitment Materials; • HRP-502-SPVM-Consent_v4.pdf, Category: Consent Form; • HRP-503-SPVM-Protocol_v3.docx, Category: IRB Protocol; • Media consent form, Category: Survey / Questionnaire; • Qualtrics survey - contact info, Category: Other; • Qualtrics survey - SPPB, Category: Other; • Qualtrics survey - subject info, Category: Other

The IRB approved the protocol on 2/8/2023.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in is detailed in the manual. If continuing review is required and approval is not granted before the expiration date, approval of this protocol expires on that date.

Use of the stamped version of the consent form is required. To document consent, use the consent documents that were approved and stamped by the IRB. Go to the Documents tab to download them.

When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Jonathan Coker
Designated Reviewer

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