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Fluctuations in Walking Speeds and Spatiotemporal Gait Parameters When Walking on a Self-Paced Treadmill at Level, Incline, and Decline Slopes

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FLUCTUATIONS IN WALKING SPEEDS AND SPATIOTEMPORAL GAIT PARAMETERS WHEN WALKING ON A SELF-PACED TREADMILL AT LEVEL, INCLINE, AND DECLINE SLOPES

by

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ABSTRACT

On a daily basis, humans walk over a variety of terrains. Studies have shown that spatiotemporal gait parameters, such as stride length, stride frequency, stride variability, etc., change when humans walk down a decline and up an incline compared to level ground. However, these studies have been limited to using fixed speed treadmills or analyzing a small number of strides when conducted over ground. Thus, there is a need to investigate the fluctuations in spatiotemporal gait parameters of humans walking at their self-selected speed, which requires recording hundreds of strides. Here we hypothesized that subjects will walk with a slower speed and have greater stride variability on an incline or decline compared to level ground. We used a self-paced treadmill and had 7 young adults walk on three slopes (+9 degrees, incline; 0 degrees, level; -9 degrees, decline). A motion capture system was used to calculate spatiotemporal gait parameters. The results showed that subjects walked the fastest on level ground (1.15 +/- 0.17 m/s). Subjects walked more slowly during decline walking (1.06 +/- 0.14 m/s) and walked the slowest during incline walking (0.92 +/- 0.18 m/s). There was not a single steady-state speed that subjects used for all slopes. Instead, there were multiple periods when the subject was not at a steady state. Only ~60% of the strides could be classified as being at steady-state. When walking down a decline, subjects needed ~10 +/- 1 more strides to reach the first steady-state period. When walking on an incline and decline, stride length variability increased by ~1.6x (0.0014m^2 ± 0.0008m^2) and ~1.2x (0.0012m^2 ± 0.0008m^2) compared to level ground (0.0005 m^2 ± 0.0003 m^2). Stride width variability

increased by ~20.6x (0.0108m^2 ± 0.0121m^2) and ~14.2x (0.0076m^2 ± 0.0044m^2) for incline and decline slopes compared to level ground (0.0005 m^2 ± 0.0003 m^2). These results provide greater insight on the fluctuations during self-selected walking speeds subjects use on different slopes. This could have implications on balance control and fall risk during walking.

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CHAPTER 1: INTRODUCTION

Environments around the world have a variety of terrains such as having slopes at various gradients. When walking about, humans often choose to walk with a walking speed and spatiotemporal parameters such as stride length, stride width, and stride frequency that correlates with their minimum metabolic cost (Elftman, 1966; Zarrugh et al., 1974). However, a person's walking speed, spatiotemporal gait parameters, and gait variability can also be influenced by walking at different slopes, visual constraints, and dual tasks (Al-Yahya et al., 2009). Walking speeds and spatiotemporal gait parameters naturally fluctuate and demonstrate a long-term pattern when walking for long distances on level ground (Terrier, Turner, & Schutz, 2005). However, many studies are limited to a small number of strides when conducted over ground or subject to limited fluctuations in spatiotemporal parameters on fixed speed treadmills. The assessment of fluctuations in walking speeds and spatiotemporal gait parameters at different slopes with no constraints may provide insight in the control of human locomotion and in gait variability for people who are at a greater fall risk or recovering from a lower limb injury.

When walking speeds are constrained, multiple combinations of stride lengths and stride frequencies could be used to walk at that fixed speed (Donelan, Kram, & Kuo, 2002; Long & Srinivasan, 2013). On a fixed speed treadmill, stride length and stride frequency are dependent on the treadmill's speed. In general, stride length typically increases with faster speeds (Grieve & Gear, 1966). The simplest relationship among stride length, SL, stride frequency, SF, and speed, v is shown in Eq. 1.

$$v = SL \times SF \quad (1)$$

A nonlinear relationship has also been used to describe the stride length and walking speed relationship independent of stride frequency, shown in Eq. 2 (Grieve & Gear, 1966; Collins & Kuo, 2013; Ojeda, Rebula, Kuo, & Adamczyk, 2015).

$$SL = \alpha \times v^{\beta} \quad (2)$$

Here, the stride length SL of a person increases with $\alpha \times v^{\beta}$, where v is walking speed and α and β are distinct constants for each walking speed. This equation could be used to compare the relationship between stride length and walking speed in different contexts such as walking on different slopes. To detrend stride widths from speed related trends we used a linear relationship represented in Eq. 3 (Collins & Kuo, 2013). The stride width SW of a person should be constant with $(\gamma \times v) + \delta$, where v is walking speed and γ and δ are distinct constants for each walking speed.

$$SW = (\gamma \times v) + \delta \quad (3)$$

When there are no constraints, there are fluctuations in walking speed, stride length, and stride frequencies from stride to stride when walking on level ground, which leads to stride variability (Collins & Kuo, 2013; Ojeda, Rebula, Kuo, & Adamczyk, 2015). Even with constraints such as fixed speeds or fixed stride frequencies, there are fluctuations in unconstrained spatiotemporal gait parameters (Hausdorff, 2005). The resulting stride variability associated with these fluctuations may be due to several factors such as the central and peripheral nervous system or a person's body composition. Therefore, examining gait fluctuations and gait variability is important for not only understanding human locomotion, but also for assessing walking ability in rehabilitation patients and fall risk in elderly patients.

Gait analyses often begin after gait initiation and once the person has reached a “steady-state.” Subjects on a fixed speed treadmill will match the set treadmill fixed speed and will be at a steady-state speed. When studies are conducted over-ground or on a self-paced treadmill, the analyses often also assume that subjects reached steady-state. However, subjects take longer to reach a steady-state on a self-paced treadmill compared to over ground walking (Plotnik et al., 2015). On some self-paced treadmills, the position of the person on the treadmill will change depending on whether the person is walking faster or slower than the treadmill belts. The treadmill belts will accelerate (or decelerate) if the person is at the front (or back) of the treadmill because the person is walking faster (or slower) than the treadmill belt speed. This mechanism allows the treadmill to match the person’s walking speed so that the person remains in the middle of the treadmill where the belts neither accelerate or decelerate but matches the person’s current walking speed (Fig. 1A). The use of self-paced treadmills at a level slope is a reliable method for recording self-paced gait speed as long as a steady-state is met (Plotnik et al., 2015). Current self-paced treadmills can also be set to a range of fixed slopes, enabling researchers to investigate whether steady state behaviors also occur for different slopes.

Previous research comparing gait parameters at a decline and incline slopes to level treadmill do not report consistent results. Some studies report a decrease in walking speed for uphill and downhill walking compared to level ground (Kawamura, Tokuhiro, & Takechi, 1991) while other studies report an increase in walking speed (McIntosh, Beatty, Dwan, & Vickers, 2006) for uphill and downhill walking compared to level ground. A different study found no change in walking speeds at an incline along with a decrease in step length at a decline (Redfern & Di Pasquale, 1997), while another study found no difference in stride length when speeds were fixed at multiple incline slopes (Lay, Hass, & Gregor, 2006). In contrast, studies using a fixed speed treadmill and over ground walking found an increase in step time as the walking inclination increased (Fellin, Seay, Gregorczyk, & Hasselquist, 2016; Tulchin, Orendurff, & Karol, 2010). Potential explanations for these conflicting results are that the overground studies at different slopes had a limited amount of data due to the ramp lengths and that the treadmill studies at different slopes were at fixed speeds.

The purpose of this study was to investigate fluctuations in walking speed and spatiotemporal gait parameters as subjects walked on a self-paced instrumented dual belt treadmill speeds at different slopes, level (0°), decline (-9°) and incline (+9°). With this approach, we can collect a longer period of continuous data at a specific slope while allowing walking speed to fluctuate more naturally as the treadmill speed is not fixed. We hypothesized that subjects will walk with a slower speed and have greater gait variability on an incline or decline slope compared to level ground. We also expect that subjects will walk with longer stride lengths but similar step width as the slope increases from decline to incline.

CHAPTER 2: METHODOLOGY

The study consisted of 8 healthy young adults (18 - 27 years) with no musculoskeletal or neurological conditions that limited mobility. All subjects provided informed written consent, and the University of Central Florida Institutional Review Board approved the protocol and consent form. Prior to participating, all subjects performed a Mini-Mental State Examination and a Berg Balance Test to examine the subjects mental and physical conditions.

Protocol

All testing was completed in a laboratory equipped with a dual-belt, instrumented treadmill (M-gait, Motekforce Link, Amsterdam, Netherlands). Subjects began the experiment by walking over ground for 10 meters three times to measure their average walking speed. The protocol for this experiment consisted of 10 conditions lasting 5 minutes in length. All subjects stood still on the treadmill for 2 minutes before and after the 10 conditions to gather a baseline reading. A 2-minute resting period was allowed in between conditions if the subject deemed necessary. For the level ground walking trials, the dual-belt treadmill remained at level ground (0°) at varying speeds (0.50,0.75,1.00,1.25 m/s), a subject specific speed (obtained from the 10 meter over ground walk), and a self-paced walking speed. For the uphill and downhill walking trials, we used the D-Flow software programing tool that is synced with the treadmill to change the slopes (9° incline and -9° decline) of the treadmill. The incline and decline speeds were 0.75 m/s, along with a self-pace speed for both slopes. Prior to starting the conditions each participant was instructed to use the treadmill with alternating modalities to acclimate them to the environment and become familiarized with self-paced mode.

Instruments

The modular treadmill system (M-Gait) used in this experiment allows the user to control pitch, sway, left and right belt speed, and measures ground reaction forces. M-Gait is controlled by D-Flow software which provides real time system control of the treadmill. The split belt treadmill has force plates on the below both belts, allowing ground reaction force measurements.

A 22-camera motion capture system (OptiTrack) tracked 16 reflective markers on the subject's lower body placed in accordance to OptiTrack's "Conventional Lower Body" biomechanics marker set. The marker set included 4 pelvis, 2 thigh, 2 knee, 2 shank, and 6-foot markers collected at 240 Hz. Specifically, the pelvis markers were placed on the left and right anterior and posterior superior iliac processes. To track each lower limb segment the markers were placed on the lateral thighs, lateral epicondyles, lateral shanks, lateral malleoli, calcanei, and second metatarsal heads. Each participant used compression shorts to ensure an accurate trace of their lower limbs. To identify gait events the calcanei and second metatarsal heads were labeled as right heel (RHEE), right toe (RTOE), left heel (LHEE), and left toe (LTOE) markers to recognize heel strikes and toe offs. Heel strikes were defined as the peaks in the anterior-posterior axis of the RHEE and LHEE markers. Toe offs were defined as the minimum values in between heel strikes along the anterior-posterior axis. The capture volume of the motion capture system is calibrated by hand using an Optitrack wand. The area of the treadmill space has been demonstrated to have submillimeter mean accuracy at every location (Aurand, Dufour, & Marras, 2017).

Analysis

The raw data from this experiment contained marker locations, analogs from treadmill, ground reaction forces, and treadmill belt speeds. The marker locations and ground reaction forces were collected at 240Hz and the treadmill belt speeds were collected at 333Hz. Consequently, we converted the treadmill belt speed to 240Hz so we could use speed to calculate temporal parameters, such as step length and step speed.

To calculate stride length, we used the anterior/posterior coordinate locations from right heel strike to the consecutive right heel. The stride width was calculated using the medial/lateral marker locations, we computed the line of progression between two heel strikes of the same foot and took the perpendicular distance between the heel strike location of the contralateral foot (Grabiner et al., 2001).

Stride length and stride width was examined for speed related trends using Eq.2 and Eq.3, respectively. All trials in a single condition for each subject were analyzed together to obtain a single combination of the parameters (α, β and γ, δ). The data was decomposed into speed-dependent (speed-trend) and speed-independent (detrended) components. Stride variance was used to quantify stride length variability and stride width variability; if the separate components (speed-trend and detrended) are uncorrelated, the components will sum linearly to equal total variance (Collins & Kuo, 2013). To yield the separate components, we subtracted the actual stride length and width from the speed-trend to equal the detrended stride parameters.

Steady-state was defined as the moment subjects maintained a steady-speed for at least 6 strides (Lindemann et al., 2008). Individual subject stride speeds were analyzed using a 6-stride standard deviation rolling window through all the condition; we determined that 6 strides give a valid representation of steady-state walking. The median standard deviation -25% was used as the metric to deem if strides were at a steady-state, everything under that value was said to be at steady-state.

Statistical tests were performed to test for differences in the spatiotemporal parameters at different slopes. We used a repeated measures ANOVA to test for a significant effect on walking speed vs slopes, followed by a t-test to compare each factor. The threshold for significance was set to $P<0.05$.

CHAPTER 3: RESULTS

When subjects walked on at a fixed speed there were less fluctuations in their speed and stride length compared to the selfpaced conditions (Fig. 1). In contrast,

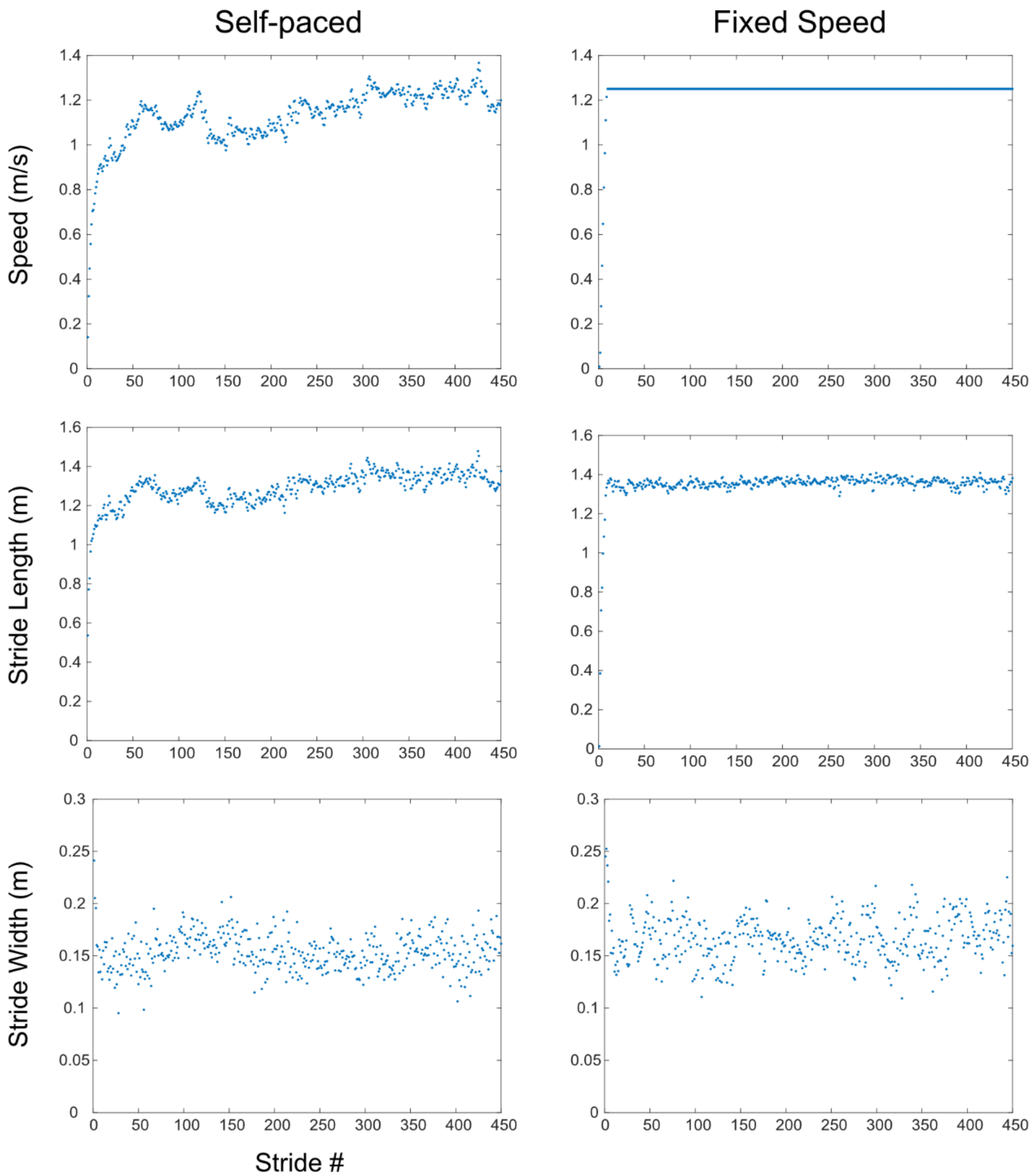

Figure 1: Comparison on the effect self-paced and fixed speed treadmill modalities have on fluctuations in speed, stride length, and stride width for a representative subject

stride width did not appear to be drastically affected by the modality; there are fluctuations in both selfpaced and fixed speed conditions (Fig.1).

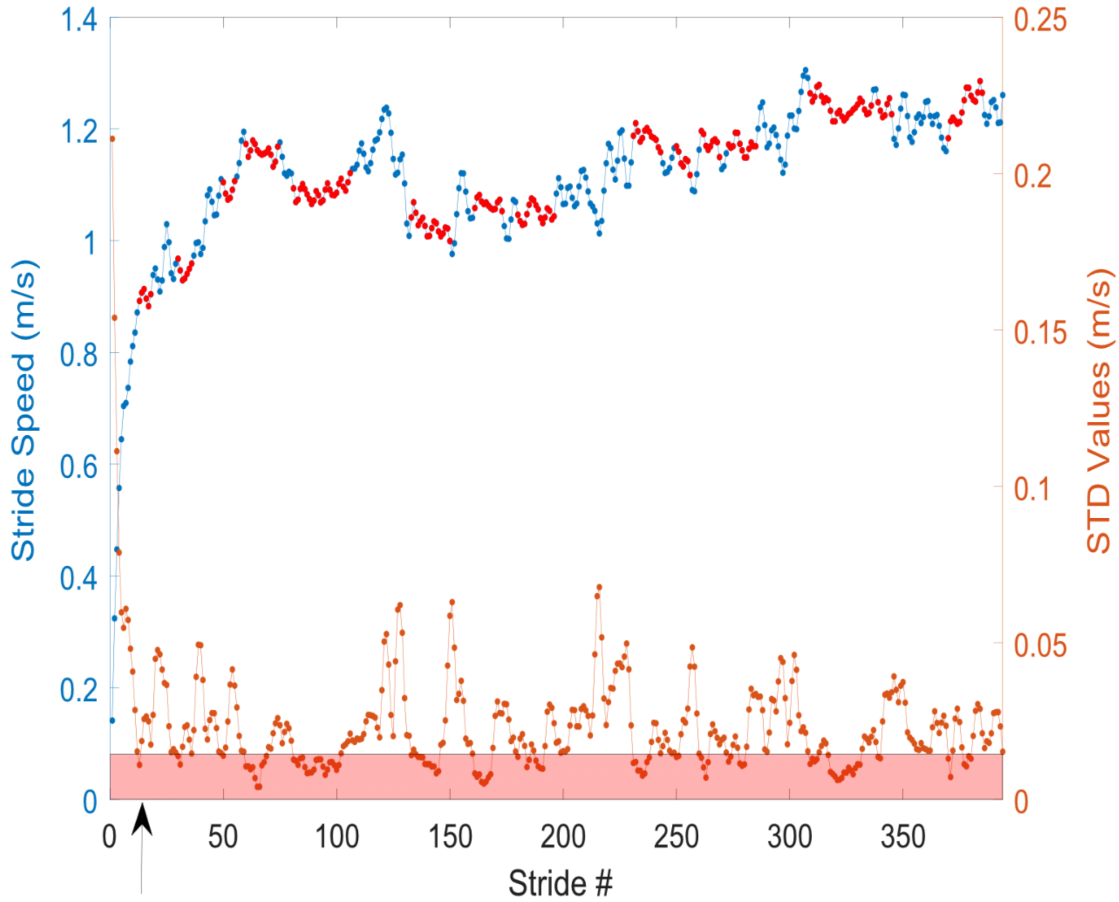

Figure 2: Stride speed and the standard deviation of strides with a first steady-state stride shown by black arrow.

The fluctuations in walking speeds during the self-paced conditions resulted in subjects entering and leaving steady-state speeds (Fig. 2). The representative subject reached their first steady-state stride on stride #12. The strides below -25% of the median standard deviation for all the strides (region shaded in red) indicates the subject was at steady-state; the corresponding stride speeds were marked red if those strides were at a steady-state.

A greater number of strides were needed to reach a steady-state at a declined slope (~25) compared to incline (~16) and level (~15) (Fig. 3A). On an incline and level slope the number of strides needed were ~10 $\pm$1 less than walking down a decline (Fig. 3A). Subject "Y2" took longer to reach a steady-state throughout all the slopes but exhibited a similar trend to the other subjects (Fig. 3A). After subjects reached their first steady-state stride, they exhibited ~60% steady-state strides for all slopes (Fig. 3B).

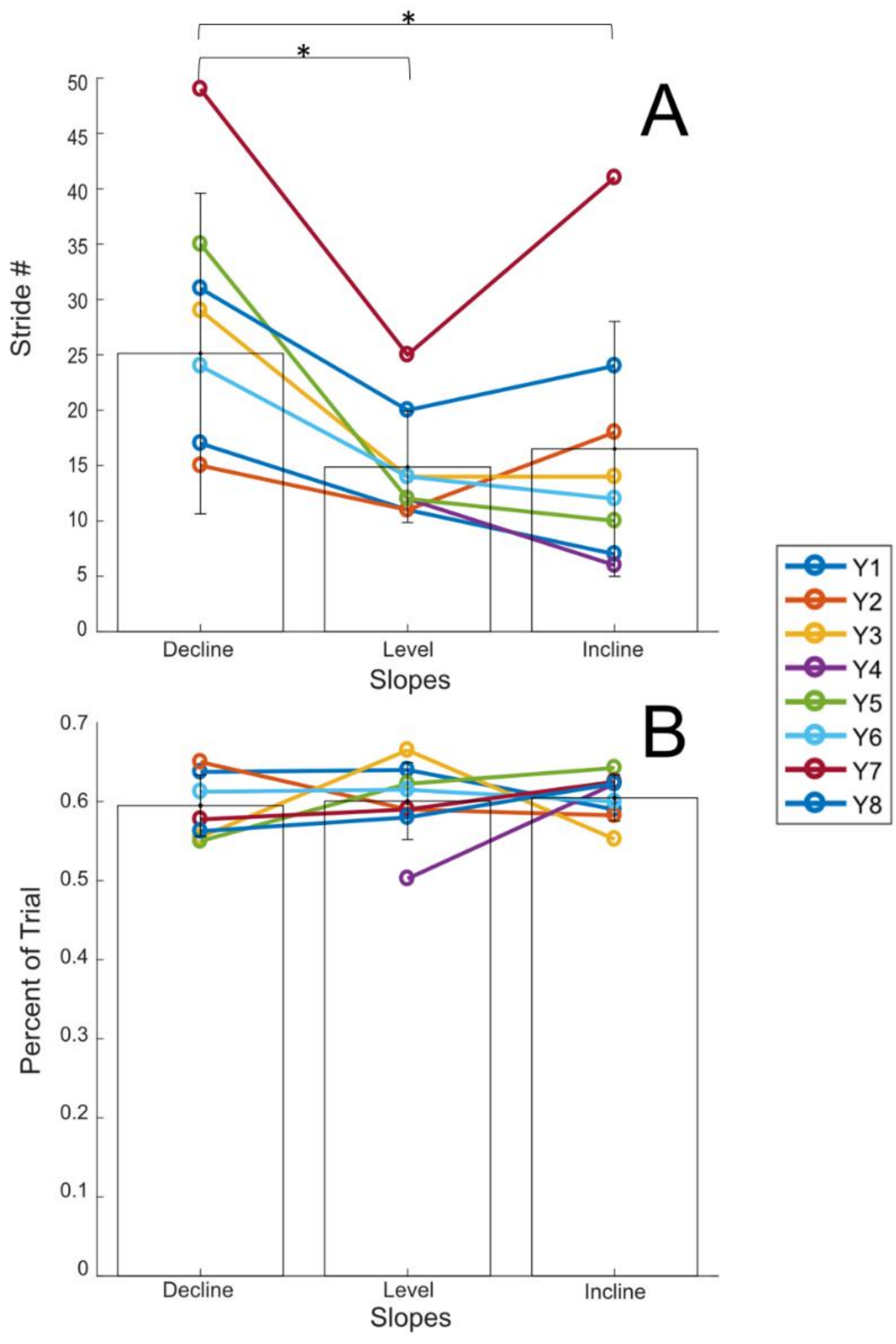

Figure 3: 3A: Number of strides needed to reach first steady-state stride for each slope.3B: Percentage of strides at steady state for each slope.

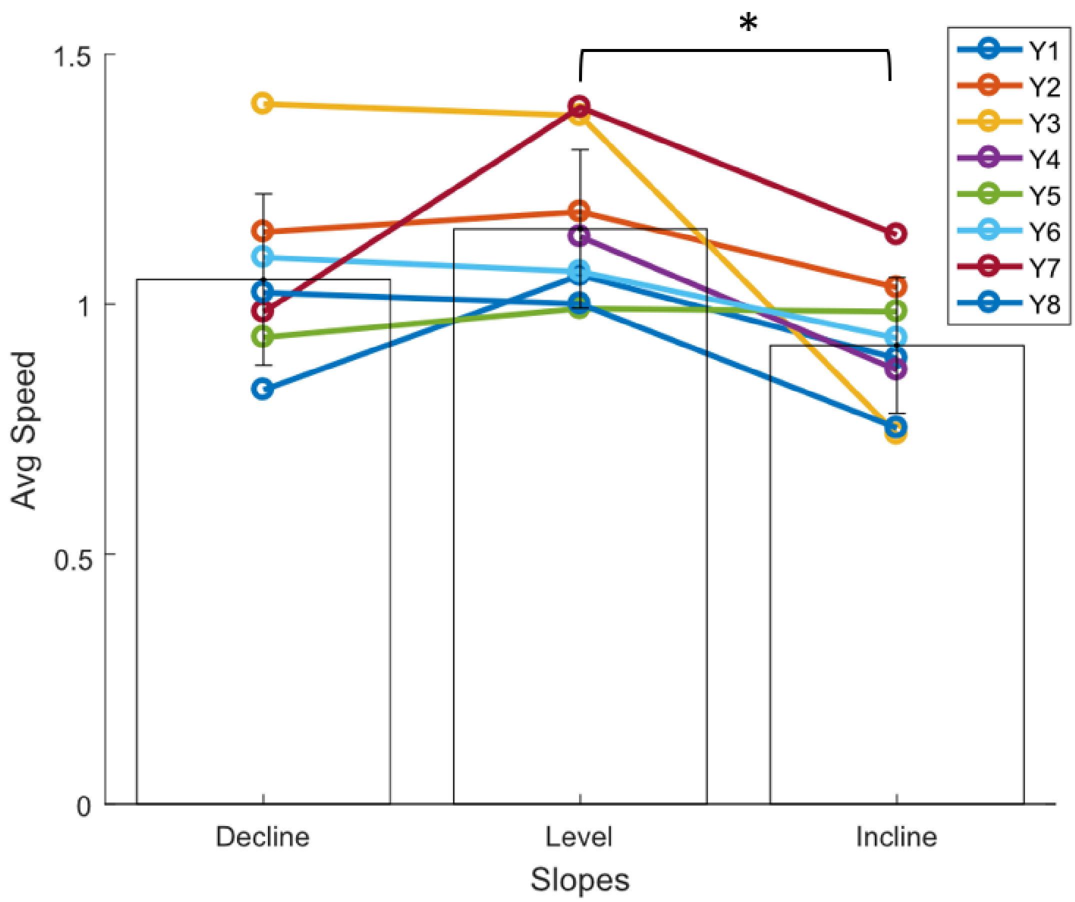

Figure 4: Average speed reached after first steady-state stride at each slope

Subjects did not maintain the same average walking speed after they reached steady-state for all slopes (P = 0.0251) (Fig. 4). The average walking speed at an inclined slope (0.92 +/- 0.18 m/s) was significantly slower than the average walking speed at level ground (1.15 +/- 0.17 m/s) (P = 0.0091). There was no significant difference in walking speeds when subjects walked at a decline (1.06 +/- 0.14 m/s) compared to the other slopes.

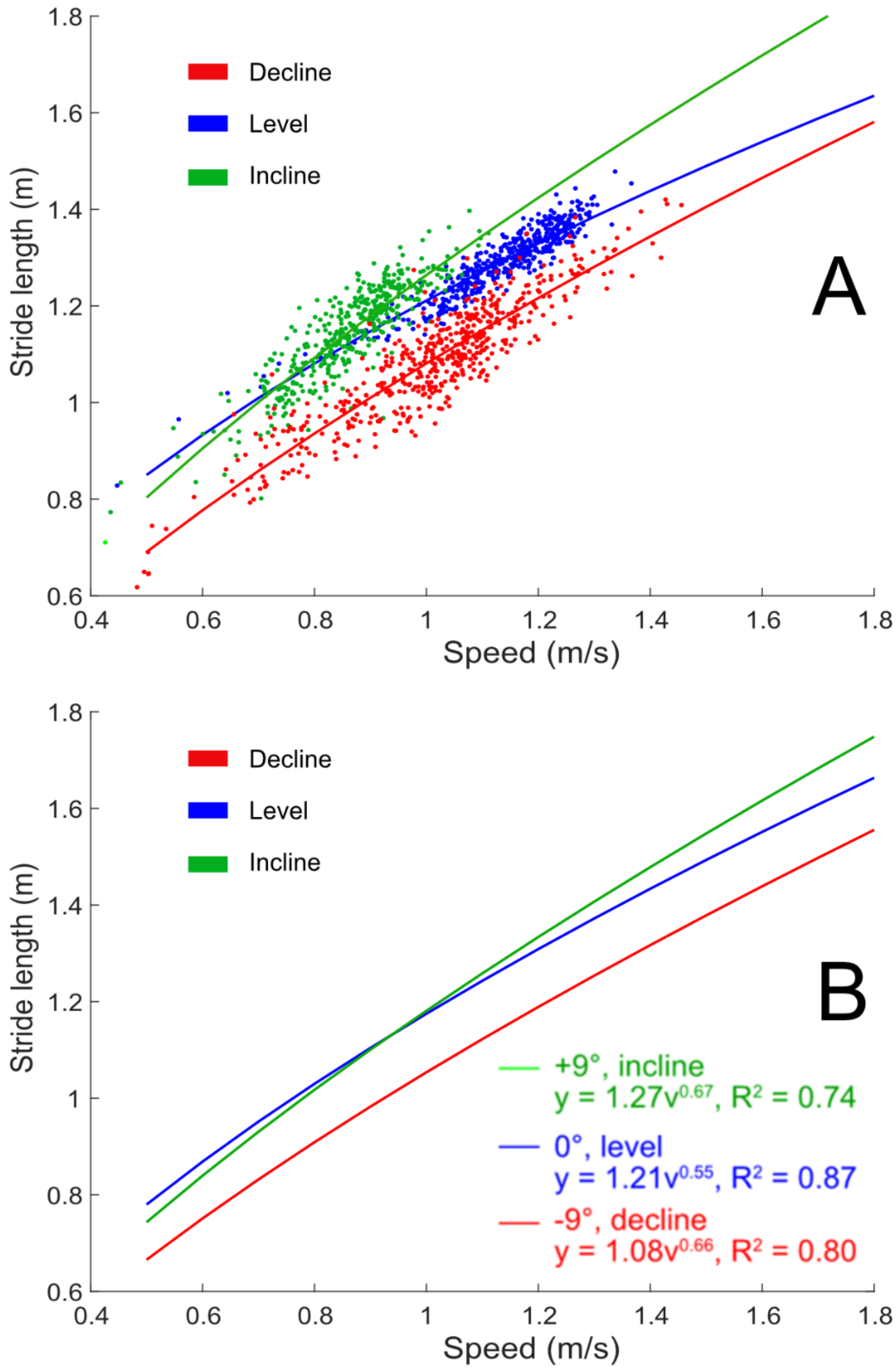

Figure 5: (A) Stride length and speed relationship for a representative subject at all slopes. (B) Average stride length and speed relationship for all subjects at all slopes.

Subjects had longer stride lengths on a self-paced treadmill at a decline slope compared to incline and level ground, no difference in stride lengths were found comparing incline and level ground (Fig.5B). The stride lengths for all the slopes increased as the walking speeds increased. The stride lengths had a greater speed related trend than stride widths (Fig.6A, Fig.7A). Once we detrended the stride length variability from the walking speeds subjects had an ~1.6x (0.0014 m^2 ± 0.0008 m^2) and ~1.2x (0.0012 m^2± 0.0008 m^2) increase in variability at an incline and decline respectively, compared to level ground (0.0005 m^2 ± 0.0003 m^2) (Fig.6B). There was no speed related trend associated with stride widths (Fig.7A). Subjects had an ~14.2x (0.0108 m^2 ± 0.0121 m^2) and ~20.6x (0.0076 m^2± 0.0044 m^2) increase in variability at in incline and decline respectively, compared to level ground (0.0005 m^2 ± 0.0003 m^2) (Fig.7B). Overall there was greater stride variability in both sloped conditions compared to level ground (Fig.6B, Fig.7B).

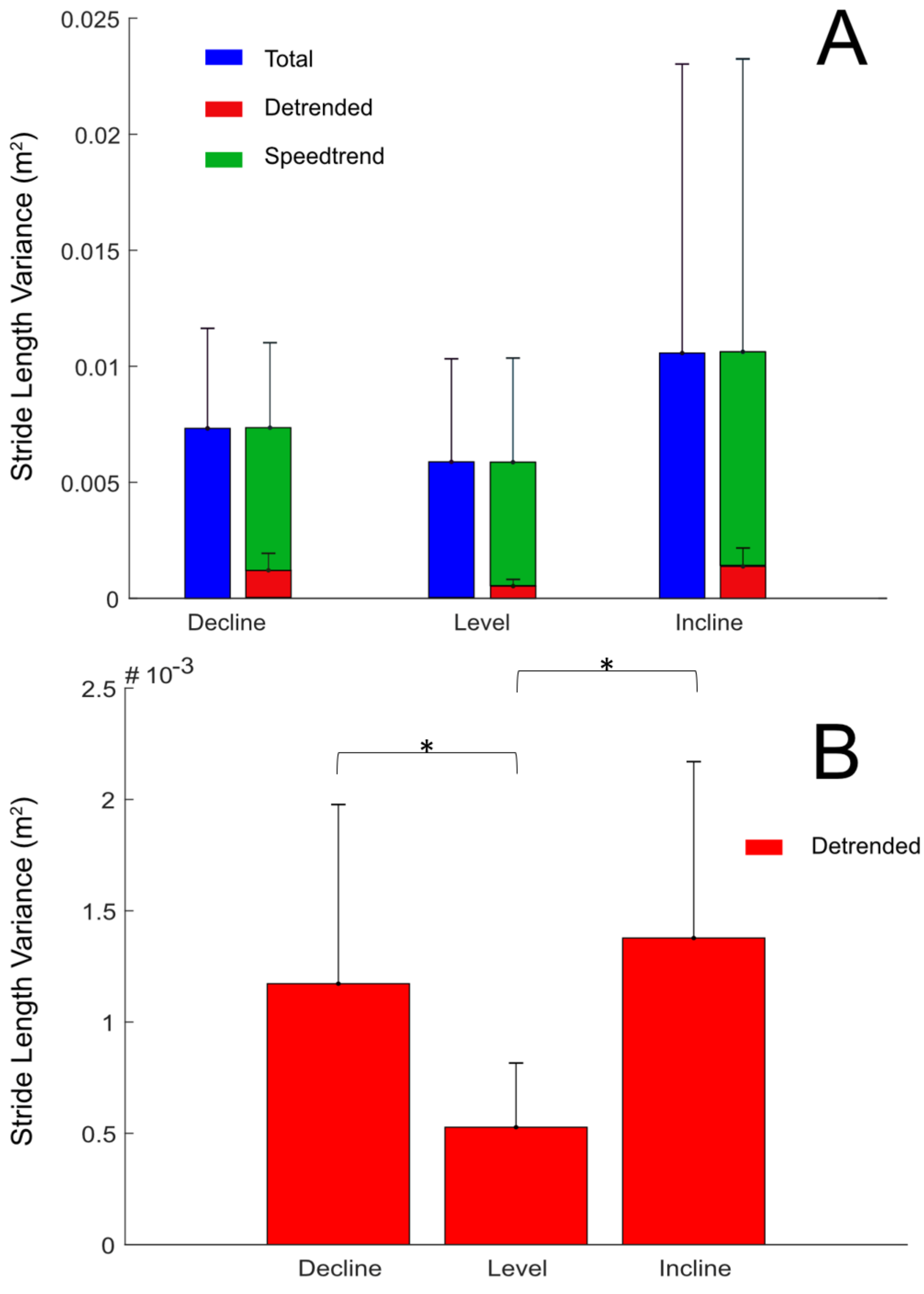

Figure 6: (A) Stride length variability represented in total variability, speed-trend, and detrended for all slopes. (B) Stride length detrended variability.

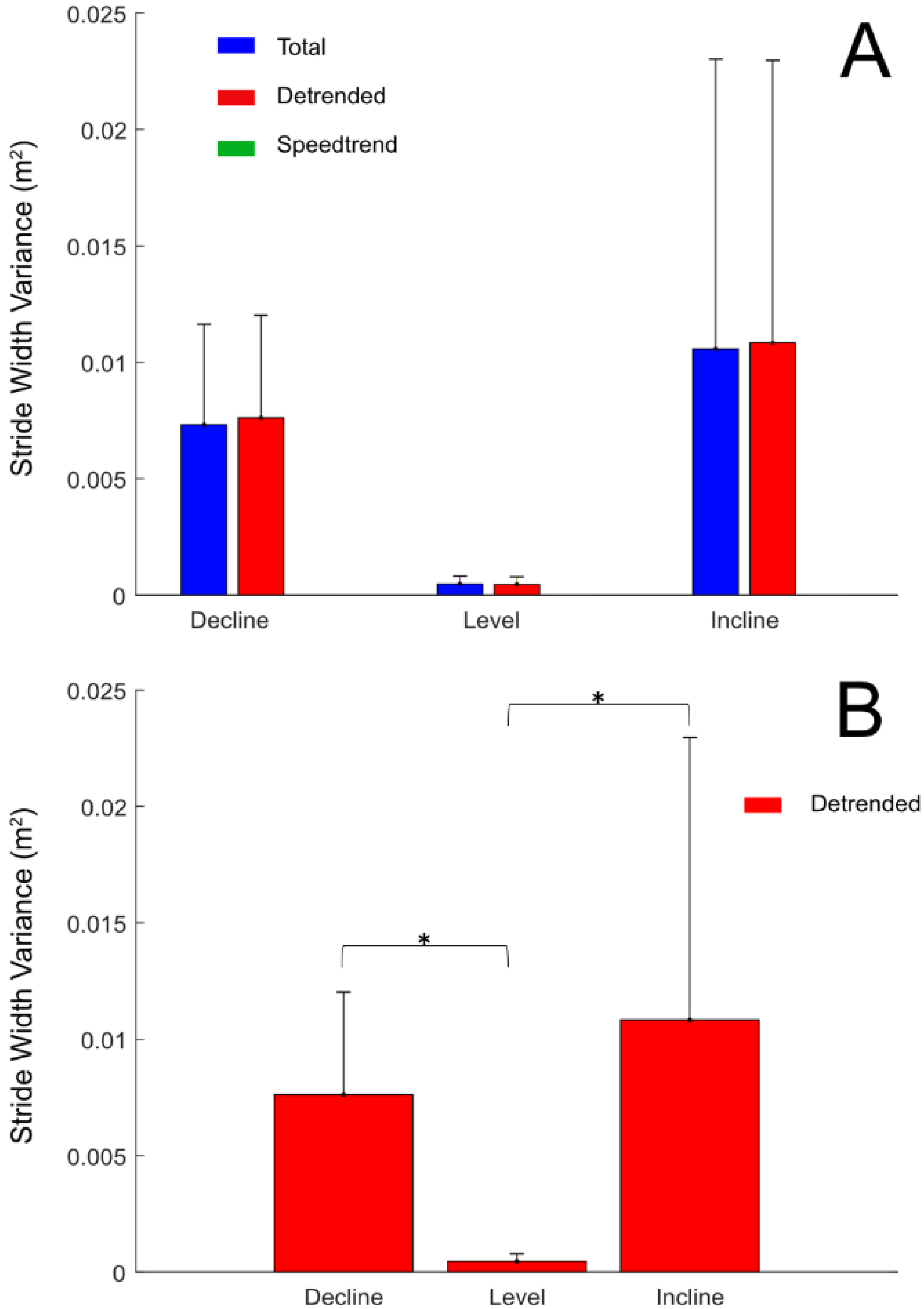

Figure 7: 7A: Stride width variability represented in total variability, speed-trend, and detrended for all slopes. 7B: Stride width detrended variability.

CHAPTER 4: DISCUSSION

We sought to investigate fluctuations during self-selected walking speeds subjects use at different slopes. Our data revealed subjects walked slowest during incline walking (0.92 ± 0.18 m/s), faster on a declined slope (1.06 ± 0.14 m/s), and the fastest at level ground (1.15 ± 0.17 m/s). Instead of converging on a single steady-state speed and remaining on that speed for the remainder of the trial, subjects had multiple steady-state speeds. Approximately only 60% of the strides could be classified as being at steady-state. When walking at a declined slope, subjects needed ~10 +/- 1 more strides to reach the first steady-state period. Subjects exhibited a ~1.6x (0.0014 m^2 ± 0.0008 m^2) and ~1.2x (0.0012 m^2± 0.0008 m^2) increase in stride length variability when walking on an incline and decline slope compared to level ground (0.0005 m^2 ± 0.0003 m^2). Additionally, there was an ~14.2x (0.0076 m^2± 0.0044 m^2) and ~20.6x (0.0108 m^2± 0.0121 m^2) increase in stride width variability for incline and decline slopes compared to level ground (0.0005 m^2 ± 0.0003 m^2).

One of the main results was that subjects did not converge on a single steady state speed when given the choice (Fig 2), which challenges the assumption that people settle on a specific walking speed. Multiple studies identify a “preferred walking speed” that minimizes metabolic cost or maximizes stability (Elftman, 1966; Zarrugh et al., 1974). However, subjects only remained at a steady-state speed for ~60% of the trail after reaching their first steady-state speed (Fig 3B). Additionally, subjects would not always settle on the same steady-state speed they first settled on. There were multiple steady-state speeds a subject converged on during a single condition. We considered several algorithms to calculate steady-state speed and regardless of the algorithm there were multiple steady-states regions in 5 minutes. Converging on a steady-state speed would only makes sense when subjects are given constraints, such as a fixed speed, stride frequency, or stride length. While previous studies have shown a long-term pattern (Terrier et al., 2005). The irregularities in stride to stride walking speed fluctuations over 5-minute interval suggest that a person's main concern deviates from that of a specific walking speed.

At a declined slope, a greatest number of strides were needed to reach a steady-state, which suggests people take a longer time finding a comfortable walking speed compared to an inclined slope and level ground (Fig. 3A). Shorter stride lengths with greater stride frequencies lead to a greater relative variability (Danion, Varraine, Bonnard, & Pailhous, 2003). We demonstrated that subjects took shorter stride lengths at a declined slope compared to an incline and level ground to reach the same speed (Fig. 5B). Therefore, if shorter stride lengths lead to greater variability it is no surprise that subjects took longer to find their first steady-state speed at a declined slope. However, once subjects reached their first steady-state stride they remained at a steady-state for the most amount of time at a declined slope. Even though studies suggest that subjects would exhibit greater variability walking at a declined slope, once subjects found their steady-state, they maintained at a steady-state longer than the rest of the slopes. Suggesting that people might have a narrower window of speeds they prefer to walk at when walking down a slope or people find it more important to maintain stability at a declined slope.

Subjects took shorter stride lengths at a declined slope compared to an inclined slope and level ground, which agrees with previous findings indicating that stride lengths at a declined slope decreases compared to inclined slopes (Lay et al., 2006)(Fig. 5B). Additionally, there were no differences in stride lengths at an inclined slope compared level ground, which challenges previous findings on a self-paced treadmill (Kimel-Naor, Gottlieb, & Plotnik, 2017). However, the difference in stride lengths could be due to the amount of time subjects were on the treadmill for each condition. Interestingly, our results display an intersection between the best fit lines at an incline and level ground. The further away the lines move from the intersection point, the greater the lines deviate away from each other. Possibly meaning that if subjects were to walk faster or slower than the speeds portrayed, there could be a difference in stride lengths at an incline compared to level ground.

Compared to level ground, incline and decline slopes show a greater detrended variability for stride length and stride width (Fig. 6B) (Fig.7B). As expected, there were no speed related trends associated with stride widths (Collins & Kuo, 2013) (Fig. 5A). The results show that walking at different slopes directly affects the gait variability, regardless of the walking speed. Increased gait variability leads to additional muscle work and a decrease in gait economy (Bajelan, Nagano, Sparrow, & Begg, 2017). Therefore, people use greater muscle work and decrease their gait economy when walking at an incline or decline compared to level ground. People who have in walking rehabilitation or at fall risk should understand that walking in terrains with steep inclines and declines will make it more difficult to maintain stability.

We found that the average walking speeds at an inclined slope were slower compared to level ground (Fig. 4), which agrees with previous slopes walking studies (Kawamura, Tokuhiro, & Takechi, 1991; Kimel-Naor, Gottlieb, & Plotnik, 2017). Additionally, even though subjects on average walked at a slower speed on an incline compared to decline, there was no significant difference. This result challenges a self-paced treadmill study that found a difference in walking speeds between and incline and decline slope(Kimel-Naor, Gottlieb, & Plotnik, 2017), but agrees with an overground study that found no walking speed difference between declined and inclined slopes (Kawamura, Tokuhiro, & Takechi, 1991). Our data supports the notion that people walk at slower speeds when walking at an inclined slope of at least 9°.

A limitation in this study is that subjects never experienced walking on a self-paced treadmill before participating. Although subjects were given time before the study started to become accustomed to the treadmill, there is still the possibility subjects were uncomfortable during the self-paced trials which could alter their spatiotemporal parameters. Another limitation is that we did not collect data at slopes in-between -9° and 9°, consequently we could only compare extreme incline and decline slopes to level ground. Given evidence that spatiotemporal gait parameters, variability, and steady-states are influenced by -9° and 9°slopes additional research is needed at varying slopes closer to level ground to help establish the impact slopes have on the human gait. Furthermore, speed fluctuations at different slopes for older adults should be investigated to study the implications different slopes could have on balance control and fall risk across all age groups.

LIST OF REFERENCES

Al-Yahya, E., Dawes, H., Collett, J., Howells, K., Izadi, H., Wade, D. T., & Cockburn, J. (2009). Gait adaptations to simultaneous cognitive and mechanical constraints. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *199*(1), 39–48.

Aurand, A. M., Dufour, J. S., & Marras, W. S. (2017). Accuracy map of an optical motion capture system with 42 or 21 cameras in a large measurement volume. *Journal of Biomechanics*, *58*, 237–240.

Bajelan, S., Nagano, H., Sparrow, T., & Begg, R. K. (2017). Effects of wide step walking on swing phase hip muscle forces and spatio-temporal gait parameters. In *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 954–957).

Collins, S. H., & Kuo, A. D. (2013). Two independent contributions to step variability during over-ground human walking. *PloS One*, *8*(8), e73597.

Danion, F., Varraine, E., Bonnard, M., & Pailhous, J. (2003). Stride variability in human gait: the effect of stride frequency and stride length. *Gait & Posture*, *18*(1), 69–77.

Donelan, J. M., Kram, R., & Kuo, A. D. (2002). Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. *The Journal of Experimental Biology*, *205*(Pt 23), 3717–3727.

Elftman, H. (1966). Biomechanics of muscle with particular application to studies of gait. *The Journal of Bone and Joint Surgery. American Volume*, *48*(2), 363–377.

Fellin, R. E., Seay, J. F., Gregorczyk, K. N., & Hasselquist, L. (2016). Spatiotemporal

Parameters are not Substantially Influenced by Load Carriage or Inclination During Treadmill and Overground Walking. *Journal of Human Kinetics*, *50*, 27–35.

Grabiner, P. C., Biswas, S. T., & Grabiner, M. D. (2001). Age-related changes in spatial and temporal gait variables. *Archives of Physical Medicine and Rehabilitation*, *82*(1), 31–35.

Grieve, D. W., & Gear, R. J. (1966). The relationships between length of stride, step frequency, time of swing and speed of walking for children and adults. *Ergonomics*, *9*(5), 379–399.

Hausdorff, J. M. (2005). Gait variability: methods, modeling and meaning. *Journal of Neuroengineering and Rehabilitation*, *2*, 19.

Kawamura, K., Tokuhiro, A., & Takechi, H. (1991). Gait analysis of slope walking: a study on step length, stride width, time factors and deviation in the center of pressure. *Acta Medicinae Okayama*, *45*(3), 179–184.

Kimel-Naor, S., Gottlieb, A., & Plotnik, M. (2017). The effect of uphill and downhill walking on gait parameters: A self-paced treadmill study. *Journal of Biomechanics*, *60*, 142–149.

Lay, A. N., Hass, C. J., & Gregor, R. J. (2006). The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis. *Journal of Biomechanics*, *39*(9), 1621–1628.

Lindemann, U., Najafi, B., Zijlstra, W., Hauer, K., Muche, R., Becker, C., & Aminian, K. (2008). Distance to achieve steady state walking speed in frail elderly persons. *Gait & Posture*, *27*(1), 91–96.

Long, L. L., 3rd, & Srinivasan, M. (2013). Walking, running, and resting under time, distance, and average speed constraints: optimality of walk-run-rest mixtures. *Journal of the Royal Society, Interface / the Royal Society*, *10*(81), 20120980.

McIntosh, A. S., Beatty, K. T., Dwan, L. N., & Vickers, D. R. (2006). Gait dynamics on an inclined walkway. *Journal of Biomechanics*, *39*(13), 2491–2502.

Ojeda, L. V., Rebula, J. R., Kuo, A. D., & Adamczyk, P. G. (2015). Influence of contextual task constraints on preferred stride parameters and their variabilities during human walking. *Medical Engineering & Physics*, *37*(10), 929–936.

Plotnik, M., Azrad, T., Bondi, M., Bahat, Y., Gimmon, Y., Zeilig, G., … Siev-Ner, I. (2015). Self-selected gait speed--over ground versus self-paced treadmill walking, a solution for a paradox. *Journal of Neuroengineering and Rehabilitation*, *12*, 20.

Redfern, M. S., & Di Pasquale, J. (1997). Biomechanics of descending ramps. *Gait and Posture*, *6*, 119–125.

Terrier, P., Turner, V., & Schutz, Y. (2005). GPS analysis of human locomotion: further evidence for long-range correlations in stride-to-stride fluctuations of gait parameters. *Human Movement Science*, *24*(1), 97–115.

Tulchin, K., Orendurff, M., & Karol, L. (2010). The effects of surface slope on multi-segment foot kinematics in healthy adults. *Gait & Posture*, *32*(4), 446–450.

Zarrugh, M. Y., Todd, F. N., & Ralston, H. J. (1974). Optimization of energy expenditure during level walking. *European Journal of Applied Physiology and Occupational Physiology*, *33*(4), 293–306.