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Regulating Stepping During Fixed-Speed and Self-Paced Treadmill Walking

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Regulating Stepping During Fixed-Speed and Self-Paced Treadmill Walking

by

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Report

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Abstract

Regulating Stepping During Fixed-Speed and Self-Paced Treadmill Walking

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Background: Treadmill walking should closely simulate overground walking for research validation and optimal skill transfer. Traditional fixed-speed treadmill (FS) walking may not simulate natural walking because of the fixed belt speed and lack of visual cues. Self-paced (SP) treadmill walking, especially feedback controlled SP treadmill walking, enables close-to-real-time belt speed changes with users' speed changes. Different sensitivity levels of SP treadmill feedback determine how fast the treadmill respond to user's speed change. Few studies have examined the differences between FS and SP treadmill walking, or the difference between sensitivity levels of SP treadmills, and their methods were questionable because of averaging kinematics and kinetics parameters, and failing to examine directly treadmill and subjects' speed data. This study compared FS with two SP modes with variation of treadmill speed and user's speed as dependent variables.

Method: Thirteen young healthy subjects participated. Subjects walked on a motorized split-belt treadmill under FS, high sensitivity SP (SP-H) and low sensitivity SP (SP-L) conditions at normal walking speed. Root mean square error (RMSE) for subject's pelvis global speed (Vpg), pelvis speed with respect to treadmill speed (Vpt), and treadmill speed (Vtg) data were collected for all trials.

Results: Significant condition effects were found between FS and the two SP modes in all RMSE values ($p < 0.001$). The two sensitivity levels of SP had similar speed patterns. Large subject × condition interaction effects were found for all variables ($p < 0.001$). Only small subject effects were found.

Conclusions: The results of the study reveal different walking patterns between FS and SP. However, the two sensitivity levels failed to differ much. More habituation time may be needed for subjects to learn to optimally respond to the SP algorithm. Future work should include training subjects for more natural responses, applying a feed-forward algorithm, and testing the effect of optic flow on FS and SP speed variation.

Keywords: Self-paced treadmill; Fixed-speed treadmill; Feedback control algorithm; Walking

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Chapter 1: Introduction

Instrumented treadmills have many advantages in gait analysis. They require less laboratory space and fewer motion capture cameras, offer precise control of walking speed and slope, allow ground reaction force (GRF) measurement through embedded force plates, and enable investigators to collect data from multiple consecutive gait cycles. Consequently, instrumented treadmills have been increasingly used in laboratory gait evaluation protocols, as well as in training and rehabilitation.

Treadmill walking should simulate overground walking as closely as possible for research validation and optimal skill transfer in training and rehabilitation. Various studies have investigated the possible differences between treadmill walking and overground walking in kinematics and kinetics parameters, energy expenditure and muscle activity patterns among healthy young adults, elderly citizens and stroke patients. Compared with overground walking, treadmill walking has higher cadence, shorter stance time, greater hip but less knee range of motion (Straty 1983, Alton 1998, Lee 2008, Watt 2010), and decreased stride time and length (Straty 1983, Watt 2010). Treadmill walking exhibits lower braking ground reaction force at early and late stance phase (Brouwer 2009, Lee 2008, Parvataneni 2009). More metabolic costs have been reported in treadmill walking (Brouwer 2009, Parvataneni 2009), and lower EMG activity signals found in tibialis anterior and gastrocnemius during treadmill walking stance phase (Lee 2008). However, some studies reported similar kinematics (Lee 2008, Parvataneni 2009) and kinetics patterns between the two modes of walking (Riley 2007). Similar patterns also have been found in fascicle behavior in medial gastrocnemius and soleus muscles (Cronin 2013) during matched-speed treadmill and overground walking.

These contradictory findings could probably result from inadequate habituation time (less than 3 minutes (Alton 1998, Brouwer 2009, Cronin 2013, Lee 2008, Strathy 1983, Watt 2010)) provided during treadmill walking. Unskilled subjects avoid falling off the treadmill by flexing their hips more and extending their knees less, which then leads to a shorter stance phase. According to Matsas (2000), treadmill walking acclimation should occur after 4-6 minutes of habituation. In addition, the magnitude differences reported have been generally small and comparable to the normal range of gait variability. Riley (2007) found significant differences in peak hip and knee flexion and extension angles when testing among experienced treadmill users, however, the 1.5 degree difference offers little clinical importance.

Even though treadmill walking mirrors overground walking in some aspects, standard fixed speed treadmill walking may not simulate natural walking. One reason is that the pre-set fixed treadmill belt speed will affect the temporal rhythm of gait and impair normal gait variability. Significantly reduced variability has been found in ankle, knee and hip kinematics in the sagittal plane during treadmill walking (Dingwell 2001). In overground walking, individuals exhibit spontaneous walking speed variations (Kito 2006). This could be due to distraction of a secondary task (Al-Yahya 2009) and subconscious attempts to minimize energy cost (Elftman 1966). Subjects should be free to change their speed on the treadmill as the same as in overground walking. Differences in subject speed and the prescribed treadmill speed may result in an unwanted and unnatural inertial force (Christensen 1998), which affects the gait pattern. In addition, for training and rehabilitation purposes, less consciousness is involved in fixed speed walking once subjects are familiar with the speed.

Another reason for differences is the lack of similar visual patterns during walking. Since overground walking engages natural optic flow, adding virtual reality (VR) displays is more likely to simulate the real life visual sensations accompanying overground walking (Sloot 2014[2]). For treadmill training and rehabilitation, VR-based treadmill training could improve overground walking proficiency in stroke patients (Yang 2007).

Self-paced (SP) treadmills have been introduced to diminish the negative effects of fixed belt speed when simulating overground walking, by updating treadmill belt speed in close-to real-time. The intention has been to provide more natural speed variations and no speed constraints. A self-propelled treadmill is one of the SP treadmill types that requires the user's own muscle exertion to drive the treadmill belt instead of using a motor. However, this equipment can be hard to operate for elderly citizens or patients having problems generating enough muscle force. Lichtenstein (2007) found that walking speed while using a self-propelled treadmill is significantly slower than individual normal walking speed, and subjects were easily to fatigue.

Another variation of a SP treadmill is the feedback-controlled treadmill, and several implementations have been introduced so far. One approach is inertial force feedback control, which simulates the inertial force during normal walking. A force tether (or harness) is attached to user's torso and artificial pull or push inertial forces are exerted on the user based on measured belt acceleration (Christensen 1998). However, one of the drawbacks of this approach is insufficient force applied to the user, even when using a stiffer harness (Checcacci 2003). Moreover, since normal walking includes various directions of inertial force, it is more complicated to simulate natural walking with this application.

A position feedback control approach is another widely used implementation. It measures the deviation of a body segment (pelvis, head, hip etc.) with a predefined reference position (normally the center of the treadmill). The deviation serves as an input into a proportional derivative (PD) controller (Minetti 2003, Bowtell 2009, Sloot 2014, Fung 2006) or proportional-integral-derivative (PID) controller (Lichtenstein 2007), which is aimed at keeping the users position close to the reference point by accelerating or decelerating the treadmill as inconspicuously and quickly as possible (Souman 2010). Methods of finding the deviation in real time include using an ultrasonic range-finder (Minetti 2003), magnetic hip trackers (Lichtenstein 2007) and a camera motion capture system (Sloot 2014, Fung 2006).

Although SP treadmills have already been used in rehabilitation, only a handful of studies have aimed to find out how closely SP treadmill walking can simulate overground walking, and to focus on whether there are significant differences between SP treadmills and the traditional Fixed-Speed (FS) treadmills. Yoon (2012) analyzed step length, cadence and pelvis acceleration under treadmill-driven walking (TDW), self-paced user-driven walking (UDW) and overground walking (OGW), when walking under three speed. Besides using anterior–posterior pelvis motion in a feedback-controller of their user-driven treadmill, they also added a feed-forward controller with the estimated pelvis speed. They observed slightly increased cadence in UDW compared to TDW. No significant effects were reported at all velocities in between OGW, UDW and TDW. Sloot (2014) also studied temporal-spatial kinematics and kinetics gait parameters under FS and three different SP modes with varying speed gains. They used pelvis position feedback to implement the SP modes. Fifteen out of seventy parameters were significantly different when comparing SP and FS. However, they neglected those differences since the quantitative amount was clinically within normal stride variability. With similar gait patterns, they concluded SP is a suitable alternative to FS.

However, methods used in previous studies may be questionable. Since stride to stride, and step to step variations are commonly seen in human walking, simply comparing the mean of each kinematic and kinetics parameter within the whole trial would be likely to average out most possible differences. Moreover, analyzing kinematics and kinetics parameters doesn't provide any information about how subject speed and treadmill speed interact with each other during a trial. The treadmill and subject's instantaneous velocity data could better reflect the real picture.

How closely the SP treadmill can resemble natural walking is highly dependent on the control algorithm. Minetti (2003) reported a 0.42s treadmill response time. This huge time delay may not be sufficient to simulate overground walking, and could be dangerous to falls. Although Sloot (2014) reported no significant differences in between SP modes, we believe that it is likely that someone is seeking optimal parameter settings that can reproduce natural walking with faster responses and more unobtrusive acceleration and deceleration. Since different sensitivity of SP modes results in different velocity gain while adjusting its speed to the users' speed, different SP modes might reveal different effects on simulating overground walking.

In this study, we were interested in two questions:

I. Is there any difference between fixed-speed (FS) and self-paced (SP) treadmill walking?

II. Is there any difference between different SP treadmill functional modes?

Instead of kinematics and kinetics analysis, we focused on speed directly by analyzing instant treadmill speed (Vtg), subject global pelvis speed (Vpg) and subject pelvis speed relative to treadmill (Vpt). Instead of comparing parameters with a single mean for the whole trial, we focused on the root mean square error (RMSE) value for each speed variable, in order to better understand the effects of speed variations. The treadmill we used in this study is the same as that used by Sloot (2014), which enables FS and different sensitivity levels of SP modes. A VR system with goggles providng with optic flow is also con nected to treadmill speed. Subjects were presented with three conditions while walking on a motorized treadmill: (i) fixed-speed walking at their self-selected preferred speed (FS), (ii) self-paced walking with a “low” (i.e., less responsive) sensitivity level (SP-L), and (iii) self-paced walking with a “high” (i.e., more responsive) sensitivity level (SP-H). The following hypotheses were made before being tested:

Hypothesis 1: FS treadmill walking will be different from the two SP modes.

Hypothesis 2: SP-H walking and SP-L treadmill walking will be different from each other:

RMSE differences between treadmill belt speeds and the subject speeds will be greatest during FS mode, reduced during SP-L mode, and smallest during SP-H mode. More specifically, the RMSE of treadmill belt speed will be largest at SP-H, smaller in SP-L, and nearly zero in FS, while the RMSE of subject speed will be greatest at FS, smaller in SP-L, and smallest in SP-H.

Chapter 2: Method

PARTICIPANTS

Thirteen young healthy adults (six males, seven females) participated in the study. Subjects had an average age of 21.77 (SD 2.83) years, height of 1.71 (SD 0.09) m, body mass of 65.42 (SD 16.68) kg and BMI of 22.36 (SD 5.00) kg/m^2.

PROTOCOLS

This experiment was carried out in the Biodynamics Laboratory in Bellmont Hall of the University of Texas at Austin. Approval of the study was obtained from the Institutional Review Board at the University of Texas at Austin, Austin, TX. All participants provided written consent before the study. No subjects reported any history of lower extremity injury, surgery or neurological condition that would affect their gait.

Basic anthropometric data were collected, including body height, mass, and dominant leg length. Body mass was measured on a scale. Leg length neasurements were completed with a tape measure.

Subjects walked on a motorized treadmill system that includes a virtual reality system with a cylindrical projection screen (Figure 1). For all trials in this study, the VR system simulated walking along a path through a forest with mountains in the background (Figure 1). On the sides of the walkway, virtual 2.4 m tall white posts were spaced every 3 m on both sides to increase motion parallax. The visual optic flow was set to match the treadmill speed. Subjects were instructed to focus on the end of the path in the virtual reality scene and keep their heads facing forward. To prevent falls, subjects were asked to wear a safety harness which was attached to a metal frame at the back of the instrumented treadmill. The harness did not interfere with their normal movements.

Kinematic data were collected at 120Hz using a 10-camera Vicon MX motion capture system (Oxford Metrics, Inc., Oxford, UK). Each subject was equipped with a total of twelve reflective markers. Four markers were placed on the head using a headband (left-front, right-front, left-back, and right-back). Another four markers were placed on each foot (first and fifth metatarsal heads, the lateral heel and the heel). The final four markers were placed on the right and left posterior superior iliac spine (PSIS) and right and left anterior superior iliac spine (ASIS).

Participants first completed a static trial in anatomical position for 1-2 seconds to verify all tracking markers were visible by manually labeling all markers in the Vicon system. Subjects then completed at least 5-min of warm-up walking to habituate to both fixed speed and self-paced treadmill walking. The velocity of the treadmill under the fixed speed condition was set at a constant individual normal walking speed for each subject, which was calculated based on the dominant leg length, as we have done in previous studies (McAndrew 2010, McAndrew 2011):

$$v_w = \sqrt{f_r \times g \times l}$$

where f_r is the Froude number, which was 0.16 for this study, $g = 9.8$ m/s^2 and l is the leg length for each subject measured in meters. This speed was used, as it closely approximates each subject's predicted preferred comfortable walking speed.

Subjects were then presented with three testing conditions: 1) fixed-speed walking at fixed, calculated individual normal walking speed, v_w (FS), 2) self-paced walking with a "low" (i.e., less responsive) sensitivity level (SP-L), and 3) self-paced walking with a "high" (i.e., more responsive) sensitivity level (SP-H). The sensitivity level of the self-paced mode was controlled by a PD-controller with a control mechanism that could adjust the treadmill speed according to the average position of the four pelvis markers on the treadmill. For SP–H and SP–L conditions, subjects were instructed to walk at their comfortable walking speed, and to keep the speed as constant as possible.

Two 5-min walking trials in each test condition for a total of six trials were randomly assigned to each subject after warm-up, using a Latin Square experimental design to minimize carry-over and learning effects. Subjects rested at least 30s and as long as they desired between trials to avoid fatigue. For each trial, subjects first walked at the FS, then changed to each assigned condition mode.

Figure 1 Subject walking on the system. For all conditions and trials, subjects walked on the same motorized treadmill with FS and SP modes. The same virtual reality scene was projected while subjects were walking. Vicon motion capture cameras were mounted above the screen and all around the treadmill. A harness was used for all subjects and all trials for safety protection.

DATA COLLECTION AND PROCESSING

Kinematic data were processed using Vicon Nexus and Visual-3D (C-Motion, Inc., Germantown, MD) software. Additional data analyses were performed using MATLAB (MathWorks, Inc., Natick, MA). Three sources of data were collected and processed. D-flow treadmill data recorded the real-time treadmill speed, D-flow marker data recorded instantaneous pelvis global position data and Vicon data recorded displacement data for all reflective markers relative to the global coordinates.

Since there might be slightly different time lags for processing and initiating data collection in the Motek and Vicon systems, we used cross-correlation to resample the D-flow treadmill and marker data to match the Vicon motion capture marker data. For each trial, D-flow was started two seconds before Vicon started to collect data. Cross-correlation was applied to find the same peak indicating the start of user's motion. The redundant D-flow data before motion start was then cut off, and the rest of the D-flow data was normalized to the Vicon data in the same time stream.

An initial 6 Hz 4th order zero-lag Butterworth filter was applied to eliminate instrumental noise for each of the three source of data. Instantaneous pelvis velocity relative to the global coordinates was calculated using a five-point derivative from the Vicon-recorded average pelvis position. A secondary 4th order zero-lag Butterworth low-pass filter was applied to the treadmill speed data and pelvis global velocity data at 0.5Hz and 0.1 Hz, to diminish step-to-step and stride-to-stride oscillation (Collins, 2013). Pelvis speed relative to treadmill velocity was then acquired by adding treadmill speed and pelvis global speed.

To determine the effect of regulating the fixed speed and self-paced treadmill speed, we focused on the change of the three velocity variables: instantaneous pelvis speed relative to the global coordinates (Vpg), instantaneous treadmill speed relative to the global coordinates (Vtg), and instantaneous pelvis speed relative to the treadmill (Vpt). The dependent variables analyzed included root mean square error (RMSE) values for the three velocity variables (RMSE_Vpg, RMSE_Vtg, RMSE_Vpt), which were calculated as the deviation of value at each time frame relative to the mean velocity over the trial. The formula used to calculated RMSE values was:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}}.$$

DATA ANALYSIS

Two-factor (subject × condition) repeated measures analysis of variance (ANOVA) was used to test for statistically significant differences of the each of the three RMSE values in the fixed speed, self-paced low and self-paced high conditions. Tukey and Bonferroni post–hoc tests were performed to assess the differences between individual conditions. The significance level was set at $p < 0.05$. All statistical analyses were conducted using Minitab 17 (Minitab Inc., PA).

Chapter 3: Results

For all three RMSE variables, clear and distinct differences could be seen between the FS and SP walking modes (Figure. 2). SP-H and SP-L exhibited similar RMSE values, whereas FS exhibited much lower values. RMSE_Vtg was higher than RMSE_Vpg in both high and low sensitivity levels of the SP mode, which supported our first hypothesis (Figure. 2A and Figure. 2B). Since Vpt was calculated by adding Vpg and Vtg, it is reasonable that RMSE_Vpt was the highest in the SP modes.

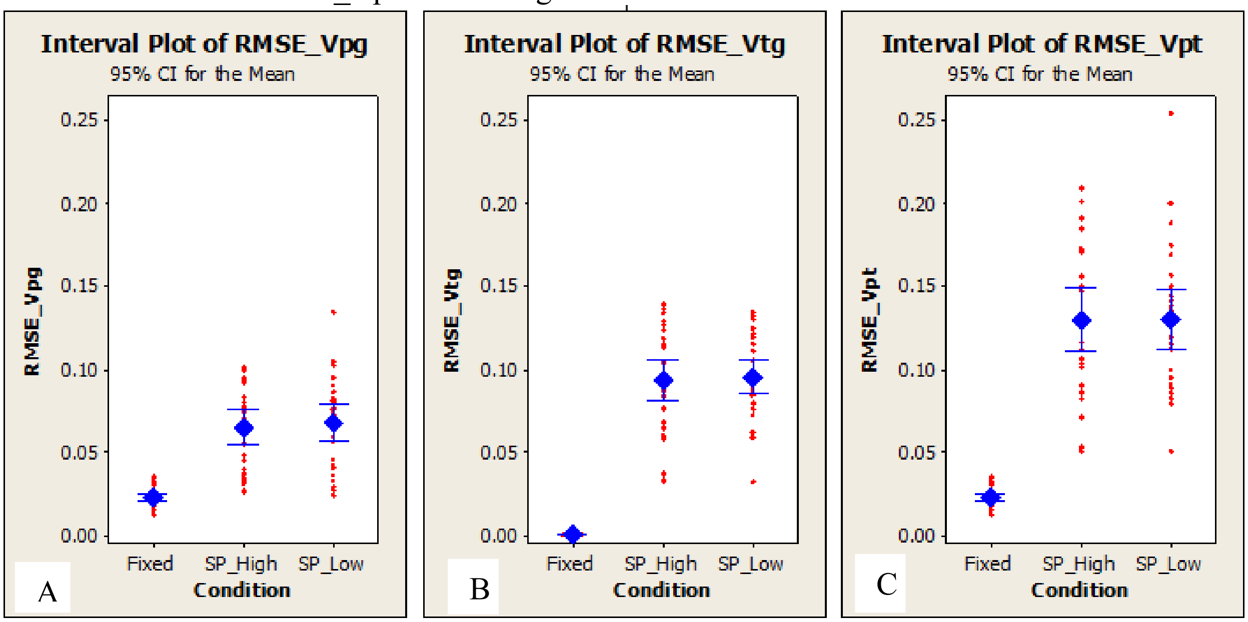

Figure 2 Interval Plots for RMSE_Vpg, RMSE_Vtg and Vpt under FS, SP-H and SP-L conditions. The confidence interval was set to 95% for each velocity mean. The blue diamonds show the mean for each variable. Error bars indicate ±95% confidence intervals for each mean. Small red dots show individual data points for each individual trial. All three graphs were scaled the same along the vertical axes to compare between variables.

Log transformation was applied to all RMSE values before ANOVA statistical tests to ensure the data met the linearity and normality assumptions of those ANOVA tests. Statistical analysis (Table 1) showed significant differences in conditions for all RMSE values (p = 0.000). Significant subject × condition interactions were also found (p<<0.001). For the subject main effect, only RMSE_Vtg showed a significant difference (p = 0.001). The other two RMSE values did not (p=0.207 and 0.704).

Table 1 Statistical analysis

p-values for RMSE

Source	RMSE_Vpg	RMSE_Vtg	RMSE_Vpt
Subject	0.207	0.001*	0.704
Condition	0.000*	0.000*	0.000*
Subject × Condition	0.000*	0.001*	0.000*

P <0.05, * significant different

Post-hoc Tukey and Bonferroni tests were conducted. The two tests revealed the same grouping information for three conditions (Table 2). FS was different from both SP modes, but high (SP-L) and low (SP-L) self-paced modes were not significantly different from each other.

Table 2 Post-hoc tests for condition differences

Group mean values and grouping information

condition	Vpg Mean	Vtg Mean	Vpt Mean	Grouping
sp-l	-2.786	-2.390	-2.096	A
sp-H	-2.822	-2.432	-2.116	A
FS	-3.812	-7.545	-3.812	B

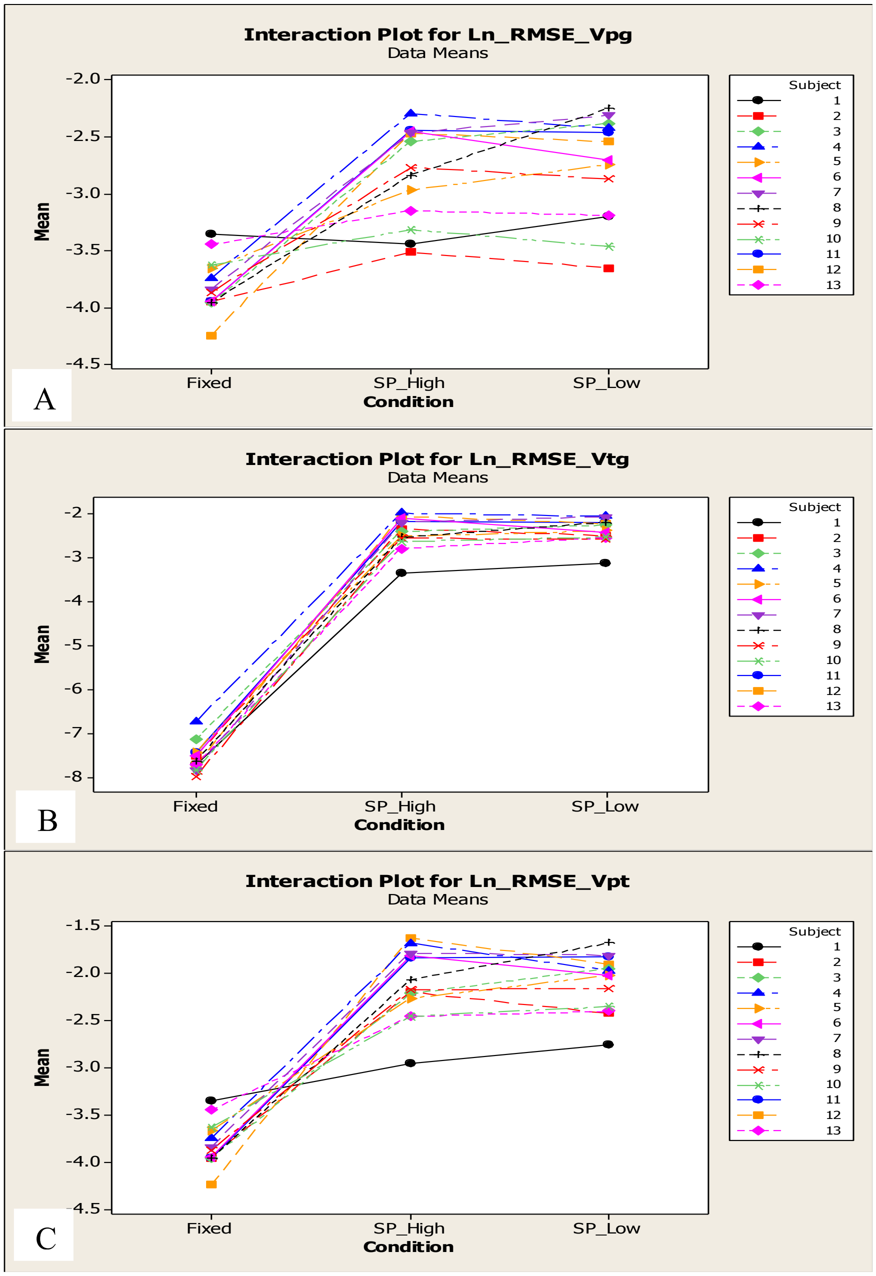

Figure 3 Subject × Condition Interaction plots for RMSE_Vpg, RMSE_Vtg, RMSE_Vpt. Each dot in an individual line represent a subject's mean score in one of the FS (Fixed), SP-H (SP_High) and SP-L (SP-Low) conditions.

Although the interaction effect was significant for all RMSE values, the interaction plots revealed a general trend reflecting the main condition effect, with only small differences between individual subjects (Figure. 3).

There were significant interaction effects in RMSE_Vpg and RMSE_Vpt according to our statistical test ($p = 0.000$), and some nonparallel lines could be seen in the interaction plots (Figure 2A and Figure 2C). Clearly, this significant interaction effect was largely affected by some subjects having inconsistent results with others (e.g., Subject 1, black line). However, since no significant difference was found in subject main effect ($p = 0.207$ and 0.704, separately), we could not conclude that large subject differences existed. Moreover, it is obvious that the data exhibited a large condition effect, and even though the interaction effect was statistically significant, it is much less relevant than the main condition effect, and also that the small differences in subjects were completely overridden by the condition effect.

Raw speed data of Vpg, Vtg and Vpt were also plotted. Low-pass filters of 0.5 Hz and 0.1 Hz were used to filter out step-to-step and stride-to-stride oscillations separately (Collins 2013).

Figure 4-6 shows data from two representative subjects that may or may not have learned to properly respond to the changes in the speed that the SP treadmill algorithm was making. In Figure 4-5, Subject 4 displayed 7-8 steps back and forth speed variation from the reference point, and the pattern is clearly detected in pelvis global speed (Vpg). Since stride-to-stride and step-to-step oscillations were already filtered out, the regular fluctuation could possibly indicate the subject's attempt to interact with the treadmill speed changes. The subject in Figure 6-7 did not have the obvious repeated back and forth pattern as the previous subject. This subject had less deviation from the reference point, as showed in Vpg. Compared with FS, Vpt exhibited more variations in SP modes, suggesting SP effectively allowed more individual change in walking speed. After filtering out the step-to-step variation (Figure 6, 0.5Hz), Vpt and Vtg shared almost the same trend of speed variation, but Vpt had an additional small oscillation within the general trend. This could be ascribable to stride–to-stride variation, since the small oscillation vanished after application of the 0.1Hz low pass filter. The differences between the two SP modes were not transparent for both subjects. Vtg had slightly greater variation in SP-H compared with SP-L (Figure 6). Our results showed 5 out of 13 subjects had the same trend as Subject 10 (Figure 6-7), while the other 8 people showed similar walking speed patterns to those of Subject 4 (Figure 4-5).

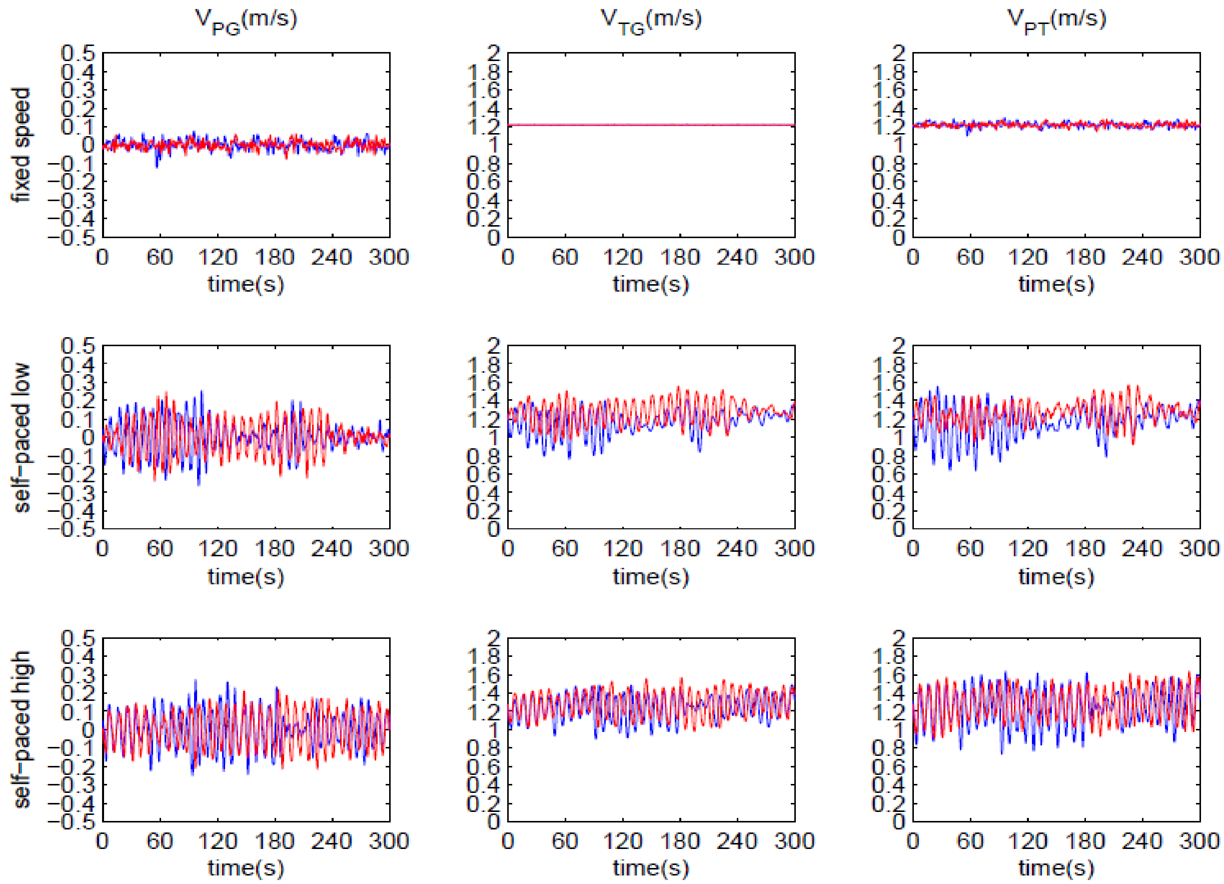

Figure 4 Treadmill and subject speed raw data plots for Subject 4, after 0.5Hz filter. This figure represents the raw speed data plots after application of a 0.5Hz low pass filter. Red and blue lines represent the two trials under each condition. Subject 4 may not fully acquire the algorithm, since after filtering out step-to-step oscillation, a repeated 7- 8 steps back and forth could still be seen.

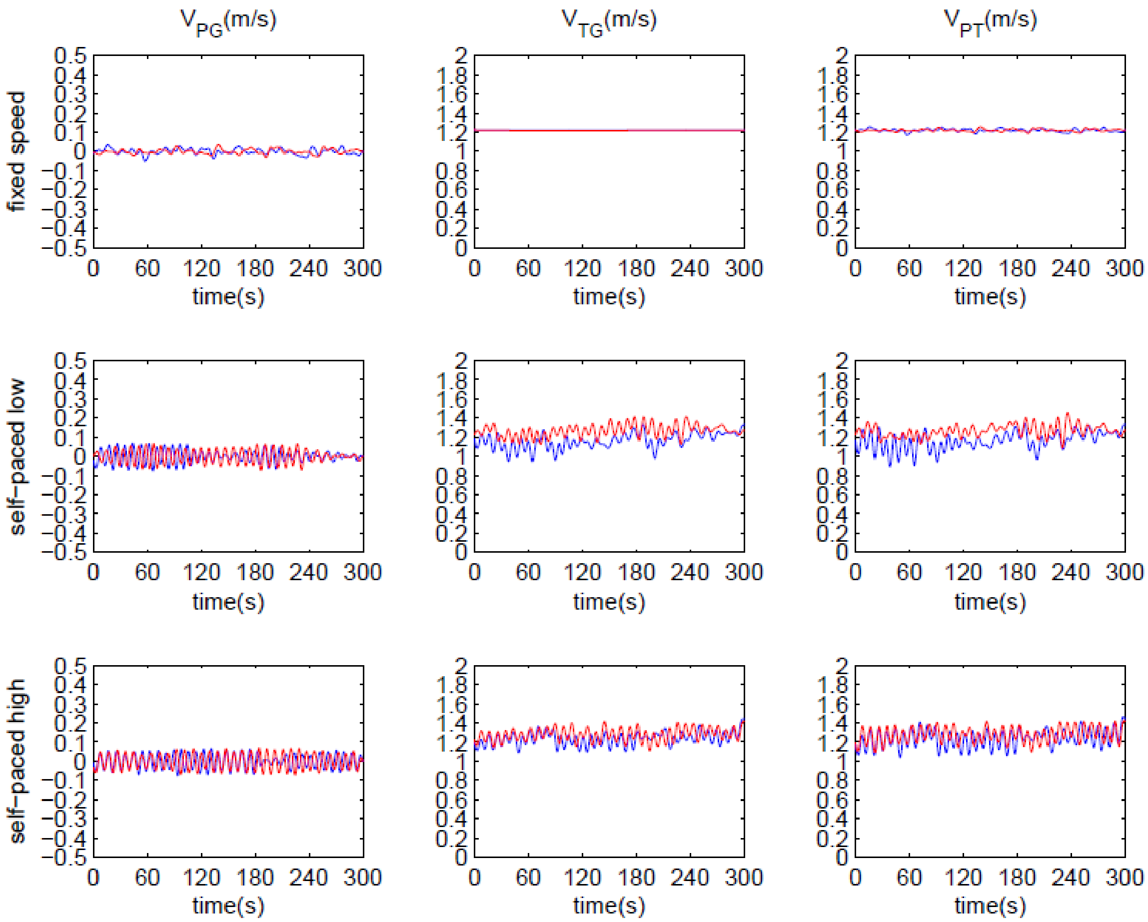

Figure 5 Treadmill and subject speed raw data plots for Subject 4, after 0.1Hz filter. This figure shows raw speed data plots after application of 0.1Hz low pass filter. Red and blue lines represent the two trials under each condition. Subject 4 may not have fully acquired the algorithm (the same subject as in Figure.3), since after filtering out stride-to-stride oscillation, a repeated pattern of 4 strides back and forth could still be seen.

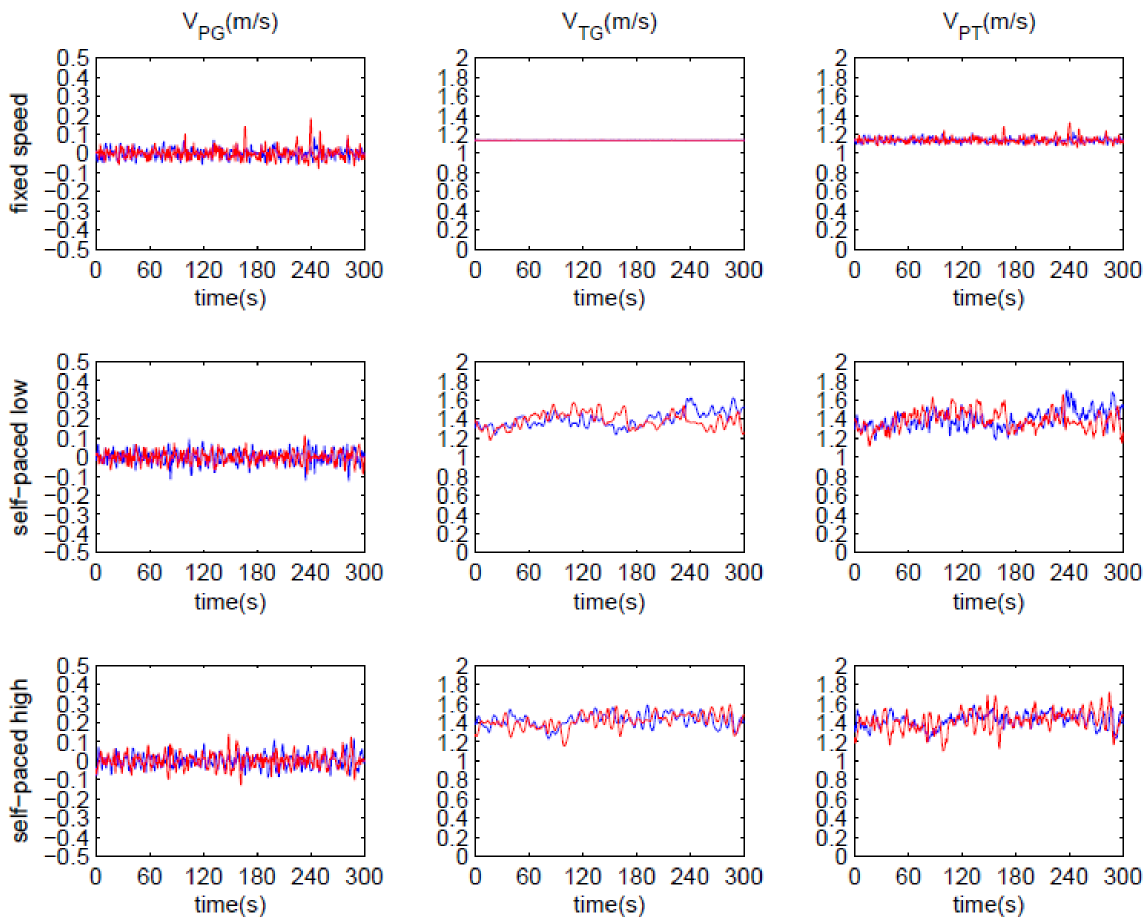

Figure 6 Treadmill and subject speed raw data plots for Subject 10, after 0.5Hz filter. This figure represent raw speed data plots after application of a 0.5Hz low pass filter. Red and blue lines represent the two trials under each condition. Subject 10 could possibly have acquire the algorithm. In self-paced high (SP-H), the subject global pelvis speed and the pelvis speed relative to treadmill showed greater variability than the self-paced low (SP-L).

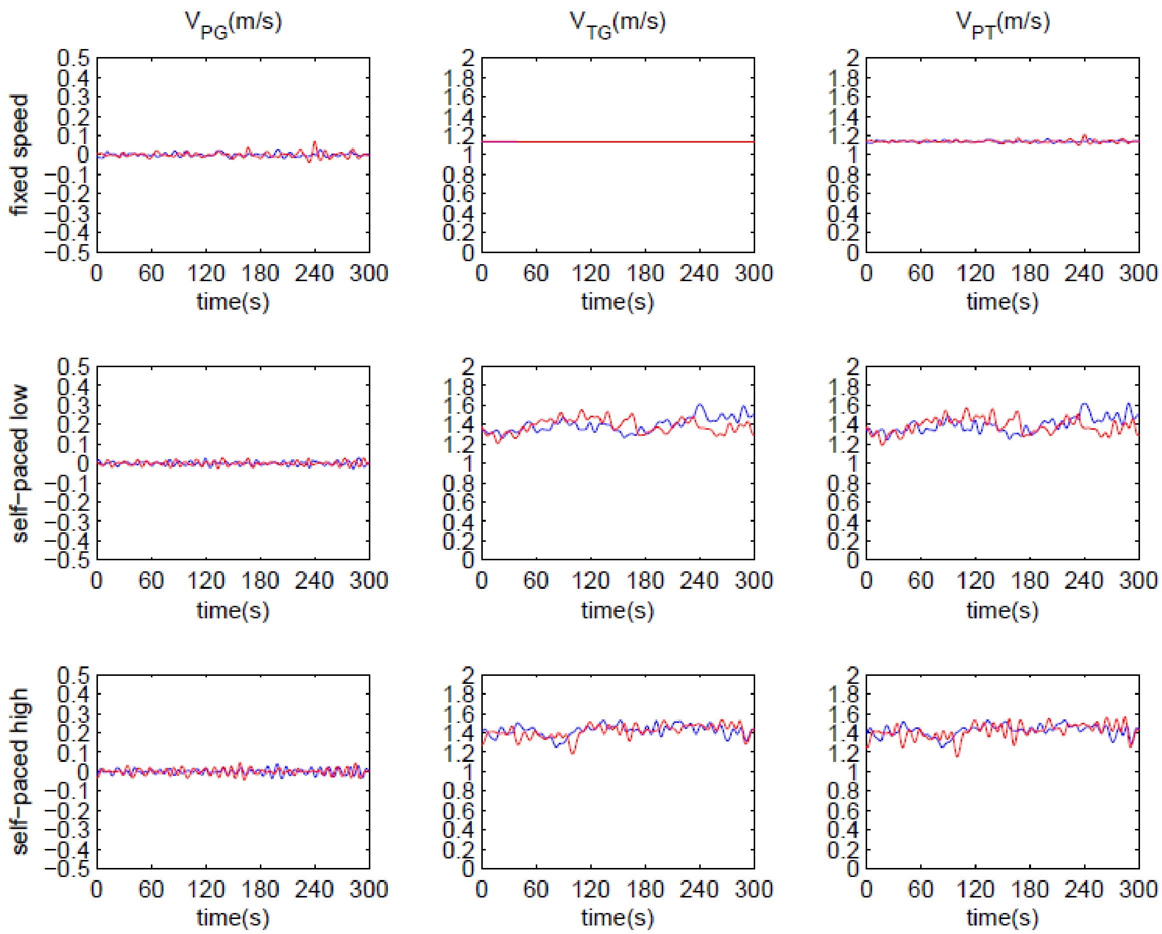

Figure 7 Treadmill and subject speed raw data plots for Subject 10, after application of a 0.5Hz filter. This figure represents raw speed data plots after application of a 0.1Hz low pass filter. Red and blue lines represent the two trials under each condition. Subject 10 (same subject in Figure 5) could possibly have acquired the algorithm. In self-paced high (SP-H), the subject global pelvis speed and the pelvis speed relative to treadmill all showed greater variability than self-paced low (SP-L).

Chapter 4: Conclusion

Our results confirmed our first hypothesis that FS is different from the two SP modes; RMSE values of the three speed variables are all significantly lower than SP modes. SP modes increased both treadmill and subjects' walking speed variations. Subjects' walking speed with respect to treadmill (Vpt) has the most variations among the three speed variables. Since the goal is to maintain the subjects' normal walking speed throughout the trial, overall performance showed that subjects may have failed to maintain their speed under SP modes. Similar RMSE values were found between the two SP modes, which did not support our second hypothesis. There was not much difference between high and low sensitivity levels of SP treadmill.

For some subjects, who had learned to properly respond to the changes in speed that the SP treadmill algorithm was making, different walking speed patterns had been developed for different conditions. Subjects demonstrated constant speed variation under FS, more smooth speed change in SP-L, and frequent little adjustments in SP-H. Both SP modes reveals similar walking speed patterns. For subjects who apparently failed to 'learn' the algorithms, there was not much alternation between conditions. These subjects had the same back and forth walking velocity patterns occurring about every 7-8 steps periodically.

Chapter 5: Discussion

By looking directly at subject speed and treadmill speed variation, instead of at raw kinematic or kinetic parameters, our results raise questions as to whether SP modes can adequately simulate overground walking or fixed speed treadmill walking (Sloot 2014). Instead of simulating overground walking, it is likely that the SP modes are a new type of walking method, just as is fixed speed treadmill walking, which requires subjects to have more skill acquisition time and to develop a new walking pattern.

SP TREADMILL ALGORITHM

In this study, SP modes were implemented by a feedback-controlled treadmill. In this context, the treadmill speed will change only after subject's average pelvis position deviates from the reference point of the treadmill (which is the center of the treadmill in this study). The pelvis position data as the treadmill speed was input would already be 'previous' data, that would inevitably result in a delayed response in treadmill speed. Minetti (2003) addressed this as "…The responsiveness, the length constraints, and the unusual situation are potentially conditioning the subjects' behavior and could influence the gait and speed choice…." Besides, if the subject should have rapidly changed speed, the suddenly increased distance from the reference point would have resulted in la arge inertial force, that would also change the subject's gait and speed (Yoon 2012). Differences in treadmill speed and subject instantaneous speed prevented subjects from maintaining their own normal walking speed. This could explain why subject walking speed variations were higher in the SP modes.

To simulate overground walking, minimizing treadmill-caused subject speed variations is the goal. Instead of using feedback, changing the control algorithm to feed-forward may help. Souman (2010) introduced a new algorithm that used subject position deviation from the reference point as an input in the feedback loop, while adding a feed-forward loop based on online speed estimation. However, some parameters still need to be adjusted, since the subjects reported a noticeable change in treadmill speed. Haiwei (2011) found strong linear correlation between walking speed and foot ground interaction force, and managed to estimate the user intended walking speed the force index. By looking into some steps forward, the feed-forward control algorithm could possibly estimate each subjects' future speed or position data, then alter the treadmill belt speed in real time. It is presumed that fthese eed-forward algorithms can provide a more natural walking experience than other SP treadmills.

SUBJECT ACCOMMODATION TO SP TREADMILL

There is some evidence in our speed data plots that subjects failed to properly respond to the SP treadmill. We did another statistical analysis and found no order effects, which suggests no overall fatigue or learning effect occurred throughout trials. The reason for this phenomenon could possibly the insufficient habituation time. Our 5 minutes habituation time was based on reports of fixed speed treadmill experiments (Matsas 2000), however, SP treadmill adaptation may require more time for subjects to walk smoothly (Minetti 2003). Future study could focus on a better training method for subjects to acquire the algorithm faster. This could be implemented by providing more feedback, such as a bar graph indicating the real-time position deviation.

SUBJECT'S WALKING SPEED

We observed a higher walking speed in SP modes than FS for all subjects. In this study, individual normal walking speed was calculated based on leg length, which may not be the 'real' walking speed. Although there is a chance that the subjects we tested were all 'fast walkers' in real life, this phenomenon could also possibly due to SP algorithms. When users were unsure of how the treadmill was going to respond, they tended to speed up so as not to drift too far backwards and to prevent falls. Another explanation is the optic flow. Optic flow can change people's feeling about their own speed, and affect subject SP walking speed. Lichtenstein (2007) found that subjects tended to underestimate the speed of a moving scene. In our study, the speed of optic flow was correlated with treadmill speed, and subjects were instructed to walk at their normal walking speed. Subjects may have felt that their walking speed was not as fast as their normal walking speed, and so with the presence of optic flow, thus tend to walk faster.

OPTIC FLOW

During the experiment, optic flow was provided for all trials. It is then hard to distinguish whether a subjects' walking was affected by optic flow. Sloot (2014[2]) studied the effect of adding VR to FS and different modes of SP treadmill. They found walking within VR results in only slightly similar gait patterns than absence of VR. However, VR × treadmill mode interaction effects were found in nearly half of the parameters they tested. Subjects exhibited much similar gait patterns in SP modes with the presence of VR.

Since Sloot (2014[2]) only focused on kinematics and kinetics parameters, they failed to provide any treadmill or subject speed information. Besides, they only examined the differences between mean values for all parameters, which was likely to minimize or obscure the possible differences. Future work is needed to examine VR effects with FS and SP treadmill walking.

Reference

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. *Exp Brain Res, 199*(1), 39-48. doi: 10.1007/s00221-009-1968-1

Alton, F., Baldey, L., Caplan, S., & Morrissey, M. C. (1998). A kinematic comparison of overground and treadmill walking. *Clin Biomech (Bristol, Avon), 13*(6), 434-440.

Bowtell, M. V., Tan, H., & Wilson, A. M. (2009). The consistency of maximum running speed measurements in humans using a feedback-controlled treadmill, and a comparison with maximum attainable speed during overground locomotion. *J Biomech, 42*(15), 2569-2574. doi: 10.1016/j.jbiomech.2009.07.024

Brouwer, B., Parvataneni, K., & Olney, S. J. (2009). A comparison of gait biomechanics and metabolic requirements of overground and treadmill walking in people with stroke. *Clin Biomech (Bristol, Avon), 24*(9), 729-734. doi: 10.1016/j.clinbiomech.2009.07.004

Checcacci, Damaso, et al. "Design and analysis of a harness for torso force application in locomotion interfaces." Proceedings of the EuroHaptics Conference. 2003.

Christensen, R., Hollerbach, J. M., Xu, Y., & Meek, S. (1998). Inertial force feedback for a locomotion interface. In Proc. ASME Dynamic Systems and Control Division, DSC (Vol. 64, pp. 119-126).

Collins, S. H., & Kuo, A. D. (2013). Two independent contributions to step variability during over-ground human walking. *PLoS One, 8*(8), e73597. doi: 10.1371/journal.pone.0073597

Cronin, N. J., & Finni, T. (2013). Treadmill versus overground and barefoot versus shod comparisons of triceps surae fascicle behaviour in human walking and running. *Gait Posture, 38*(3), 528-533. doi: 10.1016/j.gaitpost.2013.01.027

Dingwell, J. B., Cusumano, J. P., Cavanagh, P. R., & Sternad, D. (2001). Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *J Biomech Eng, 123*(1), 27-32.

Elftman, H. (1966). Biomechanics of muscle with particular application to studies of gait. *J Bone Joint Surg Am, 48*(2), 363-377.

Fung, J., Richards, C. L., Malouin, F., McFadyen, B. J., & Lamontagne, A. (2006). A treadmill and motion coupled virtual reality system for gait training post-stroke. *Cyberpsychol Behav, 9*(2), 157-162. doi: 10.1089/cpb.2006.9.157

Haiwei Dong, W., Meng, J., & Luo, Z. (2011, November). Real-time estimation of human's intended walking speed for treadmill-style locomotion interfaces. In Ubiquitous Robots and Ambient Intelligence (URAI), 2011 8th International Conference on (pp. 14-19). IEEE.

König, N., Singh, N. B., von Beckerath, J., Janke, L., & Taylor, W. R. (2013). Is gait variability reliable? An assessment of spatio-temporal parameters of gait variability during continuous overground walking. *Gait Posture*. doi: 10.1016/j.gaitpost.2013.06.014

Lee, S. J., & Hidler, J. (2008). Biomechanics of overground vs. treadmill walking in

healthy individuals. *J Appl Physiol (1985), 104*(3), 747-755. doi: 0.1152/japplphysiol.01380.2006
Lichtenstein, L., Barabas, J., Woods, R. L., & Peli, E. (2007). A feedback-controlled interface for treadmill locomotion in virtual environments. ACM Transactions on Applied Perception (TAP), 4(1), 7.
Matsas, A., Taylor, N., & McBurney, H. (2000). Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. *Gait Posture, 11*(1), 46-53.
McAndrew, P. M., Dingwell, J. B., & Wilken, J. M. (2010). Walking variability during continuous pseudo-random oscillations of the support surface and visual field. *J Biomech, 43*(8), 1470-1475. doi: 10.1016/j.jbiomech.2010.02.003
McAndrew, P. M., Wilken, J. M., & Dingwell, J. B. (2011). Dynamic stability of human walking in visually and mechanically destabilizing environments. *J Biomech, 44*(4), 644-649. doi: 10.1016/j.jbiomech.2010.11.007
Minetti, A. E., Boldrini, L., Brusamolin, L., Zamparo, P., & McKee, T. (2003). A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans. *J Appl Physiol (1985), 95*(2), 838-843. doi: 10.1152/japplphysiol.00128.2003
Parvataneni, K., Ploeg, L., Olney, S. J., & Brouwer, B. (2009). Kinematic, kinetic and metabolic parameters of treadmill versus overground walking in healthy older adults. *Clin Biomech (Bristol, Avon), 24*(1), 95-100. doi: 10.1016/j.clinbiomech.2008.07.002
Riley, P. O., Paolini, G., Della Croce, U., Paylo, K. W., & Kerrigan, D. C. (2007). A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait Posture, 26*(1), 17-24. doi: 10.1016/j.gaitpost.2006.07.003
Sloot, L. H., van der Krogt, M. M., & Harlaar, J. (2014a). Effects of adding a virtual reality environment to different modes of treadmill walking. *Gait Posture, 39*(3), 939-945. doi: 10.1016/j.gaitpost.2013.12.005
Sloot, L. H., van der Krogt, M. M., & Harlaar, J. (2014b). Self-paced versus fixed speed treadmill walking. *Gait Posture, 39*(1), 478-484. doi: 10.1016/j.gaitpost.2013.08.022
Souman, J. L., Giordano, P. R., Frissen, I., Luca, A. D., & Ernst, M. O. (2010). Making virtual walking real: Perceptual evaluation of a new treadmill control algorithm. ACM Transactions on Applied Perception (TAP), 7(2), 11.
Strathy, G. M., Chao, E. Y., & Laughman, R. K. (1983). Changes in knee function associated with treadmill ambulation. *J Biomech, 16*(7), 517-522.
Watt, J. R., Franz, J. R., Jackson, K., Dicharry, J., Riley, P. O., & Kerrigan, D. C. (2010). A three-dimensional kinematic and kinetic comparison of overground and treadmill walking in healthy elderly subjects. *Clin Biomech (Bristol, Avon), 25*(5), 444-449. doi: 10.1016/j.clinbiomech.2009.09.002
Yang, Y. R., Tsai, M. P., Chuang, T. Y., Sung, W. H., & Wang, R. Y. (2008). Virtual reality-based training improves community ambulation in individuals with stroke: a randomized controlled trial. Gait & posture, 28(2), 201-206.

Yoon, J., Park, H. S., & Damiano, D. L. (2012). A novel walking speed estimation scheme and its application to treadmill control for gait rehabilitation. *J Neuroeng Rehabil, 9,* 62. doi: 10.1186/1743-0003-9-62