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Walking speed and spatiotemporal step mean measures are reliable during feedback-controlled treadmill walking; however, spatiotemporal step variability is not reliable

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ABSTRACT

The purpose of the study was to compare the effects of a feedback-controlled treadmill (FeedbackTM) to a traditional fixed-speed treadmill (FixedTM) on spatiotemporal gait means, variability, and dynamics. The study also examined inter-session reliability when using the FeedbackTM. Ten young adults walked on the FeedbackTM for a 5-minute familiarization followed by a 16-minute experimental trial. They returned within one week and completed a 5-minute familiarization followed by a 16-minute experimental trial each for FeedbackTM and FixedTM conditions. Mean walking speed and step time, length, width, and speed means and coefficient of variation were calculated from all experimental conditions. Step time, length, width, and speed gait dynamics were analyzed using detrended fluctuation analysis. Mean differences between experimental trials were determined using ANOVAs and reliability between FeedbackTM sessions was determined by intraclass correlation coefficient. No difference was found in mean walking speed nor spatiotemporal variables, with the exception of step width, between the experimental trials. All mean spatiotemporal variables demonstrated good to excellent reliability between sessions, while coefficient of variation was not reliable. Gait dynamics of step time, length, width, and speed were significantly more persistent during the FeedbackTM condition compared to FixedTM, especially step speed. However, gait dynamics demonstrated fair to poor reliability between FeedbackTM sessions. When walking on the FeedbackTM, users maintain a consistent set point, yet the gait dynamics around the mean are different when compared to walking on a FixedTM. In addition, spatiotemporal gait dynamics and variability may not be consistent across separate days when using the FeedbackTM.

1. Introduction

The treadmill is a popular tool in clinical and laboratory set- tings, particularly for gait analyses. It provides the ability to collect consecutive steps in a secured, controlled environment while limiting the amount of space required. Treadmills provide a common alternative to overground walking, yet the gait patterns are not entirely similar. Previous literature, focusing on mean kinematic and kinetic variables, has suggested the two walking modes are similar (Damiano et al., 2011; Gates et al., 2012; Lee and Hidler, 2008). Conversely, alterations in walking (Hollman et al., 2016a, b) and running dynamics (Lindsay et al., 2014) on a fixed-speed treadmill (FixedTM), as compared to overground, exist. These conflicting reports may exist due to the method of analysis, as descriptive measures examine magnitude and variability, while other measures examine the structural characteristics of the walking pattern.

Gait dynamics refer to the stride-to-stride fluctuations over time (Hausdorff, 2007). These fluctuations are an important feature in healthy behavior (Buzzi et al., 2003) and are an inherent component of the locomotor system. Detrended fluctuation analysis (DFA) is typically used to study gait dynamics (Choi et al., 2015; Hausdorff et al., 1997, 1996). DFA estimates the statistical persistence in a time series, and describes the self-similarity of the data by comparing the fluctuations at different time scales (Almurad and Delignières, 2016). This method requires longer duration, continuous time series, more easily recorded during treadmill versus overground walking. However, gait dynamics are altered by the treadmill (Hollman et al., 2016a, b) and speed (Chien et al., 2015). The constant speed of the treadmill belt constrains stride-to-stride fluctuations, in particular stride speed, which becomes tightly organized around the treadmill belt speed (Dingwell and Cusumano, 2010). The user must adapt a movement strategy that matches the speed of the treadmill. Rather than 'walking freely,' the user adjusts step length and/or timing to the treadmill. Gait dynamics may then be influenced by the necessary task of matching the treadmill belt speed, rather than allowing for the typical inherent dynamics that exist during overground walking. Therefore, to accurately measure gait dynamics when walking on a treadmill, there is need for a method of removing, or attenuating, the constraints produced by a treadmill.

One potential solution is using a treadmill that is dependent on feedback from the user's movement, allowing belt speed to fluctuate. A feedback-controlled treadmill (FeedbackTM) algorithm was recently developed (Wiens et al., 2017) that expands previous algorithms and control schemes (Bowtell et al., 2009; Choi et al., 2015; Christensen et al., 2000; Dong et al., 2011; Feasel et al., 2011; Fung et al., 2006; Kim et al., 2012; Lichtenstein et al., 2007; Manurung et al., 2010; Minetti et al., 2003; Sloot et al., 2014). The algorithm integrates components of the user's walking behavior, resulting in an estimation of walking speed, and updating the treadmill belt speed accordingly. Mean treadmill speed is reliable within and across sessions, and treadmill speed variability is reliable within session when using this algorithm (Wiens et al., 2017). However, it is currently unknown if this type of FeedbackTM affects users' gait dynamics.

As movement over time is dynamic, it is important to under- stand if movement strategies and/or the inherent variability in movement are consistent from day-to-day (reliability) when walking on a FeedbackTM. In the context of FixedTM walking, both within-day and between-day ICC coefficients were excellent (0.914 and 0.769, respectively) for stride time DFA (Pierrynowski et al., 2005). In the context of FeedbackTM, Choi et al. (2015) reported a high within-day and between-day reliability of stride time DFA. In contrast, the treadmill belt speed coefficient of variation was not reliable across sessions when using a FeedbackTM (Wiens et al., 2017). However, it is unknown if step dynamics, in particular step speed fluctuations, are consistent from day-to-day. The aims of this paper are: (1) to compare user's spatiotemporal mean, variability, and gait dynamics when walking on a Feed- backTM compared to a FixedTM; and (2) to assess the inter- session reliability of spatiotemporal mean, variability, and gait dynamics when walking on a FeedbackTM. We hypothesized that spatiotemporal means would be similar between the two types of treadmills, while spatiotemporal variability would be greater in the FeedbackTM. Based on previous literature (Damiano et al., 2011; Gates et al., 2012; Hollman et al., 2016a, b; Lee and Hidler, 2008; Lindsay et al., 2014), it was anticipated that the gait dynamics – specifically step speed – would be significantly more persistent when using the FeedbackTM compared to the FixedTM. It was also hypothesized that gait dynamics would be significantly reliable between-sessions when walking on a FeedbackTM based on previous findings (Choi et al., 2015).

2. Methods

Ten healthy, young adults (21.10 ± 1.52 years; 172.75 ± 11.05 cm; 71.62 ± 9.96 kg) free from any musculoskeletal and neuromuscular disorders participated in the study. The University's Institutional Review Board approved the experimental protocol. Informed consent was obtained prior to the study.

The experimental protocol consisted of two sessions (Table 1). During Session 1, participants were asked to wear a form-fitting suit. Retro-reflective markers were anatomically placed, using a lower-body, bi-lateral 27-marker set (Houck et al., 2005). The algorithm (Wiens et al., 2017) required position data from the retroreflective markers (Vicon T160 (100 Hz); Oxford, UK) to control the split-belt treadmill (TM-07-B, Bertec; Columbus, OH). The FeedbackTM algorithm was programmed into a software application (D-Flow, Motekforce Link; Netherlands) to process position data for calculation and adjustment of treadmill belt speed in real-time.

The FeedbackTM algorithm allowed the user to start the treadmill from a static, standing position. After instructing the participants on how to use the treadmill, they were asked to walk at their preferred speed for five minutes to adapt to the treadmill. Handrails were only installed at the front of the treadmill; however, participants were instructed to only use them if needed. After familiarization, a 16-minute experimental trial and a 5-minute trial using the FeedbackTM algorithm were completed (Table 1). A 5-minute familiarization trial allowed the participant to explore and experience walking on the treadmill, particularly the FeedbackTM. The 5-minute experimental trial was completed to determine whether duration of FeedbackTM walking had an effect on walking behavior (data not presented in this paper). At least a five-minute break was given between trials. During the break, the Trail Making Test A & B (Corrigan and Hinkeldey, 1987; Lezak, 1995; Reitan, 1958) was completed and each participant walked overground throughout the building. These procedures were intended to distract the participant from spending the break thinking about the experience walking on the treadmill. The participants then returned after one week. Session 2 entailed four trials total (familiarization and experimental trials for both the FeedbackTM and FixedTM; Table 1). The familiarization trials always preceded the respective experimental trial; however, the order of FeedbackTM or FixedTM walking were randomized between participants. The treadmill belt speed for the FixedTM condition was determined at the beginning of the FixedTM familiarization trial, during which the speed was incrementally changed until the participant stated it was his/her comfortable walking speed. Breaks between trials were identical to Session 1.

The FeedbackTM and FixedTM conditions were of differing length to allow one minute for the participant to find a steady walking speed during FeedbackTM condition. All experimental trials were then cut to 14-minutes in length. The first minute in all experimental trials (15- and 16-minute trials) and the last minute from the 16-minute FeedbackTM trials were excluded from analyses. From all walking trials, step length, time, width, and speed were calculated (Fig. 1). Step length was calculated as the distance in the anterior-posterior direction from heel to contralateral heel at heel strike. Step time was quantified as the time between heel strike and subsequent heel strike of the contralateral leg. The mediolateral distance from the middle of both feet at heel strike calculated step width. Step speed was calculated as step length divided by step time. Mean and variability (coefficient of variation) were quantified from all spatiotemporal time series.

DFA – gait dynamics – was quantified from all three experimental trials. DFA analysis has been described previously (Almurad and Delignières, 2016; Delignières and Torre, 2009). Data were trimmed to match the lowest data series to allow more controlled comparisons (N = 1384). Box sizes used were minimum 10 to maximum N/4 with N = length of data. The slope of the linear relationship between the size of fluctuations and the box sizes determined the scaling exponent alpha (a) and quantified the degree of persistence in the signal. For stationary time series, $0 < a < 0.5$ describes a negatively correlated time series (anti-persistent), and $0.5 < a < 1.0$ defines a positively correlated time series, while $a = 0.5$ represents uncorrelated data (i.e., white noise). For $a > 1.0$, data are considered non-stationary (Peng et al., 1995).

Dependent variables subjected to statistical analyses were mean walking speed, spatiotemporal mean and coefficient of variation, and the DFA a for step time, length, speed, and width. One-way repeated measures ANOVAs were used to compare experimental trials' mean walking speed, and mean, coefficient of variation, and DFA for step time, length, speed and width. To assess the between-session reliability of spatiotemporal mean, coefficient of variation, and gait dynamics when walking on a FeedbackTM, intraclass correlation coefficient (ICC) of type (3, 1) and standard error of measurement ($SD * \sqrt{1\text{-}ICC}$) was used. Between-session reliability wasconducted using 14-minutes from the Session 1 FeedbackTM and Session 2 FeedbackTM experimental trials. Interpretation of ICC strength was: poor (*ICC* < 0.40), fair (0.40 ≤ *ICC* ≤ 0.59), good (0.60 ≤ *ICC* ≤ 0.74), and excellent (0.75 ≤ ICC ≤ 1.00) (Cicchetti, 1994). SPSS (Version 20, IBM, Armonk, NY) was the software used in analysis. Level of statistical significance was set at a p-value < 0.05.

Table 1

Diagram of the trials performed each session. Note: Bolded trials were used for analysis. The first minute of each trial was excluded from data analyses to allow user to find steady walking speed.

Session 1		Session 2		
Trial	Duration (min)	Trial	Duration (min)	
FeedbackTM (Familiarization)	5	FeedbackTM (Familiarization)	5	Randomized between Feedback and Fixed
FeedbackTM	16	FeedbackTM	16	
FeedbackTM[a]	5	FixedTM (Familiarization)	5	
		FixedTM	15	

[a] These data are not presented in this paper.

3. Results

Mean walking speeds between the three treadmill trials were not significantly different (p = 0.80) (Table 2). Mean step time (p = 0.57), length (p = 0.80), and speed (p = 0.82) were not different between the FeedbackTM and FixedTM experimental trials (Fig. 2). Step width did have a significant effect of treadmill trial (p = 0.006). Step width was significantly wider during Session 1 FeedbackTM compared to Session 2 FeedbackTM (p = 0.03) and during Session 1 FeedbackTM compared to Session 2 FixedTM (p = 0.02). However, step width was not different between Session 2 FeedbackTM and FixedTM (p = 0.22). Step time, length, and speed coefficient of variation was significantly different during both FeedbackTM conditions compared to FixedTM (Table 2). Step width coefficient of variation was not different between treadmill conditions.

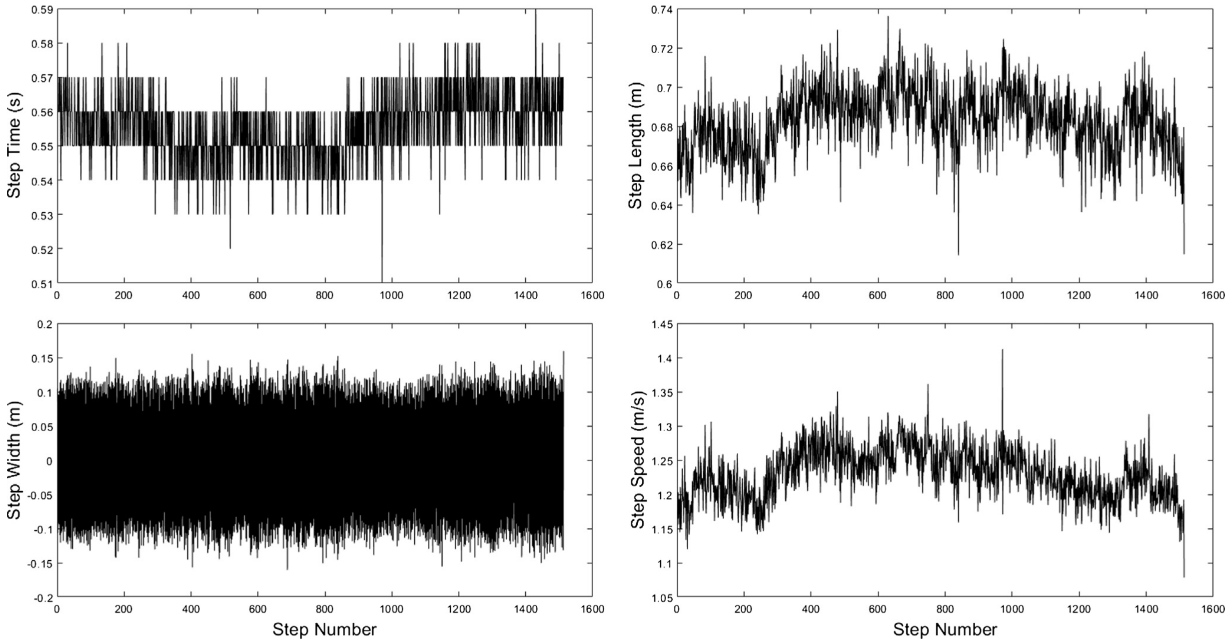

Fig. 1. Representative data from one subject.

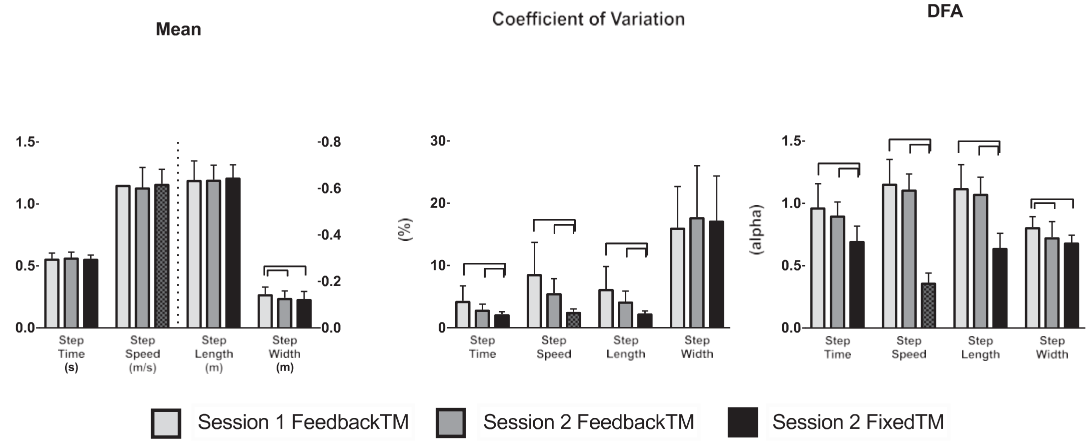

Fig. 2. Comparison of mean, coefficient of variation, and a values between feedback-controlled and fixed-speed treadmill walking. Mean step time and speed values relate to the left y-axis, while mean step length and width relate to the right y-axis. There were no significant differences in spatiotemporal means between the feedback-controlled and fixed-speed treadmill conditions, except for step width. Both FeedbackTM spatiotemporal variability – except step width – were significantly greater than FixedTM. Except for step width, all the spatiotemporal dynamics were significantly more correlated in the feedback-controlled treadmill conditions compared to fixed-speed.

The participants' gait dynamics (i.e., DFA a) were significantly different between the three treadmill trials ($p < 0.001$ for step time, length, and speed; $p = 0.006$ for step width). Step time was not significantly different between the two FeedbackTM trials ($p = 0.23$); however, it was significantly more persistent during both FeedbackTM trials compared to the FixedTM (Session 1 FeedbackTM v. Fixed TM: $p < 0.001$ and Session 2 FeedbackTM v. Fixed TM: $p = 0.001$). Similarly, step length was not significantly different between the two FeedbackTM trials ($p = 0.52$); however, it was significantly more persistent during both FeedbackTM trials compared to the FixedTM (Session 1 FeedbackTM v. Fixed TM: $p < 0.001$ and Session 2 FeedbackTM v. Fixed TM: $p < 0.001$). Step width demonstrated significantly more persistent gait dynamics during Session 1 FeedbackTM v. Session 2 Feedback TM ($p = 0.046$) and during

Session 1 FeedbackTM v. FixedTM ($p = 0.003$). However, step width gait dynamics were not significantly different between Session 2 FeedbackTM v. FixedTM ($p = 0.26$). As with step time and length, step speed was not significantly different between the two FeedbackTM trials ($p = 0.44$); however, it was significantly more persistent during both FeedbackTM trials compared to the FixedTM (Session 1 Feed- backTM v. Fixed TM: $p < 0.001$ and Session 2 FeedbackTM v. Fixed TM: $p < 0.001$).

Table 2

Group means (1SD) for the three treadmill experimental conditions. Mean differences between FeedbackTM trials and the FixedTM trial are presented, as well as between-session reliability. Significant values ($p < 0.05$) are bolded.

		Session 1	Session 2	Session 2	Mean Difference		Between-Session[c]		
		FeedbackTM	FeedbackTM	FixedTM	*p*-Value	F-value	ICC	*p*-Value	SEM
Walking Speed	Mean (m/s)	1.22 (0.22)	1.20 (0.18)	1.23 (0.13)	0.80	0.22	0.74	0.005	0.10
Step Time	Mean (s)	0.56 (0.04)	0.57 (0.04)	0.56 (0.03)	0.57	0.59	0.78	0.002	0.02
	CV (%)	4.33 (2.40)[a]	2.91 (0.89)[a]	2.19 (0.39)	0.008	6.4	0.27	0.22	1.63
	a	0.97 (0.19)[a]	0.90 (0.11)[a]	0.70 (0.12)	<0.001	18.7	0.48	0.07	0.11
Step Length	Mean (m)	0.64 (0.08)	0.64 (0.06)	0.65 (0.06)	0.80	0.22	0.84	0.001	0.03
	CV (%)	6.23 (3.60)[a]	4.22 (1.68)[a]	2.31 (0.41)	0.001	9.6	0.37	0.13	2.32
	a	1.12 (0.19)[a]	1.08 (0.13)[a]	0.64 (0.12)	<0.001	41.8	0.13	0.35	0.13
Step Width	Mean (m)	0.15 (0.03)[a]	0.13 (0.03)[b]	0.12 (0.03)	0.006	7.0	0.81	0.001	0.01
	CV (%)	16.07 (6.59)	17.77 (8.26)	17.20 (7.18)	0.70	0.37	0.44	0.09	5.47
	a	0.81 (0.08)[a]	0.73 (0.13)[b]	0.69 (0.06)	0.006	6.9	0.46	0.08	0.11
Step Speed	Mean (m/s)	1.15 (0.20)	1.13 (0.16)	1.16 (0.12)	0.82	0.21	0.75	0.004	0.09
	CV (%)	8.61 (5.10)[a]	5.56 (2.35)[a]	2.55 (0.49)	0.001	11.5	0.38	0.13	0.38
	a	1.16 (0.19)[a]	1.11 (0.13)[a]	0.36 (0.08)	<0.001	106.7	0.36	0.14	0.15

NOTE: CV = coefficient of variation.

[a] Significantly different from FixedTM.

[b] Significantly different from Session 1 FeedbackTM.

[c] Only Session 1 Feedback TM and Session 2 Feedback TM data were used for reliability of gait dynamics.

Mean walking speed demonstrated good reliability between FeedbackTM conditions (ICC = 0.74, $p = 0.005$). All spatiotemporal means had significantly, excellent reliability between sessions (ICC

0.75) (Table 2). However, the coefficient of variation of the spatiotemporal variables demonstrated non-significant, fair to poor reliability between sessions (ICC range: 0.44–0.13). Step time and step width dynamics had fair reliability between sessions (ICC = 0.476, $p = 0.07$ and 0.459, $p = 0.08$, respectively). Step length and speed dynamics had poor reliability between sessions (ICC = 0.130, $p = 0.35$ and 0.362, $p = 0.14$, respectively).

4. Discussion

The purpose of this research was to compare the spatiotemporal mean, variability, and gait dynamics when using a FeedbackTM versus a FixedTM and to assess the inter-session reliability when using a FeedbackTM. It was hypothesized that (1) spatiotemporal means would be similar between treadmill types while spatiotemporal variability would be greater in FeedbackTM; (2) the gait dynamics during the FeedbackTM condition would be significantly more persistent than during the FixedTM conditions; and (3) spa- tiotemporal gait dynamics when walking on a FeedbackTM would be reliable between-sessions. Our findings partially support both hypotheses. Spatiotemporal means were similar and variability was greater during FeedbackTM, with the exception of step width variability. FeedbackTM gait dynamics were more persistent as compared to FixedTM; however, not reliable between sessions.

Results from this study suggest a more persistent walking behavior (i.e., faster steps followed by faster steps and slower steps followed by slower steps), rather than a less persistent walking behavior – or even an anti-persistent strategy as in step speed (i.e., alternating between faster and slower steps) – that is found when using a FixedTM (Dingwell and Cusumano, 2010). Previous literature analyzing gait dynamics on a position-dependent Feed- backTM have reported a similar increase in persistence compared to a FixedTM (Choi et al., 2014). While on the FixedTM, to avoid walking off the back of the treadmill, the user would have to correct and walk faster in the subsequent steps (with the opposite occurring at the front), similar to a corrective behavior in order to continue walking on a treadmill constrained at a certain speed. This forces the treadmill user to control his/her speed to match the treadmill speed. In contrary, while using a FeedbackTM, the tread- mill speed is the one adapting to the user.

The change from anti-persistence in the FixedTM to persistence in the FeedbackTM walking suggests a change in control strategy of step speed, from each step speed being tightly controlled (FixedTM) to it being more loosely controlled (FeedbackTM) (Dingwell and Cusumano, 2010). The FeedbackTM adjusts the treadmill speed to match the persistent walking behavior of the user. If the user continues to increase speed, the treadmill speed continues to increase; the treadmill speed adjusts to the user, rather than the user adjusting to the treadmill speed. The other spatiotemporal gait dynamics that were significantly different between the two modes of walking – step time and length – are the two factors of step speed. The two variables were more persistent (more loosely controlled) when walking on the FeedbackTM. Step width was wider when walking on the FeedbackTM during Session 1, but there was no difference between FeedbackTM and FixedTM step width during the same session. This could be due to learning effect of walking on a FeedbackTM and/or possible difference in walking strategy from session to session.

These results indicate that the FeedbackTM algorithm alters the gait dynamics compared to a FixedTM, but it does not reveal if this is a positive or negative adjustment. However, it is hypothesized that the FeedbackTM is more similar to overground walking, as it has attenuated the speed constraint of a FixedTM, which does not exist when normally walking overground. It has been previously reported that overground walking is characterized by persistent, long-range correlations ($0.5 < a < 1.0$) in walking speed, step frequency, and step length (Terrier et al., 2005). In the current study, the mean values of a ranged between 0.73 and 0.90 for step width and step time. Step length and step speed produced a values > 1.0. Alpha values greater than 1.0 are considered nonstationary and unbounded, moving toward strong persistence. The transition point from a correlated, persistent signal ($a \sim 1.0$) to an unbounded, non-stationary, persistent signal (a ~ 1.5) is unknown. The mean step length a was 1.08 and for step speed was 1.11; closer to a correlated, persistent signal as compared to unbounded, persistent noise. Therefore, it can be inferred that the FeedbackTM maintained long-range correlations similar to walking behavior present in overground walking. Simply put, step speed was unconstrained and it is possible that subjects walked slightly faster and faster (or slower and slower) without perceiving it, up to a certain point when they 'came back' to their original step speed, which created more non-stationarities. Future studies directly comparing overground walking to the FeedbackTM will be necessary to address this question.

When comparing the mean spatiotemporal variables between the FeedbackTM and FixedTM, the means were similar between the two modes. Although the users seem to maintain a consistent set point (similar means between conditions), the fluctuations around the mean are different. This suggests different step-to- step control strategies when walking on a FeedbackTM compared to a FixedTM. A FixedTM places constraints on the user, particularly speed-related. A treadmill that has the ability to change speed based on the user's behavior reduces that constraint, as depicted by the increased a value of step speed when walking on the FeedbackTM. In this study, the average speeds were not different between FeedbackTM and FixedTM, although the speeds could have fluctuated throughout while walking on the Feedback TM.

These findings could have implications for treadmill-based gait retraining or rehabilitation. A FeedbackTM may be useful in situa- tions in which a more natural walking behavior is the goal. This might also make FeedbackTM walking more enjoyable, or a more effective exercise session, as it parallels the concept of interval training. A FixedTM might be more beneficial to perhaps create a more controlled walking environment, such as during initial rehabilitation sessions for those who have never walked on a treadmill. Moreover, FeedbackTMs have been developed previously (Bowtell et al., 2009; Choi et al., 2015; Christensen et al., 2000; Dong et al., 2011; Feasel et al., 2011; Fung et al., 2006; Kim et al., 2012; Lichtenstein et al., 2007; Manurung et al., 2010; Minetti et al., 2003; Sloot et al., 2014), but none have been equipped with the type of biomechanical influence as the one used in this study. Therefore, differences between the FeedbackTM algorithms may occur more in the interaction and experience of the user when using a FeedbackTM.

Our results indicate that consistent mean spatiotemporal variables when using this feedback-controlled algorithm multiple times, even with a week between visits. Conversely, the variability (coefficient of variation) and fluctuations in spatiotemporal variables during a trial were not similar to a trial completed on a different session. This partially supported our hypothesis and is in contrast with previous research (Choi et al., 2015). Possible complementary reasons are: (1) the fluctuations in a person's walking behavior may be different from session to session and (2) there may be a learning effect, resulting in the user being more equipped to interact with the FeedbackTM during the second session. As with any new activity, humans, especially healthy individuals, are able to adapt and learn the requirements of a new task, influencing future behavior. However, it is a possibility that some never ''learned" how to walk on a FeedbackTM. Further research investigating potential learning effects of FeedbackTM and the effects of FeedbackTM walking on different populations are deemed necessary.

Choi and authors have also demonstrated the within- and between-session reliability of walking speed and gait dynamics when using a position-dependent FeedbackTM algorithm (Choi et al., 2015). Our results are in partial agreement, as between- session coefficient of variation was not reliable in our study. Although spatiotemporal variability was decreased to similar values as found in two previous studies (Choi et al., 2017, 2015), there could be multiple reasons for the differences. First, there could be a learning effect of using this FeedbackTM. Second, this study used step data, while the other group used stride. While it is not known if this had an effect, but a stride may mask changes in a step, as it is the combination of steps that consist of one stride. For example, over two strides of 2 s each (low coefficient of variation), the step time could be 0.95, 1.05, 1.1, and 0.9 (higher coefficient of variation). Another difference between the studies was the use of intraclass correlation coefficient. To asses reliability, this study compared two individual conditions using an ICC type (3,1), while the other group used an averaging technique by using an ICC type (3,*k*). We were interested if a single trial on the FeedbackTM would be reliable to another single trial on a different session.

There were limitations within this study. The participants were young and healthy, implying they may be able to quickly learn and adapt to the algorithm. The effects may be different for other populations. Due to the study design, participants had 26 min of experience (Session 1) more on the FeedbackTM compared to the FixedTM at the start of Session 2. Mean spatiotemporal variables were not significantly different between the FeedbackTM and the FixedTM inferring that overall gait was not different due to the additional 5 min of famililarization on the FeedbackTM. Due to the fact that the algorithm is based off the position of the center of mass rather than the center of pressure, there was a possible effect on the treadmill's speed changes. There are two known rea- sons the algorithm's delay may affect the accuracy of the velocity change: (1) calculating change at heel strike and (2) gradual adjustment of treadmill belt velocity. For calculating change at heel strike: the main parameters used in estimating walking speed are calculated at end of the gait cycle (every heel strike); therefore, this forces the adjustments in treadmill belt velocity to occur, primarily, when heel strikes occur. Throughout the early iterations of the algorithm, it became clear that this caused the issue of creating 'jerking' of the treadmill belt due to the instantaneous adjustment of the belt velocity. This leads us to the second reason of the delay. We then decided to incrementally adjust the belt velocity towards the estimated velocity. This provides a smoother transition; how- ever, it may still provide a delay that could affect the accuracy.

In conclusion, these results suggest that users on the FeedbackTM walk at consistent mean values, yet the amount of variability and fluctuations (gait dynamics) around the mean are different when comparing to a FixedTM. In addition, when using the FeedbackTM, spatiotemporal means are consistent across days, gait dynamics may not be. Future directions in this project are to investigate the effects on other kinematic and kinetic variables, the effectiveness of the algorithm in other populations (e.g. elderly, walking disorder), and comparison to overground.

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Conflict of interest

A patent (Serial No. PCT/US17/57050) contains the feedback- controlled treadmill algorithm that was developed by authors CW, WD, and MNS. RH, VM, SAM, and JMY have no conflicts to disclose.

References

Almurad, Z.M.H., Delignières, D., 2016. Evenly spacing in detrended fluctuation analysis. Phys. A Stat. Mech. Appl. 451, 63–69. https://doi.org/10.1016/ j.physa.2015.12.155.

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, 2569–2574. https://doi.org/10.1016/j.jbiomech.2009.07.024.

Buzzi, U.H., Stergiou, N., Kurz, M.J., Hageman, P.A., Heidel, J., 2003. Nonlinear dynamics indicates aging affects variability during gait. Clin. Biomech. 18, 435–

443. https://doi.org/10.1016/S0268-0033(03)00029-9.

Chien, J.H., Yentes, J., Stergiou, N., Siu, K.-C., 2015. The effect of walking speed on gait variability in healthy young, middle-aged and elderly individuals. J. Phys. Act. Nutr. Rehabil. 2015.

Choi, J.-S., Kang, D.-W., Seo, J.-W., Tack, G.-R., 2015. Reliability of the walking speed and gait dynamics variables while walking on a feedback-controlled treadmill. J. Biomech. 48, 1336–1339. https://doi.org/10.1016/j.jbiomech.2015.02.047.

Choi, J.S., Kang, D.W., Bae, J.H., Shin, Y.H., Lee, J.H., Tack, G.R., 2014. Long-range correlations of stride time, stride length and stride velocity during feedback- controlled treadmill walking. In: Goh, J. (Ed.), The 15th International Conference on Biomedical Engineering, IFMBE Proceedings. Springer International Publishing, Cham, pp. 920–923. https://doi.org/10.1007/978-3-319-02913- 9_237.

Choi, J.S., Kang, D.W., Seo, J.W., Tack, G.R., 2017. Fractal fluctuations in spatiotemporal variables when walking on a self-paced treadmill. J. Biomech. 65, 154–160. https://doi.org/10.1016/j.jbiomech.2017.10.015.

Christensen, R.R., Hollerbach, J.M., Xu, Y., Meek, S.G., 2000. Inertial-force feedback for the treadport locomotion interface. Presence Teleoperators Virtual Environ. 9, 1–14. https://doi.org/10.1162/105474600566574.

Cicchetti, D.V., 1994. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychol. Assess. 6, 284.

Corrigan, J.D., Hinkeldey, N.S., 1987. Relationships between parts A and B of the Trail Making Test. J. Clin. Psychol. 43, 402–409.

Damiano, D.L., Norman, T., Stanley, C.J., Park, H.-S., 2011. Comparison of elliptical training, stationary cycling, treadmill walking and overground walking. Gait Posture 34, 260–264. https://doi.org/10.1016/j.gaitpost.2011.05.010.

Delignières, D., Torre, k., 2009. Fractal dynamics of human gait: a reassessment of the 1996 data of Hausdorff et al. J. Appl. Physiol. 106, 1272–1279. https://doi.org/10.1152/japplphysiol.90757.2008.

Dingwell, J.B., Cusumano, J.P., 2010. Re-interpreting detrended fluctuation analyses of stride-to-stride variability in human walking. Gait Posture 32, 348–353. https://doi.org/10.1016/j.gaitpost.2010.06.004.

Dong, W.H., Meng, Jianjun, Luo, Zhiwei, 2011. Real-time estimation of human's intended walking speed for treadmill-style locomotion interfaces. In: 2011 8th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI). IEEE, pp. 14–19. https://doi.org/10.1109/URAI.2011.6145925.

Feasel, J., Whitton, M.C., Kassler, L., Brooks, F.P., Lewek, M.D., 2011. The integrated virtual environment rehabilitation treadmill system. IEEE Trans. Neural Syst. Rehabil. Eng. 19, 290–297. https://doi.org/10.1109/TNSRE.2011.2120623.

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. Cyber Psychology Behav. 9, 157–162. https://doi.org/10.1089/cpb.2006.9.157.

Gates, D.H., Darter, B.J., Dingwell, J.B., Wilken, J.M., 2012. Comparison of walking overground and in a Computer Assisted Rehabilitation Environment (CAREN) in individuals with and without transtibial amputation. J. Neuroeng. Rehabil. 9, 81. https://doi.org/10.1186/1743-0003-9-81.

Hausdorff, J.M., 2007. Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. Hum. Mov. Sci. 26, 555–589. https://doi.org/10.1016/j.humov.2007.05.003.

Hausdorff, J.M., Mitchell, S.L., Firtion, R., Peng, C.K., Cudkowicz, M.E., Wei, J.Y., Goldberger, A.L., 1997. Altered fractal dynamics of gait: reduced stride-interval correlations with aging and Huntington's disease. J. Appl. Physiol. 82, 262–269. Hausdorff, J.M., Purdon, P.L., Peng, C.K., Ladin, Z., Wei, J.Y., Goldberger, a.L., 1996.

Fractal dynamics of human gait: stability of long-range correlations in stride interval fluctuations. J. Appl. Physiol. 80, 1448–1457. https://doi.org/N/A.

Hollman, J.H., Watkins, M.K., Imhoff, A.C., Braun, C.E., Akervik, K.A., Ness, D.K., 2016a. Complexity, fractal dynamics and determinism in treadmill ambulation: implications for clinical biomechanists. Clin. Biomech. 37, 91–97. https://doi.org/10.1016/j.clinbiomech.2016.06.007.

Hollman, J.H., Watkins, M.K., Imhoff, A.C., Braun, C.E., Akervik, K.A., Ness, D.K., 2016b. A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions. Gait Posture 43, 204–209. https://doi.org/10.1016/j.gaitpost.2015.09.024.

Houck, J.R., Duncan, A., De Haven, K.E., 2005. Knee and hip angle and moment adaptations during cutting tasks in subjects with anterior cruciate ligament deficiency classified as noncopers. J. Orthop. Sport. Phys. Ther. 35, 531–540. https://doi.org/10.2519/jospt.2005.35.8.531.

Kim, Jonghyun, Stanley, C.J., Curatalo, L.A., Park, Hyung-Soon, 2012. A user-driven treadmill control scheme for simulating overground locomotion. In: IEEE Engineering in Medicine and Biology Society. IEEE, pp. 3061–3064. https://doi.org/10.1109/EMBC.2012.6346610.

Lee, S.J., Hidler, J., 2008. Biomechanics of overground vs. treadmill walking in healthy individuals. J. Appl. Physiol. 104, 747–755. https://doi.org/ 10.1152/japplphysiol.01380.2006.

Lezak, M.D., 1995. Neuropsychological Assessment. Oxford University Press, New York.

Lichtenstein, L., Barabas, J., Woods, R.L., Peli, E., 2007. A feedback-controlled interface for treadmill locomotion in virtual environments. ACM Trans. Appl. Percept. 4. https://doi.org/10.1145/1227134.1227141. 7–es.

Lindsay, T.R., Noakes, T.D., McGregor, S.J., 2014. Effect of treadmill versus overground running on the structure of variability of stride timing. Percept. Mot. Skills 118, 331–346. https://doi.org/10.2466/30.26.PMS.118k18w8.

Manurung, A., Yoon, J., Park, H.-S., 2010. Speed adaptation control of a small-sized treadmill with state feedback controller. In: 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics. IEEE, pp. 15–20. https://doi.org/10.1109/BIOROB.2010.5626105.

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. 95, 838–843. https://doi.org/ 10.1152/japplphysiol.00128.2003.

Peng, C.K., Havlin, S., Stanley, H.E., Goldberger, A.L., 1995. Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos 5, 82–87. https://doi.org/10.1063/1.166141.

Pierrynowski, M.R., Gross, A., Miles, M., Galea, V., McLaughlin, L., McPhee, C., 2005. Reliability of the long-range power-law correlations obtained from the bilateral stride intervals in asymptomatic volunteers whilst treadmill walking. Gait Posture 22, 46–50. https://doi.org/10.1016/j.gaitpost.2004.06.007.

Reitan, R.M., 1958. Validity of the trail making test as an indicator of organic brain damage. Percept. Mot. Skills 8, 271–276.

Sloot, L.H., van der Krogt, M.M., Harlaar, J., 2014. Self-paced versus fixed speed treadmill walking. Gait Posture 39, 478–484. https://doi.org/10.1016/ j.gaitpost.2013.08.022.

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. Hum. Mov. Sci. 24, 97–115. https://doi.org/10.1016/j. humov.2005.03.002.

Wiens, C., Denton, W., Schieber, M.N., Hartley, R., Marmelat, V., Myers, S.A., Yentes, J. M., 2017. Reliability of a feedback-controlled treadmill algorithm dependent on the user's behavior. In: 2017 IEEE International Conference on Electro Information Technology (EIT). IEEE, pp. 545–550. https://doi.org/10.1109/ EIT.2017.8053423.