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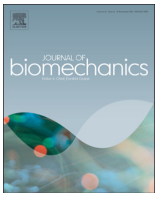

Short communication

Reliability of the walking speed and gait dynamics variables while walking on a feedback-controlled treadmill

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ABSTRACT

The purpose of this study is to identify the reliability of walking speed and gait dynamics measured with a feedback-controlled treadmill and to assess the applicability of the treadmill to gait dynamics studies. The intraclass correlation coefficient (ICC) and the standard error of measurement (SEM) for the walking speed and the mean, variability (coefficient of variance, CV), and fractal dynamics (the scaling exponent α of detrended fluctuation analysis, DFA) of the stride time and stride length were used to evaluate the within-day and between-day reliability. Fifteen subjects walked on a feedback-controlled treadmill for three trials that were each more than 10 min in length (within-day); this protocol was repeated on another day to identify the between-day reliability. The results showed that all variables were consistent for within-day and between-day reliability (ICC: 0.633–0.982, $p < 0.05$; SEM: 0.02–0.43). The within- and between-day reliability of the walking speed and the mean, variability, and fractal dynamics for the stride time and stride length were identified. Good ICCs and low SEMs for within-day and between-day reliability were obtained for all variables. Therefore, it is concluded that it is possible to use a feedback-controlled treadmill to the study of gait dynamics.

1. Introduction

In gait dynamics analysis, stride-to-stride variable is regarded as the final output of the neuro-musculo-skeletal regulatory mechanisms of the human body, and fluctuations in stride-to-stride time are analyzed (Hausdorff et al., 1996; Hausdorff, 2007). In gait dynamics, the magnitude and structure of the stride-to-stride fluctuations are analyzed by using the continuous stride-to-stride time for relatively long walking durations (Hausdorff et al., 1995; Hausdorff, 2007). The magnitude of the stride-to-stride fluctuations indicating changes over time during walking represents gait variability and can be quantitatively expressed using the coefficient of variance (CV). The structure of these fluctuations describes the fractal dynamics and can be quantitatively expressed using the scaling exponent α, which is calculated using detrended fluctuation analysis (DFA), a nonlinear analysis method (Peng et al., 1994; Hausdorff, 2007; Hunt et al., 2014; Jordan et al., 2007). In other words, the scaling exponent α represents whether stride-to-stride fluctuations have a long-range correlation.

To analyze fractal dynamics, natural and continuous walking data for approximately 10 min or an average of three trials that are each 6 min in duration (Damouras et al., 2010; Delignieres et al., 2006; Pierrynowski et al., 2005) are usually necessary. For this reason, using a treadmill offers a significant advantage. The kinematic variables (spatiotemporal variables and joint angles) and the kinetic variables (ground reaction force and joint torque) during treadmill walking were reported to be similar to those during ground walking (Alton et al., 1998; Lee and Hidler, 2008; Sloot et al., 2014).

However, from the gait dynamics viewpoint, the variability in the stride time during treadmill walking was reduced (Dingwell et al., 1999, 2001), and Dingwell and Cusumano (2010) reported that, consistent with previous findings, stride time and stride length exhibited statistical persistence of fractal dynamics or long-range correlation, whereas stride speed exhibited consistent and statistically significant anti-persistence dynamics. These previous results differ from the result of unconstrained ground walking in which stride time, length, and speed exhibited statistical persistence of a long-range correlation (Terrier et al., 2005).

Therefore for gait dynamics studies, it is possible to use a feedback-controlled treadmill (or self-paced treadmill) in which the speed of the belt is controlled by the subject's walking speed. There are no reports regarding the use of feedback-controlled

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treadmills in gait dynamics studies, especially fractal dynamics; therefore, it is necessary to conduct basic studies using a feedback-controlled treadmill.

First, to use a feedback-controlled treadmill in gait dynamics studies, the reliability of the treadmill should be verified. Indeed, it is necessary to verify whether a walker's average speed is consistent with a treadmill and whether constant walking speed and spatiotemporal variables are maintained with repeated experiments. Therefore, the purpose of the present investigation was to verify the within-day and between-day reliabilities of walking speed and spatiotemporal variables during feedback-controlled treadmill walking for its application in gait dynamics studies.

2. Methods

2.1. Participants

The participants in the experiments were 15 male college students who did not have any musculoskeletal disorders in the lower extremities (age: 22.7 ± 1.6 years, height: 176.8 ± 5.1 cm, weight: 72.1 ± 11.8 kg). The protocol for this study was confirmed from the Ethics Committee of Konkuk University. Before the experiment, experimental procedures were explained to all subjects, and written consent was received. Moreover, all authors who contributed to this experiment have approved this manuscript.

2.2. Experimental design

All experiments in this study were conducted on an inexpensive, commercial feedback-controlled treadmill (RX9200S, TOBEONE, Korea); the belt speed of the treadmill was automatically controlled depending on the location of the participants' body weight with an installed loadcell under the treadmill floor. The treadmill belt speed could be tuned to the participant's walking speed, with the treadmill belt speed increasing when the walker's location was in front of the treadmill center and decreasing when the walker's location was posterior to the treadmill center (Choi and Tack, 2013). The track size of the treadmill was $510 \times 1580\ \text{mm}^2$, and the treadmill had a single belt. The track belt was rotated by a three horsepower AC motor, which was driven by the field-oriented control method. In the pre-test, it was confirmed that when the walker on the treadmill deviated approximately 50 mm from the center line of the track, the treadmill motor was accelerated or decelerated within a response time of approximately 0.11 s.

The changing belt speeds were recorded to a computer with a 10 Hz sampling frequency through RS232 cables in all experiments. Participants performed sufficient practice walking to adapt to the feedback-controlled treadmill. All participants performed three walking trials of more than 10 min each and had enough time (approximately 15 min) to rest between trials. After 3 or 4 days, the same experiments were repeated. Participants were asked to maintain their preferred walking speed throughout the experiment and were also asked to keep their eyes focused straight ahead.

Two 13-mm infrared reflective markers were attached at the right toe and heel of the participants. The motion data were obtained with a 120 Hz sampling frequency using a three-dimensional motion capture system with six high-speed infrared cameras (Motion Analysis Corps, Santa Rosa, CA, USA). All marker data were low pass filtered at 10 Hz with a 4th-order zero-lag Butterworth filter (Dingwell and Cusumano, 2010; Winter, 2009).

2.3. Analysis

Ten minutes of walking data was used for the analysis. Heel contact events were determined using a foot velocity algorithm (O'Connor et al., 2007). The stride time was calculated from the interval between heel strikes, and the stride length was computed as the distance covered by one foot during the swing phase plus the distance covered by the other foot during this time interval (Danion et al., 2003).

To identify the within-day and between-day reliabilities, the average walking speed and the average, variability, and fractal dynamics of the spatiotemporal variables (i.e., stride time and stride length) were compared. The average walking speed of the participants was defined as the average treadmill speed recorded to the computer.

The coefficient of variance (CV = standard deviation/mean × 100) was used for the variability of the average walking speed and spatiotemporal variables. The scaling exponent α from DFA was used for the fractal dynamics characteristics (Peng et al., 1994). Briefly, the time series of data length, N from 528 to 647 strides (mean 593 ± 33 strides) after discarding depending on the individual's 10-min walking, was integrated (Damouras et al., 2010; Delignieres et al., 2006; Hunt et al., 2014; Pierrynowski et al., 2005). Then, the accumulated sum of the integrated series depending on the specific window size was calculated by increasing the range of data from 4 to $N/4$. At this point, the log of the average size of the fluctuation at each window size was plotted against the log of the window size (power-law graph). The slope (scaling exponent α) of this graph denoted the self-similarity and was used in the analysis. When $0.5 < \alpha < 1$, the data exhibited statistical persistence and a fractal-like long-range correlation; by contrast, when $\alpha < 0.5$, there was an anti-persistent correlation, and when $\alpha = 0.5$, the data were completely uncorrelated, i.e., white noise (Dingwell and Cusumano, 2010; Jordan et al., 2007; Terrier and Dériaz, 2012).

All of the variables were calculated using MATLAB (Mathworks Inc., Natick, MA, USA). For the within-day and between-day reliability of the variables, the intraclass correlation coefficient (ICC) of the type $(3, k)$ and standard error of measurement (SEM) were used. For all statistical processing, SPSS Statistics ver. 19 (IBM Corps, Somers, NY, USA) was used, and the significance level was set to.05.

3. Results

Table 1 shows the within-day reliability depending on three trials of repeated walking data from the same day. There was no significant difference in the average walking speed in the within-day test, and the reliability using ICC is shown. There was also no significant difference between the average, CV, and scaling exponent α of DFA for the stride time and stride length, and significant reliability was shown for all variables.

Table 1 also shows the results of the between-day reliability test based on trials performed on different days. There was no significant difference in any variable between days. Fig. 1 shows the average, maximum, minimum, and quartile of the scaling exponent α of DFA for the stride time and stride length of the within- and between-day measurements.

4. Discussion and conclusion

In most gait dynamics studies, stride intervals have been acquired for ground walking by using pressure-sensitive foot switches and inertial sensors (Bollens et al., 2010; Hausdorff, 2007). However, early gait dynamics studies revealed that the

Tables 1

Within-day and between-day reliabilities in treadmill speed, stride time and stride length.

Variables		**Day 1**			**Day 2**			**Within-day**			**Between-day**		
		Trial 1	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**	**ICC**	***p*-Value**	**SEM**	**ICC**	***p*-Value**	**SEM**
Treadmill speed (m/s)	**Mean**	1.35 (0.20)	1.37 (0.22)	1.40 (0.22)	1.40 (0.18)	1.40 (0.19)	1.39 (0.19)	0.982	0.000	0.03	0.965	0.000	0.04
	CV (%)	2.93 (0.99)	2.75 (1.09)	2.91 (1.30)	2.52 (1.26)	2.28 (1.04)	2.51 (0.88)	0.851	0.000	0.43	0.977	0.000	0.17
Stridetime(s)	**Mean**	1.09 (0.07)	1.09 (0.08)	1.08 (0.07)	1.07 (0.07)	1.06 (0.07)	1.06 (0.06)	0.958	0.000	0.02	0.951	0.000	0.02
	CV (%)	2.01 (0.58)	1.72 (0.51)	1.96 (0.43)	1.79 (0.46)	1.68 (0.50)	2.12 (0.38)	0.633	0.012	0.31	0.712	0.013	0.27
	DFA (α)	0.90 (0.07)	0.88 (0.09)	0.81 (0.10)	0.87 (0.08)	0.87 (0.07)	0.85 (0.13)	0.665	0.007	0.05	0.870	0.000	0.03
Stridelength(m)	**Mean**	1.15 (0.12)	1.17 (0.14)	1.17 (0.14)	1.17 (0.11)	1.16 (0.11)	1.15 (0.11)	0.977	0.000	0.02	0.914	0.000	0.04
	CV (%)	3.36 (0.73)	3.13 (0.74)	3.07 (0.86)	3.07 (0.71)	2.79 (0.78)	3.06 (0.76)	0.883	0.000	0.27	0.759	0.006	0.38
	DFA (α)	0.84 (0.12)	0.84 (0.13)	0.83 (0.11)	0.83 (0.10)	0.82 (0.13)	0.83 (0.12)	0.713	0.002	0.09	0.722	0.014	0.09