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Differences in reproducibility of gait variability and fractal dynamics according to walking duration

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Abstract.
BACKGROUND: Gait variability and fractal dynamics may be affected by the walking duration.
OBJECTIVE: The purpose of this study is to examine the reproducibility of stride time while walking on a self-paced treadmill.
METHODS: Fifteen young and healthy subjects walked on the treadmill for 10 minutes. Three to eight minutes duration of the data were used to compare the trial-to-trial and day-to-day reproducibility of the average, variability, and fractal dynamics of stride time.
RESULTS: The results show that all variables had high trial-to-trial reproducibility. In the day-to-day results, the average walking speed and mean stride time showed reproducibility without regard for duration, but the variability and gait fractal dynamics showed differences in reproducibility according to duration. The variability and fractal dynamics showed better reproducibility in less than 5 minutes and over time, respectively. However, both variables generally showed improved reproducibility when average data from two to three rounds were used.
CONCLUSION: Based on the results of this study, it is proposed that variability should be examined using data of 5 min or less, and fractal dynamics should be examined using 5 min or more of repeated data when performing walking tests from a gait dynamics perspective.

Keywords: Reproducibility, self-paced treadmill, walking duration, fractal dynamics, variability

1. Introduction

Fluctuations in continuous human walking data are not simply caused by irregular data. Walking studies that consider this phenomenon are known as "gait dynamics studies," and long-range correlation is a widely used method for representing this phenomenon quantitatively [1]. In particular, there have been studies on using detrended fluctuation analysis (DFA) to quantify long-range correlations in gait interval time data. Following these studies, there have been various studies on gait fractal dynamics, and this phenomenon has been used in studies up to the present time. There have also been studies on changes in the fractal dynamics of gait interval times resulting from neuro-diseases and walking conditions [1,2], and

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the analysis methods for this research have been supplemented and improved [3]. Based on these various previous studies, it is known that the long-range correlation characteristics of gait fractal dynamics can disappear because of the artificial (intended) adjustment of gait variables [4–6], and gait fractal dynamics can change because of neuro-diseases and reductions in body balance caused by aging [1,7,8]. It is also generally known that there is a need for walking data gathered over a long time to analyze gait dynamics [9].

Treadmills have been used in previous gait studies as a means of overcoming restrictions on experiment equipment and space. Conventional treadmills have a fixed belt speed and a limited gait speed for the walker. However, various forms of self-paced treadmill are currently being used to improve experimental environments. From a gait dynamics perspective, it is expected that self-paced treadmills will provide conditions that are somewhat more similar to over-ground walking than conventional treadmills [6,10–13]. However, it is necessary to perform additional studies on this matter.

In the case of elderly people suffering from a disease or falling, it is not easy to participate in a long walking experiments. Therefore, it is necessary to confirm the minimum walking time that is necessary to analyze gait dynamics. In a previous study by Pierrynowski et al. on walking duration (3–8 min) and the reproducibility of gait fractal dynamics while walking on a conventional treadmill, the highest trial-to-trial day and day-to-day reproducibility was seen in walking for 8 min. For shorter periods of walking duration, it was shown that reproducibility can be improved through repeated trials data, such as four trials of 3 min or three trials of 6 min [14]. Choi et al. reported on the trial-to-trial day and day-to-day reproducibility for a self-paced treadmill, but the analysis was not performed according to walking duration [10]. Therefore, there is a need to confirm the results regarding walking duration and reproducibility on a self-paced treadmill. The goal of this study is to examine trial-to-trial and day-to-day reproducibility according to walking duration on a self-paced treadmill. In addition, this study aims to examine the reproducibility of gait variability and fractal dynamics according to walking duration.

2. Methods

Fifteen healthy male university students (ages 22 $\pm$ 2 years, height 177 $\pm$ 5 cm, weight 72 $\pm$ 12 kg) participated in the experiments. We explained the purpose and process of the experiment to the subjects before the experiment and proceeded when they provided written informed consent.

The participants performed three treadmill walking sessions of 10 min each at their preferred walking speed (Day 1). After three to four days, the same experiments were repeated (Day 2). Before the experiment, participants were given enough practice time for treadmill adaptation, and more than 10 min of break time was provided between each experiment. They were also instructed to stare forward while walking and to maintain a constant walking speed.

All walking experiments were conducted on a treadmill with single belt (RX9200S, DRAX, Korea) that automatically controls its belt speed depending on the walking speed of the participants [10]. The treadmill belt speed was stored in a PC at a sampling frequency of 10 Hz.

Two reflective markers were attached at both the toe and heel of the participants. A three-dimensional motion analysis system consisting of six infrared cameras was used to collect motion data while walking at a sampling frequency of 120 Hz (Motion Analysis Corps, USA). The foot velocity algorithm method was used to detect gait events such as heel contact. The stride time is calculated as the time between successive heel contacts [15].

From 10 min of acquired data, 8 min was analyzed by excluding the first and the last minute. To identify the reproducibility with the walking durations, the data were cut into 3, 4, 5, 6, 7, and 8 min and compared.

For the analysis, the average walking speed and the mean stride time, stride time variability, and fractal dynamics of the stride time were compared. The average walking speed of the subjects was used as the average of the treadmill belt speed stored in the PC. The coefficient of variance (CV) was used for the variability of the stride time. The scaling exponent α in DFA was used for the fractal dynamic characteristics [1,16]. DFA was used to show the characteristics of long-range correlation (power-law) in the long-term time series data [3,10]. Box sizes for analyzing were used from 4 to N/4 with $N =$ length of each of the data. When α is 0.5, the experimental data is uncorrelated, and when α is between 0.5 and 1.0, the experimental data means that the long range correlation persists. If α is less than 0.5, it means that the correlation does not persist [1,10,13,17]. All variables used in the analysis were calculated with Matlab (MathWorks Inc., USA).

To investigate the trial-to-trial and day-to-day reproducibility of the variables, the intraclass correlation coefficient (ICC) and standard error of measurement (SEM) were used. Type (3, k) is used for ICC, and SEM is as shown below. The meaning of ICC size can be interpreted as follows [10,13,18]:

$$\text{SEM} = \text{standard deviation} \times \sqrt{1 - ICC}$$

	Poor	Fair	Good	Excellent
ICC	< 0.40	$0.40 \sim 0.59$	$0.60 \sim 0.74$	$0.75 \sim 1.00$

To confirm reproducibility by date (day-to-day), the averages of Trial 1, Trials 1 and 2, and Trials 1, 2, and 3 of each date were also checked. To investigate the differences between trials, repeated ANOVA were performed. SPSS Statistics version 25 (IBM Corp., Somers, NY, USA) was used in the statistical analysis. The statistical significance (p-value) was used based on 0.05.

3. Results

3.1. Trial-to-trial reproducibility

Table 1 presents the reproducibility results for the variables according to three walking trials on the same day (Day 1). For all variables, there is no significant difference between trials, and the reproducibility was high. Also, there is no significant difference according to the walking duration (3–8 min), and the reproducibility was high for all variables.

3.2. Day-to-day reproducibility

Table 2 shows the reproducibility results by date for three trials performed on Days 1 and 2. The average walking speed and the mean stride time showed reproducibility by date without regard to the number of trials or the walking duration. However, the CV and DFA results generally showed good reproducibility only when there were an average of two trials or more. When the results of one trial were compared, the CV only showed reproducibility when the duration was 5 min or less, and the DFA showed reproducibility only when the duration was 6 min or more (Fig. 1).

4. Discussion

The trial-to-trial and day-to-day reproducibility of the average walking speed and the mean, variability, and gait fractal dynamics of the stride time when young adults walked on a self-paced treadmill were

Table 1
Trial-to-trial reproducibility of gait variables by walking duration

Variables	Duration (min.)	Trial 1	Trial 2	Trial 3	ANOVA	ICC	p	SEM
Walking speed (m/sec)	3	1.42 (0.15)	1.44 (0.17)	1.44 (0.17)	*0.52*	0.99	**0.00**	0.06
	4	1.42 (0.15)	1.44 (0.17)	1.43 (0.17)	*0.35*	0.99	**0.00**	0.06
	5	1.42 (0.15)	1.44 (0.17)	1.43 (0.17)	*0.35*	0.99	**0.00**	0.07
	6	1.42 (0.15)	1.44 (0.17)	1.44 (0.18)	*0.46*	0.99	**0.00**	0.07
	7	1.42 (0.15)	1.44 (0.18)	1.44 (0.18)	*0.43*	0.99	**0.00**	0.07
	8	1.42 (0.15)	1.44 (0.18)	1.44 (0.18)	*0.32*	0.99	**0.00**	0.07
Stride time								
Mean (sec)	3	1.06 (0.05)	1.07 (0.06)	1.06 (0.06)	*0.23*	0.96	**0.00**	0.01
	4	1.06 (0.05)	1.07 (0.06)	1.06 (0.06)	*0.32*	0.97	**0.00**	0.01
	5	1.06 (0.05)	1.07 (0.06)	1.06 (0.06)	*0.25*	0.97	**0.00**	0.01
	6	1.06 (0.05)	1.07 (0.06)	1.06 (0.06)	*0.32*	0.98	**0.00**	0.01
	7	1.06 (0.05)	1.07 (0.05)	1.06 (0.05)	*0.29*	0.98	**0.00**	0.01
	8	1.06 (0.05)	1.07 (0.06)	1.06 (0.06)	*0.21*	0.98	**0.00**	0.01
CV (%)	3	1.43 (0.28)	1.36 (0.39)	1.32 (0.25)	*0.57*	0.60	**0.05**	0.19
	4	1.47 (0.29)	1.43 (0.36)	1.37 (0.27)	*0.41*	0.97	**0.00**	0.05
	5	1.48 (0.28)	1.46 (0.37)	1.38 (0.26)	*0.41*	0.78	**0.01**	0.14
	6	1.49 (0.29)	1.47 (0.38)	1.47 (0.35)	*0.97*	0.78	**0.01**	0.16
	7	1.52 (0.35)	1.45 (0.34)	1.52 (0.39)	*0.64*	0.75	**0.02**	0.18
	8	1.54 (0.33)	1.45 (0.35)	1.54 (0.41)	*0.44*	0.77	**0.01**	0.17
DFA (α)	3	0.83 (0.13)	0.76 (0.15)	0.76 (0.14)	*0.23*	0.62	**0.04**	0.09
	4	0.82 (0.11)	0.79 (0.15)	0.80 (0.11)	*0.52*	0.69	**0.01**	0.07
	5	0.84 (0.11)	0.80 (0.12)	0.82 (0.10)	*0.42*	0.63	**0.02**	0.07
	6	0.84 (0.12)	0.82 (0.12)	0.84 (0.10)	*0.51*	0.73	**0.01**	0.06
	7	0.85 (0.12)	0.82 (0.13)	0.85 (0.10)	*0.63*	0.76	**0.00**	0.06
	8	0.86 (0.12)	0.84 (0.11)	0.87 (0.11)	*0.47*	0.73	**0.01**	0.06

Bold letters are p values, indicating statistical significance of the ICC results.

examined. Also it was examined the difference in these variables according to a walking duration of 3–8 min. The results can be summarized as follows. The trial-to-trial day results generally showed good reproducibility with a high ICC and low SEM for all variables. For the day-to-day results, the reproducibility of the average walking speed and the mean stride time was constant regardless of the duration, but the reproducibility of the variability and the gait fractal dynamics of the stride time varied according to the duration. In a comparison using single walking trials on different dates, the variability showed reproducibility for relatively short durations of 5 min or less, while the fractal dynamics had good reproducibility only for long duration data of 6 min or more. However, when the average data from two to three trials were used for each variable, the reproducibility generally improved (Table 2, Fig. 1).

Wiens et al. used 14-min data from a self-paced treadmill to examine the day-to-day reproducibility of step time variability and fractal dynamics, as well as the differences compared with a conventional treadmill. In the results of day-to-day, the variability and fractal dynamics were represented low reproducibility [13]. When the single-trial experiment data were compared for each date, the variability and fractal dynamics were represented relatively low reproducibility, and this corresponded to the results of this study. However, the step time used in the previous paper was different from the stride time, and no repeated experiment was performed. Pierrynowski et al. examined the reproducibility of gait fractal dynamics on a conventional treadmill [14]. According to our results, trial-to-trial reproducibility was consistent regardless of the walking duration, but the day-to-day reproducibility was affected by the duration ($3 \sim 8$ min). The best reproducibility was seen at 8 min of walking. During walking duration of less than 8 min, it was found that the reproducibility could be improved through repeated trials. In their conclusions, Pierrynowski et al. proposed repeated walking for a minimum of 6 min during experiments

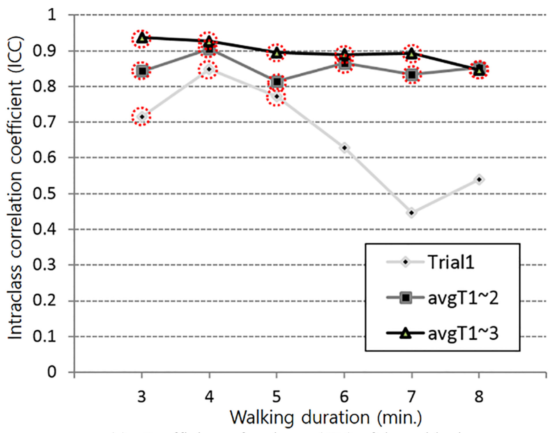
Table 2
Day-to-day reproducibility of gait variables by walking duration

Variables	Duration (min.)	Use of trials								
		1 trial			Average of 2 trials			Average of 3 trials		
		ICC	*p*	SEM	ICC	*p*	SEM	ICC	*p*	SEM
Walking speed (m/sec)	3	0.96	**0.00**	0.11	0.98	**0.00**	0.08	0.98	**0.00**	0.08
	4	0.95	**0.00**	0.12	0.97	**0.00**	0.09	0.98	**0.00**	0.08
	5	0.95	**0.00**	0.12	0.98	**0.00**	0.08	0.98	**0.00**	0.08
	6	0.96	**0.00**	0.11	0.98	**0.00**	0.08	0.98	**0.00**	0.08
	7	0.96	**0.00**	0.1	0.98	**0.00**	0.08	0.98	**0.00**	0.08
	8	0.96	**0.00**	0.1	0.98	**0.00**	0.08	0.98	**0.00**	0.09
Stride time										
Mean (sec)	3	0.85	**0.00**	0.02	0.9	**0.00**	0.02	0.93	**0.00**	0.01
	4	0.85	**0.00**	0.02	0.91	**0.00**	0.02	0.93	**0.00**	0.01
	5	0.85	**0.00**	0.02	0.92	**0.00**	0.02	0.93	**0.00**	0.01
	6	0.85	**0.00**	0.02	0.92	**0.00**	0.02	0.93	**0.00**	0.01
	7	0.86	**0.00**	0.02	0.93	**0.00**	0.01	0.93	**0.00**	0.01
	8	0.88	**0.00**	0.02	0.93	**0.00**	0.01	0.94	**0.00**	0.01
CV (%)	3	0.71	**0.04**	0.15	0.84	**0.00**	0.1	0.94	**0.00**	0.06
	4	0.85	**0.00**	0.11	0.91	**0.00**	0.09	0.93	**0.00**	0.07
	5	0.77	**0.01**	0.14	0.81	**0.01**	0.12	0.89	**0.00**	0.08
	6	0.63	*0.07*	0.18	0.86	**0.00**	0.11	0.89	**0.00**	0.09
	7	0.45	*0.20*	0.25	0.83	**0.01**	0.12	0.89	**0.00**	0.09
	8	0.54	*0.12*	0.23	0.85	**0.00**	0.12	0.84	**0.01**	0.12
DFA (α)	3	0.17	*0.37*	0.13	0.43	*0.22*	0.08	0.73	**0.04**	0.06
	4	0.48	*0.08*	0.09	0.61	**0.05**	0.08	0.84	**0.01**	0.04
	5	0.36	*0.15*	0.1	0.54	*0.08*	0.07	0.81	**0.01**	0.04
	6	0.66	**0.04**	0.07	0.79	**0.01**	0.05	0.84	**0.01**	0.04
	7	0.62	**0.03**	0.08	0.74	**0.01**	0.06	0.78	**0.02**	0.05
	8	0.63	**0.05**	0.09	0.71	**0.02**	0.06	0.73	**0.03**	0.05

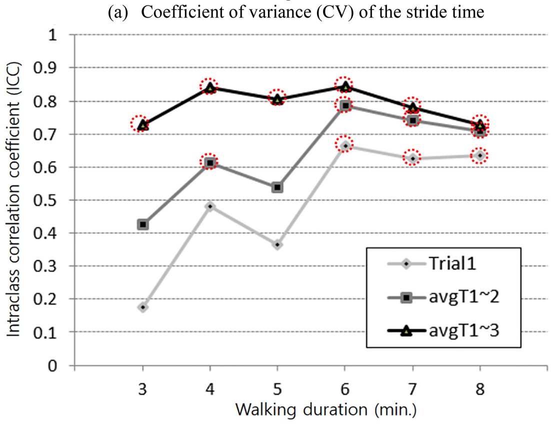
Bold letters are p values, indicating statistical significance of the ICC results.

on gait dynamics [14]. These results are considered to match the results of the present study. Even though a conventional treadmill was used, it can be reasoned that reproducibility on a belt-type treadmill is fairly similar. It may be possible to use common guidelines for walking duration when performing experiments regarding gait dynamics on a treadmill.

Another notable result of this study is that the variability and fractal dynamic characteristics showed opposite to each other around 5 $\sim$ 6 minutes. A previous study has reported that there were differences in variability between essential tremor patients and healthy adults, but there was no difference in fractal dynamics [19]. For elderly patients who have experienced falls, it was also reported that there was more of a difference in the fractal dynamics than the variability [7]. In general, experiments that use the walking variables' fluctuations often examine the magnitude and the structure of the fluctuation simultaneously. These are derived from the same gait variable (i.e., stride time), but variability and fractal dynamics can be considered as the magnitude and the structure of the fluctuation, respectively. The variability is the quantified value of the magnitude of the fluctuation itself, while the fractal dynamics are known to depend on the walking adjustment mechanism, independent of the magnitude of the fluctuation. However, to examine why this difference occurs, it is necessary to perform additional studies that compare the kinematics, kinetics, electromyography, and fatigue of the legs that are directly related to the walking motion. Considering only the reproducibility results of this experiment, it was found that using 5 min or less of walking duration is suitable for examining the magnitude of the fluctuation (i.e., variability) and using 6 min or more of data is suitable for examining the structure of the fluctuation (i.e., fractal dynamics).



(a) Coefficient of variance (CV) of the stride time



(b) α from detrended fluctuation analysis (DFA) of the stride time

Fig. 1. Day-to-day reproducibility of (a) the variability (CV) and (b) fractal dynamics (DFA) of the stride time by walking duration. (avgT1 ∼ 2: the average of trial 1 and trial 2, avgT1 ∼ 3: the average of trial 1, trial 2 and trial 3; Red dotted circle indicates that it is reproducible).

This study has several limitations. First, this study was performed on only healthy adults, and senior citizens or patient with any diseases may produce different results. Also, the walking speed (i.e., preferred walking speed) and variables (i.e., stride time) were limited by the experiment conditions. As with the previous experiments that were compared above, it can be expected that there will be some degree of relationship with the step time and spatial data (length, width, etc.) results, but the same results cannot be guaranteed. Finally, a standardized algorithm for self-paced treadmills has not been proposed yet, and, therefore, the results may have been influenced by the speed control algorithm.

5. Conclusions

The trial-to-trial day and day-to-day reproducibility of young adults' average walking speed and the mean, variability, and fractal dynamics of their stride time when walking on a self-paced treadmill were examined. The differences in each variable according to a walking duration of 3–8 min were also examined. The results can be summarized as follows: In the trial-to-trial day results, all variables generally showed good reproducibility with a good ICC and a small SEM. In the day-to-day results, the average walking speed and the mean stride time reproducibility was consistent regardless of duration, but the variability and the fractal dynamics of the stride time showed differences in reproducibility according to duration. In a comparison using single walking trials on different dates, the variability showed reproducibility for relatively brief durations of 5 min or less, while the fractal dynamics had good reproducibility only for long-duration data of 6 min or more. However, when the averages of the data from two to three trials were used, the reproducibility generally improved for all variables. Based on the results of this study, it is proposed that variability should be examined using 5 min or less of data, and fractal dynamics should be examined by repeatedly measuring 5 min or more of data when performing walking tests from a gait dynamics perspective.

Acknowledgments

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Conflict of interest

None to report.

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