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Reliability of the fluctuations within the stride time series measured in runners during treadmill running to exhaustion

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ABSTRACT

Background: The fluctuations within stride time series (i.e., stride time variability and complexity) during running exhibit long-range correlation. Detecting the breakdown of the long-range correlation was proposed for monitoring the occurrence of running-related injuries during running. However, the stride time fluctuations were only measured from the unilateral side. In addition, the reliability of the stride time fluctuations of within-subject repeated measures remains largely unknown, particularly during exhaustive running.

Purposes: This study investigated between-side and between-day reliabilities of the stride time variability and complexity of right and left sides during an exhaustive running.

Methods: The stride time variability and complexity of bilateral sides were obtained while 24 healthy participants performed a 31-minute treadmill running at their individual anaerobic threshold speed. Seven of the 24 participants performed the treadmill running test twice at two different days 5–7 days apart. Limits of agreement (LoA) and intraclass correlation coefficient (ICC) were respectively used to assess the absolute and relative between-side and between-day reliabilities.

Results: The stride time variability and complexity of right and left sides were highly symmetrical (LoA: (-0.500%, 0.459%) and (-0.052, 0.051), respectively; ICC: 0.94 (0.87, 0.97) and 0.98 (0.95, 0.99), respectively). The overall stride time variability and complexity revealed good between-day reliability (LoA: (-1.044%, 0.724%) and (-0.067, 0.115), respectively; ICC: 0.78 (0.45, 0.92) and 0.81 (0.48, 0.93), respectively). However, the segmented stride time complexity showed poor between-day reliability (ICCs < 0.40).

Conclusion: The findings demonstrated that the stride time series showed equivalent fluctuations between right and left sides and good between-day reliability in fluctuations during exhaustive running. Given the poor between-day reliability in the segmented stride time series, stride time series during exhaustive running could be collected from either right or left side and should be processed as an overall in the future.

1. Introduction

Running-related injuries (RRIs) are quite common [1]. Understanding the risk factors of RRIs allows for identifying runners at high risk of RRIs development and implementing appropriate interventions for RRIs prevention. The fluctuations within the stride time series during running, through advanced statistical analysis (e.g., Detrended fluctuation analysis (DFA)), were found to be associated with RRIs [2,3]. The stride time fluctuations have been employed as an indicator to distinguish injured runners from their healthy counterparts [2] and determine runners' training status [4]. Some researchers even proposed to monitor the occurrence of RRIs through detecting the breakdown of the internal structure of the stride time series during running [5].

Given the significances in practice, the stride time fluctuations during running have been frequently studied [2–8]. The stride time fluctuations were oft-times evaluated from two aspects: stride time variability, which reflects the overall distribution features of the stride time series and is quantified using coefficient of variation (CV) and/or standard deviation (SD); and stride time complexity, which reflects the internal structure of the stride time series and is quantified using scaling exponent alpha calculated through DFA [2–8]. In these studies [2–8], with the assumption of equivalence between right and left legs, the stride time series was mostly obtained from either right or left side during running. However, leg preferences have been largely discussed [9] and asymmetries in running biomechanics have been frequently reported between right and left legs [10–12]. Besides, a previous study reported that alpha was significantly different between right and left sides [13], in which 23 participants walked on treadmill for 8 min and

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alpha of right and left sides were respectively calculated using the stride time series measured from right and left heel markers. They found that alpha of the right side was significantly smaller than that of the left side. Although running is similar to walking with many of the basic biomechanics [14], so far, it remains unknown whether similar inter-limb differences in the stride time fluctuations (CV and alpha) would be observed during running.

Moreover, the inter-limb differences may increase with progression of fatigue [12] because the dominant leg was previously found to behave significantly different from that of the non-dominant leg during running [9]. In the study by Radzak et al. [12], running biomechanics of 20 participants at fresh and fatigued conditions were compared, and they found that the knee movement pattern became more asymmetrical with progression of fatigue. Nevertheless, it remains unclear whether the inter-limb differences in the stride time fluctuations would be magnified during an exhaustive running.

In addition, the stride time series was mostly acquired only for one time in previous studies [2–8]. However, these studies rarely provided information about the reliability of the stride time fluctuations of within-subject repeated measures, for example, the stride time series being measured at two different days. Good between-day reliability of the stride time fluctuations is critical to running assessment because it ensures that the identified changes are real changes instead of measurement errors. Between-day reliability of alpha during walking was previously demonstrated to be good [13], where the stride time series was measured when 8 healthy participants performed 8-min treadmill walking. Another study [15] found that alpha revealed good between-day reliability (intraclass correlation coefficient (ICC) = 0.74–0.87) during running. In their study [15], 10 healthy male distance runners ran on treadmill for 6 min at 11, 13 and 15 km/h at two different days. Because of a quite short duration in both the two aforementioned studies [13,15], alpha was calculated using a limited count of strides, i.e., 402.5 (346–452) strides during walking [13], and around 500 strides during running [15]. However, a minimum of 600 strides are required when alpha is used to differentiate normal and pathological walking with a reasonable accuracy [16]. Although fatigue is unavoidable during distance running, the between-day reliability of the stride time variability and complexity during an exhaustive running is still unknown.

Therefore, this study aimed to investigate the reliability of the stride time variability (CV) and complexity (alpha) estimated from the stride time series of right and left sides during an exhaustive running. Both between-side and between-day reliabilities were analyzed. It was hypothesized that the stride time variability and complexity would present poor between-side reliability because of interactions of leg preference and fatigue, and good between-day reliability.

2. Methods

Twenty-four (6 females, 18 males) asymptomatic recreational runners were recruited to participate in this study. Their mean (SD) age, height, body mass, and body mass index were 24.2 (6.0) years, 170.3 (7.6) cm, 61.5 (10.1) kg, and 21.1 (2.5) kg/m^2, respectively. The participants were rearfoot strikers, self-reported right leg dominance, and had some treadmill running experience. This study was approved by the university institutional review board. They all provided written informed consent prior to data collection.

To obtain a long continuous sequence of stride time and to mimic an exhaustive running, the participants were required to finish an adopted running protocol [8,17,18]. Specifically, they were asked to run on treadmill for 31 min at their individual anaerobic threshold speed. It has been confirmed that runners regardless of training level would be fatigued at the end of the running test [8,17,18]. The anaerobic threshold speed was determined one week before the running test by asking each participant to perform a preliminary running test. The preliminary running test adopted a widely-used incremental load running protocol [8,17,18]. Briefly, the speed was initially set at 8.0 km/h and increased by 1.0 km/h per 2 min until reaching 15.0 km/h; the breathing air was real-time analysed using a spiroergometry system (Cortex Metalyzer 3B, Germany), and the anaerobic threshold speed was defined as the speed corresponding to initially steep increase of the ratio of ventilation to oxygen consumption. To investigate the between-day reliability, seven (all are males) of the 24 recruited participants were invited to revisit the laboratory 5–7 days after and to perform the same treadmill running test again.

During the running test, two reflective markers were attached to the middle of the heel counter of running shoes, and three-dimensional positions of the markers were thoroughly acquired at 200 Hz using motion capture system (Qualisys Inc., Sweden) with a reported error of less than 0.4 mm. Prior to and immediately after the running test, blood lactate accumulation was measured using a drop of blood from the ring finger by a portable lactate meter (Nova Biomedical Corp., USA), and rating of perceived exertion (RPE) was measured using a 6–20 scale. The inclination of the treadmill was set at 0 °. The participants wore their own running shoes and were given around 10 min for warm-up and familiarizing themselves with the whole procedures.

Post-processing was performed in Matlab (The Mathworks Inc., Natick, MA, USA). Marker position data were low-pass filtered at 7 Hz with a second-order, zero-lag Butterworth filter. Stride time series was obtained by identifying the local minimum of the vertical displacements of the markers. To minimize the start-up and end effects, data of the initial and last 30 s were removed from analysis. Data of the remaining 30 min were evenly segmented into three parts (S1, S2 and S3). CV and alpha were calculated for each segmented and overall stride time series. Accordingly, CV was the ratio of the SD to the mean of the interested dataset and expressed in percentage. Alpha was calculated using DFA according to previously described procedures (details see [8]). The window size used for DFA was set from 16 to N/9, where N is the number of stride time of the interested dataset [8,16].

Descriptive statistics were conducted to gain the overall features of the stride time series. ICC was used to determine the between-side (24 participants, 1 day (Day1), and 2 sides (Right and Left)) and between-day (7 participants, 2 days (Day1, Day2), and 2 sides (Right and Left)) relative reliability. A 95% confidence interval (95% CI) was provided to account for sampling variation. The absolute reliability was estimated using limits of agreement (LoA). Paired samples t-tests were performed to investigate the differences between right and left sides and between Day1 and Day2. Significance level was set at $p = 0.05$. All the statistical analyses were performed using a statistical software (SPSS Version 21.0, IBM Inc., Chicago, IL, USA).

3. Results

All the participants finished the 31-minute treadmill running test. For the 24 participants used for evaluating between-side reliability, the mean (SD) running speed was 11.8 (1.4) km/h; the blood lactate accumulation before and after the running test was 1.3 (0.7) and 7.5 (1.4) mmol/L, respectively; the RPE score was 8.3 (2.0) ("Extremely light") before the running test and 17.4 (2.0) ("very hard") after the running test. For the 7 participants used for assessing between-day reliability, the mean (SD) running speed was 11.4 (0.8) km/h; the blood lactate accumulation before and after the running test was respectively 1.2 (0.4) and 5.0 (2.5) mmol/L at Day1, and was respectively 1.9 (1.0) and 5.2 (2.8) mmol/L at Day2; the RPE score before the running test was 6.9 (1.9) at Day1 and 7.4 (1.3) at Day2, and after the running test was 16.0 (2.8) at Day1 and 16.0 (2.1) at Day2. There were no statistical differences in both the blood lactate accumulation and RPE score between Day1 and Day2 ($p > 0.05$).

3.1. Between sides (Right vs. Left)

The mean (95% CI) count of strides of S1, S2, S3 and overall were

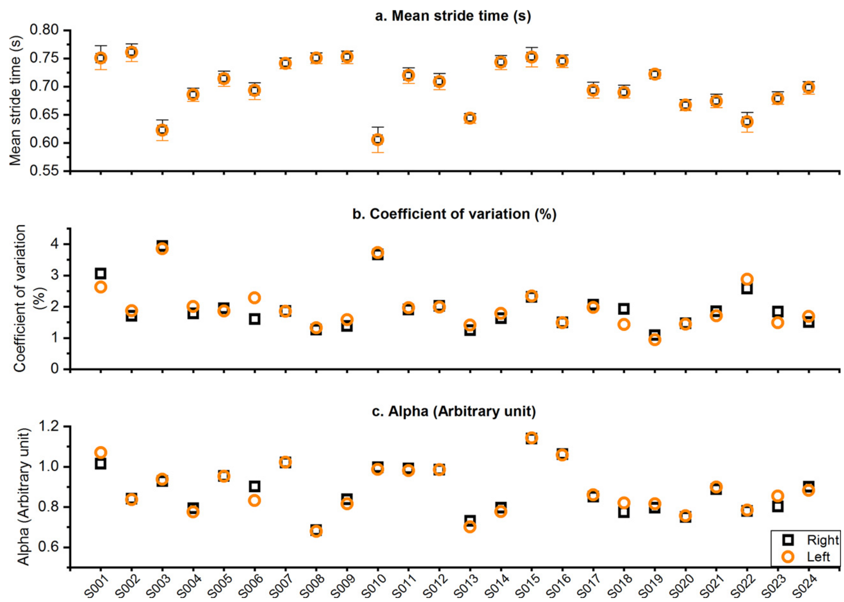

Fig. 1. The mean stride time, coefficient of variation (CV) and alpha of the overall stride time series for right and left sides of each participant during 31-minute treadmill running.

Table 1
Mean alpha and mean coefficient of variation (CV) for right and left sides, and relative and absolute between-side reliability.

			Mean (95% CI)	T test	Relative reliability ICC (95% CI)	Absolute reliability (%) Mean difference (LoA)
CV	S1	Right	1.833 (1.590, 2.076)	t_{23} = 0.30; p = 0.77	0.92 (0.82, 0.96)	0.014 (-0.442, 0.470)
		Left	1.819 (1.580, 2.057)			
	S2	Right	1.652 (1.415, 1.890)	t_{23} = 0.04; p = 0.97	0.94 (0.86, 0.97)	−0.002 (-0.417, 0.414)
		Left	1.654 (1.403, 1.905)			
	S3	Right	1.814 (1.578, 2.049)	t_{23} = 0.29; p = 0.78	0.92 (0.82, 0.96)	0.014 (-0.436, 0.463)
		Left	1.800 (1.568, 2.032)			
	Overall	Right	1.961 (1.661, 2.262)	t_{23} = 0.42; p = 0.68	0.94 (0.87, 0.97)	−0.021 (-0.500, 0.459)
		Left	1.982 (1.686, 2.278)			
Alpha	S1	Right	0.783 (0.715, 0.851)	t_{23} = 0.25; p = 0.80	0.95 (0.88, 0.98)	−0.003 (-0.108, 0.103)
		Left	0.786 (0.718, 0.854)			
	S2	Right	0.726 (0.678, 0.773)	t_{23} = 0.97; p = 0.34	0.92 (0.83, 0.96)	−0.009 (-0.094, 0.077)
		Left	0.734 (0.690, 0.779)			
	S3	Right	0.763 (0.697, 0.828)	t_{23} = 1.02; p = 0.32	0.97 (0.94, 0.99)	0.008 (-0.063, 0.079)
		Left	0.755 (0.691, 0.820)			
	Overall	Right	0.884 (0.834, 0.933)	t_{23} = 0.15; p = 0.88	0.98 (0.95, 0.99)	−0.001 (-0.052, 0.051)
		Left	0.885 (0.834, 0.935)			

Note:
CV, coefficient of variation;
95% CI, 95% confidence of interval;
ICC, intraclass correlation coefficient;
LoA, limits of agreement.

866.0 (842.6, 889.4), 858.3 (835.4, 881.2), 858.1 (835.7, 880.5) and 2577.1 (2508.9, 2645.3), respectively. The mean stride time, CV and alpha of bilateral sides of the overall stride time series during the running test are plotted for each participant in Fig. 1. The descriptive and statistical results are summarized in Table 1.

There were no statistical differences in both CV and alpha between right and left sides (p > 0.30). For CV, the mean (LoA) absolute differences were 0.014% (-0.442%, 0.470%) for S1, -0.002% (-0.417%, 0.414%) for S2, 0.014% (-0.436%, 0.463%) for S3 and -0.021% (-0.500%, 0.459%) for overall; for alpha, the absolute differences were -0.003 (-0.108, 0.103), -0.009 (-0.094, 0.077), 0.008 (-0.063, 0.079) and -0.001 (-0.052, 0.051) for S1, S2, S3 and overall, respectively. To illustrate the absolute reliability between right and left sides, the Bland-Altman plots for the CV and alpha of the overall stride time series are presented in Fig. 2. Both CV and alpha revealed ICCs of greater than 0.92 (Table 1), which indicates excellent relative reliability according to the guidelines suggested by Koo and Li [19].

3.2. Between days (Day1 vs. Day2)

The mean (95% CI) count of strides of S1, S2, S3 and overall for Day1 were respectively 863.6 (814.7, 912.5), 848.7 (803.5, 893.9), 849.4 (803.1, 895.8) and 2556.4 (2416.7, 2696.2), and for Day2 were 860.3 (797.4, 923.2), 848.0 (790.1, 905.9), 844.0 (795.4, 892.6) and 2547.0 (2379.5, 2714.5), respectively. The mean stride time, CV and alpha of bilateral sides of the overall stride time series during the running test were plotted for each participant at both days in Fig. 3. Collapsed across right and left sides of the 7 participants, the descriptive and statistical results are summarized in Table 2.

There were no significant differences in both CV (p > 0.20) and alpha (p > 0.07) between Day1 and Day2. For CV, the mean (LoA) absolute differences were 0.053% (-0.501%, 0.606%) for S1, -0.098%

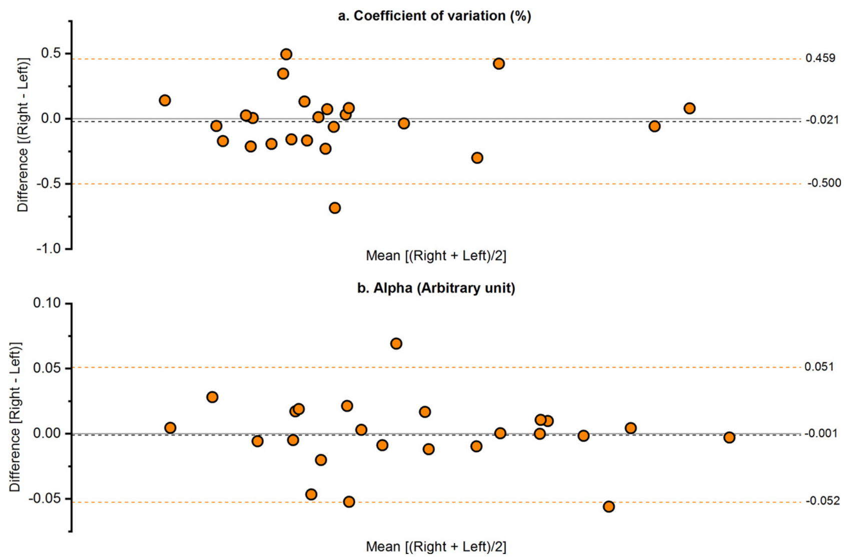

Fig. 2. Bland-Altman plots indicating agreements of the coefficient of variation (CV) and alpha of the overall stride time series between right and left sides during 31-minute treadmill running.

(-0.525%. 0.328%) for S2, 0.059% (-0.536%, -0.653%) for S3 and -0.160% (-1.044%, 0.724%) for overall; for alpha, the absolute differences were 0.061 (-0.175, 0.298), 0.008 (-0.333, 0.349), 0.008 (-0.294, 0.309) and -0.024 (-0.067, 0.115) for S1, S2, S3 and overall, respectively. The absolute between-day reliability of the CV and alpha was further illustrated by presenting the Bland-Altman plots for the CV and alpha of the overall stride time series in Fig. 4.

For CV, the ICCs were greater than 0.78, which indicates good between-day reliability but with a wide range (i.e., 95% CI was from 0.45 to 0.96). For the alpha of the overall stride time series, the ICC (95% CI) was 0.81 (0.48, 0.93) indicating a good between-day reliability but with a wide range. For the alpha of each segmented stride time series, the mean (95% CI) ICCs were 0.37 (0.22, 0.64), 0.20 (0.10, 0.47) and 0.25 (0.13, 0.55) for S1, S2 and S3, respectively, which indicates poor between-day reliability.

4. Discussion

This study aimed to investigate the between-side and between-day reliabilities of the stride time variability (CV) and complexity (alpha) during an exhaustive running. It was hypothesized that there would be a poor between-side reliability and a good between-day reliability. The CV and alpha were measured from 24 healthy participants when they performed a 31-minute treadmill running at their individual anaerobic threshold speed. The findings, partially conflicting to the hypotheses, indicated that both CV and alpha revealed excellent between-side reliability (ICCs > 0.92); the between-day reliability for CV was good (ICCs > 0.78) and for alpha was poor when calculated using segmented dataset (ICCs < 0.40) but good when calculated using overall dataset (ICC = 0.81).

The CV (Right: 1.96% (0.71%); Left: 1.98% (0.70%)) and alpha (Right: 0.88 (0.12); Left: 0.89 (0.12)) estimated in this study were within the previously reported range (CV: 1.17-2.31%; alpha:

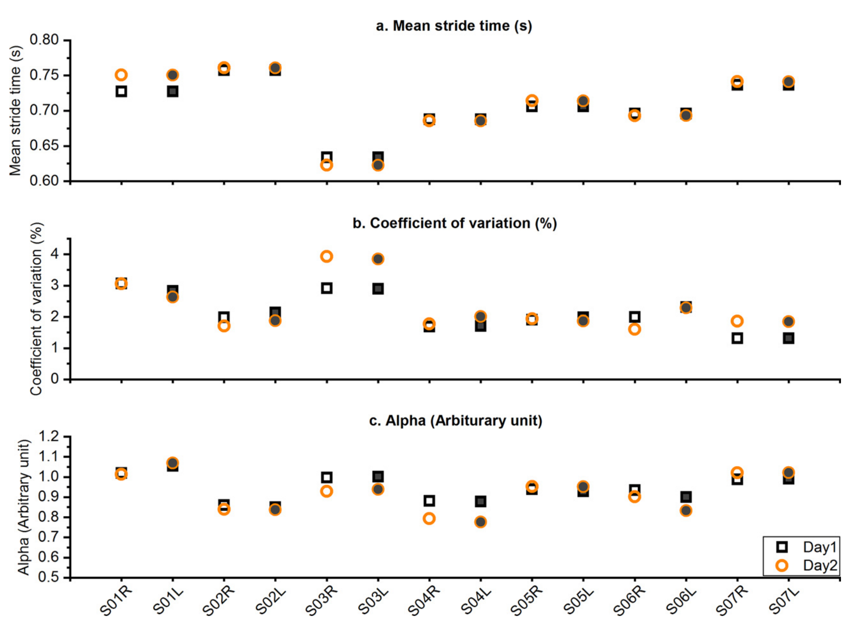

Fig. 3. The mean stride time, coefficient of variation (CV) and alpha of the overall stride time series for right and left sides of each participant at Day1 and Day2 during 31-minute treadmill running.

Table 2
Mean alpha and mean coefficient of variation (CV) for Day1 and Day2, and relative and absolute between-day reliability.

			Mean (95% CI)	T test	Relative reliability ICC (95% CI)	Absolute reliability (%) Mean difference (LoA)
CV	S1	Day1	2.143 (1.846, 2.440)	t_{13} = 0.70; p = 0.50	0.87 (0.66, 0.96)	0.053 (-0.501, 0.606)
		Day2	2.090 (1.749, 2.432)			
	S2	Day1	1.777 (1.568, 1.987)	t_{13} = 1.69; p = 0.11	0.85 (0.59, 0.95)	−0.098 (-0.525, 0.328)
		Day2	1.876 (1.609, 2.142)			
	S3	Day1	2.105 (1.824, 2.386)	t_{13} = 0.72; p = 0.48	0.83 (0.57, 0.94)	0.059 (-0.536, 0.653)
		Day2	2.046 (1.728, 2.364)			
	Overall	Day1	2.143 (1.807, 2.479)	t_{13} = 1.33; p = 0.21	0.78 (0.45, 0.92)	−0.160 (-1.044, 0.724)
		Day2	2.303 (1.855, 2.751)			
Alpha	S1	Day1	0.809 (0.763, 0.855)	t_{13} = 1.91; p = 0.08	0.37 (0.22, 0.64)	0.061 (-0.175, 0.298)
		Day2	0.747 (0.681, 0.814)			
	S2	Day1	0.749 (0.685, 0.813)	t_{13} = 0.17; p = 0.87	0.20 (0.10, 0.47)	0.008 (-0.333, 0.349)
		Day2	0.741 (0.669, 0.814)			
	S3	Day1	0.796 (0.718, 0.874)	t_{13} = 0.19; p = 0.85	0.25 (0.13, 0.55)	0.008 (-0.294, 0.309)
		Day2	0.788 (0.743, 0.832)			
	Overall	Day1	0.944 (0.907, 0.982)	t_{13} = 1.96; p = 0.07	0.81 (0.48, 0.93)	−0.024 (-0.067, 0.115)
		Day2	0.920 (0.866, 0.974)			

Note:
CV, coefficient of variation;
95% CI, 95% confidence of interval;
ICC, intraclass correlation coefficient;
LoA, limits of agreement.

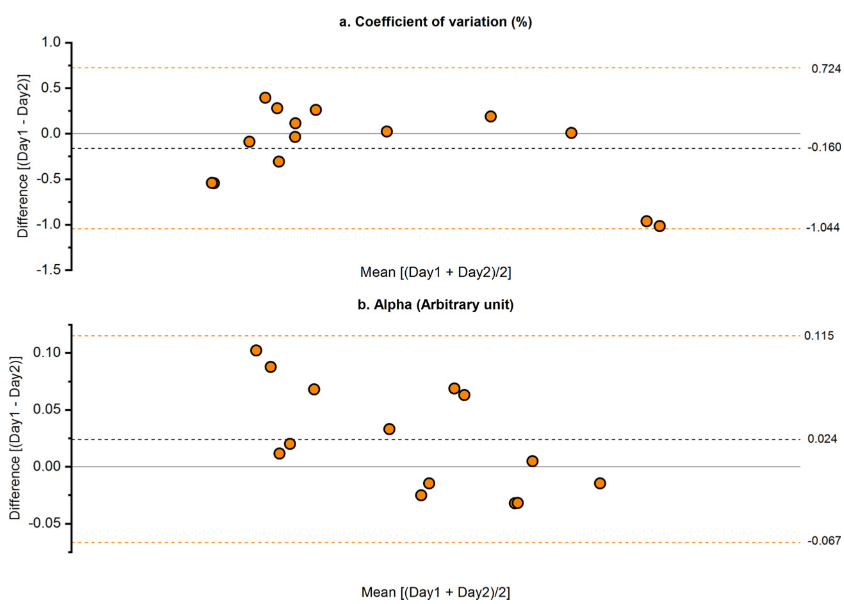

Fig. 4. Bland-Altman plots indicating agreement agreements of the coefficient of variation (CV) and alpha of the overall stride time series between two Day1 and Day2 during 31-minute treadmill running.

0.88–1.05) [2] which was estimated from healthy runners during a prolonged running on a 300-m indoor track at their 5-k race paces. The findings demonstrated no leg preference by fatigue interactions on the stride time fluctuations, because CV and alpha showed no differences between right and left sides, and good between-side reliabilities were observed. Stride time, a ‘final output’ of the locomotor system [20], could be viewed as ‘clock’ set by the central system (e.g., basal ganglia). Symmetry could be maintained although the degrees of freedom of bilateral legs may vary according to the demands of internal and external constraints (e.g., fatigue). A study [21] found that the participants could automatically change temporal motor output (e.g., stride time) to restore inter-limb symmetry during walking in an asymmetric environment, e.g., split-belt treadmill. Further, asymmetry would put one at a disadvantage during performing physical activities (e.g., running) because the stronger leg (dominant) may increase work to compensate for the weaker leg (non-dominant). Pierrynowski et al. [13] simultaneously collected stride time series of bilateral sides when 23 asymptomatic participants performed 8-minute walking on a motorized treadmill. They reported a greater alpha of the left side compared to the right side, which indicates asymmetry in alpha. However, the difference between left (0.688) and right (0.664) was subtle [13]. Therefore, in future related studies, the stride time series obtained from either right or left side is sufficient.

The between-day reliability was poor for the segmented alpha (ICCs < 0.40). In this study, all the participants were fatigued (RPE score = 16.0) after the running test. Poor between-day reliability for each segment may indicate different strategies being employed with progression of fatigue because of various running experience of the 7 participants (from novice to experienced). Runners with different running experience displayed significant differences in running kinematics with progression of fatigue [17,22,23]. Alpha of the experienced and novice runners was also found to change differently with progression of fatigue [8]. However, the between-day reliability was good (ICC = 0.81) when alpha was calculated using the overall dataset. This was partially consistent to the previously reported values (95% CI: 0.74–0.87) [15]. In that study [15], data were collected at two different days during 6-minute treadmill running at 11, 13, and 15 km/h. In another study [13], alpha also displayed good between-day reliability (ICC = 0.77), in which data were obtained from 8 participants during 8-minute treadmill walking. It should be acknowledged that alpha was measured in unfatigued conditions in the two aforementioned studies [13,15]. Additionally, the different length of the stride time series may contribute to the different between segmented and overall alpha since the DFA accuracy was influenced by the number of strides [16]. Compared to the segmented dataset, the count of strides for the overall stride time series almost tripled, thereby producing a more consistent alpha. However, a minimum of 600 strides were expected to estimate alpha with an accuracy of ± 0.1 [16]. All the segmented stride times series contained at least 800 strides in this study. The alpha should be accurately estimated. Further studies are required to understand the mechanisms. It would help to correctly interpret the findings because some studies [2,8] segmented the data during processing. Overall, alpha calculated using overall instead of segmented dataset revealed good between-day reliability. Further study is required to explore the mechanism and results should be interpret with caution when alpha was calculated using segmented data.

This study has four limitations. First, the participants wore their own running shoes. However, running shoes affected limb symmetry during running [24]. Future study should control running shoes. Second, leg symmetry was associated with running experience [25]. However, this study recruited participants with various running experience (6 months to more than 5 years). Moreover, running speed was found to affect the take-off symmetry during running [26]. In this study, individual anaerobic threshold speed was used. Although the absolute speed may be different between participants, the relative intensity of the speed was the same. Given the variable running abilities of the recruited participants and the purpose of running to exhaustion, this study standardized the relative intensity rather than used a fixed running speed. Lastly, stride time series was obtained using motion capture system instead of wearable sensors, which are commonly used in previous publications [2–7]. Although wearable sensors could accurately detect stride time [27], the reliability of the stride time fluctuations may be different between the two methods.

In conclusion, this study investigated between-side and between-day reliability of the stride time variability and complexity during an exhaustive running. The findings suggested equivalent stride time variability and complexity between right and left sides and good between-day reliability for the overall stride time complexity whereas poor for the segmented stride time complexity. In future application, stride time series is suggested to be collected from one side (either right or left), and data are recommended to be processed as an overall during distance running. Alpha obtained through segmented data, like the previously used methods [2,8], should be interpreted with caution.

Declaration of Competing Interest

None.

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