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Stride-to-stride variability and fluctuations at intensities around lactate threshold in distance runners

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ABSTRACT

Stride-to-stride variability and fluctuations in running have been widely investigated in relation to fatigue, injury, and other factors. However, no studies have examined the relationship of stride-to-stride variability and fluctuations with lactate threshold (LT), a well-known performance indicator for distance runners that represents the threshold at which fast-twitch muscle fibers are activated and the glycolytic system is hyperactivated. In this study, we examined a relationship between LT and stride-to-stride variability and fluctuations in trained middle- and long-distance runners (n = 33). All runners were asked to perform multistage graded exercise tests while wearing accelerometers on the upper surface of their shoes. The LT was determined by measuring blood lactate concentrations after each stage. Three gait parameters for each step were calculated based on the acceleration data: stride time (ST), ground contact time (CT), and peak acceleration (PA). The coefficient of variation (CV) and the long-range correlations (α) for each parameter were also calculated. The effects of the runner's group and the relative intensity for CV and α on gait parameters were evaluated using a two-way repeated measures analysis of variance. Although no significant effect was observed in the CV and α of ST, significant intensity main effects were observed for the CV and α of CT and PA. The lack of significant changes in ST might be the result of runners' adequate control of ST to minimize energy cost. All the parameters showing significant changes with increasing intensity decreased dramatically when they were close to LT. This might have been caused by an increase in physiological load near LT and be interpreted as a variation in motor control because of alternations in the mobilized muscle fibers and physiological changes around the LT. The α should be useful for non-invasive LT detection.

1. Introduction

For distance runners to achieve high performance, they must not only develop a higher physiological adaptive capacity but also acquire the ability to control movement variability through training [1]. Long-term running practice can improve interlimb coordination and produce a stable and consistent running gait cycle [2].

Variability in repetitive movements decreases as the pace increases, leading to a decreased degree of freedom of movement and an

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increased risk of fatigue and injury [3]. As the stride time (ST) reflects the internal rhythmicity of the locomotor system [4], stride-to-stride variability has generally been assessed using the coefficient of variation (CV) of ST [2,5–14]. The CV of other parameters, such as ground contact time (CT) [7,11,13], peak force [6], and peak acceleration (PA) [7], has also been used to assess stride-to-stride variability. These parameters have been investigated in relation to various factors, such as running experience [2], fatigue [13], and injury history [5].

Long-range correlations have been used as indicators to evaluate stride-to-stride fluctuations that depend on control mechanisms other than variability [2,5–12] and are an important concept for deciphering the dynamics of systems such as gait. They imply the self-similarity of time-series data that there is dependence between the present and all points in the past and are also described as the fluctuations of time-series data or the structure of the time-series variability. They are quantified using a detrended fluctuation analysis, which is known to yield a scaling exponent α [15]. The exponent "α" represents the correlation of fluctuations in the time series data. An $\alpha = 0.5$ indicates that the newly observed value is completely uncorrelated with earlier observations. An α of >0.5 and < 1.0 indicates persistent long-range correlations, whereas an $\alpha < 0.5$ indicates no persistent long-range correlations. Although stride-to-stride fluctuations have traditionally been assessed using α of the ST [2,5–12], CT [7,11] and PA [7] have also been used. Changes in the α with increasing running intensity reflects the inter-relatedness of gait parameters [6]. The α also varies depending on multiple factors, such as running duration [5,7,8], performance [7], and running experience [2]. However, no studies have examined whether physiological factors affect stride-to-stride variability and fluctuations.

The lactate threshold (LT) is well known as an indicator of the physiological performance of middle- and long-distance athletes [16], and it represents the intensity at which metabolic changes occur and the physiological load begins to increase as intensity increases. The LT is the threshold at which fast-twitch muscle fibers are mobilized, the glycolytic system is hyperactivated, and blood lactate and adrenaline concentrations begin to rise [17–19]. In addition, the LT is consistent with the starting intensity of the increase in blood potassium concentration [20], which activates respiration [21]. There is a possibility that the increase in physiological load around the LT affects stride-to-stride variability and fluctuations.

In terms of motor learning, the precision of movement is improved through repetition [22]. Long-distance runners are assumed to have a higher precision of movement than middle-distance runners because long-distance runners require a greater total training volume compared to middle-distance runners [23]. Thus, there may be a difference in stride-to-stride variability and fluctuations between these two groups.

This study aimed to investigate the effects of proximity to the LT on the variability and fluctuations in a group of middle- and long-distance runners. We hypothesized that 1) stride-to-stride variability and fluctuations at intensities higher than the LT would dramatically change compared to that at lower intensities, and 2) long-distance runners would have less variability and fluctuations in gait than middle-distance runners at the same relative intensity.

2. Materials and methods

2.1. Subjects

A minimum sample size of 12 subjects per group was calculated based on a significance level of 0.05, a statistical power of 0.8, and a medium effect size [24]. The subjects for this study were 17 middle-distance and 16 long-distance well-trained runners. Statistical powers for $n = 33$ based on a medium and a small effect size [24] are 0.94 and 0.45, respectively. All subjects had participated in running practice (about four times per week, an hour per session) for at least 2 years and had experience with treadmill running. Physical characteristics and personal best records for each track event are shown in Table 1. The nature and risk of the experimental procedures were fully explained to all subjects before submitting written informed consent. This study was approved by the Research Ethics Committee of the University of Tokyo (No.689–3) and performed in accordance with the Declaration of Helsinki.

Table 1
Physical characteristics and personal best records of each track event.

	Middle-distance (*n* = 17)	Long-distance (*n* = 16)
Physical characteristic		
Age (years)	24.5 ± 4.0	22.9 ± 2.6
Height (cm)	175.8 ± 4.5	169.7 ± 3.8
Weight (kg)	63.7 ± 4.3	57.3 ± 3.7
Personal best records (min' sec")		
400 m	51″0 ± 1″6 (*n* = 10)	None
800 m	1′54″4 ± 5″0 (*n* = 16)	1′59″6 ± 4″6 (*n* = 9)
1500 m	4′06″5 ± 15″7 (*n* = 17)	4′08″0 ± 12″1 (*n* = 16)
5000 m	15′54″6 ± 44″5 (*n* = 13)	15′11″3 ± 48″6 (*n* = 16)
10000 m	34′29″1 ± 54″0 (*n* = 2)	32′04″6 ± 1′43″8 (*n* = 13)
Half-marathon	74′42" ± 3′53" (*n* = 7)	70′12" ± 4′09" (*n* = 15)

All values are displayed as the mean ± standard deviation.

2.2. Experimental design and apparatus

The experiment was conducted between November and December, after the end of track season. Subjects were instructed to refrain from intense exercise 48 h before testing. They were also instructed to refrain from eating or drinking anything other than water for at least 3 h and to abstain from caffeine for at least 8 h before the testing.

The test began at a running speed of 3.33 m/s after self-conducted warm-up exercises. Running speed was thereafter increased by 0.417 m/s between stages. Each running stage was 180 s, and the subjects rested for 60 s in a standing position between stages. During each rest period, blood lactate concentrations were measured by each subject using Lactate Pro 2 (LT-1730, ARKRAY Inc., Japan), and the rate of perceived exertion (RPE), measured via the Borg's RPE scale (6−20) [25], was reported. The experiment was terminated when RPE was greater than 17 or blood lactate concentration was greater than 8.0 mmol/l.

All subjects performed multistage graded exercise tests on a motorized treadmill (T.K.K. 1255, Takei Scientific Instruments Co., Ltd., Japan) while wearing triaxial accelerometers (Wearable Sensor, CMT-F10, CASIO, Japan). While some recommend that treadmill incline be adjusted to 1% for experiments testing physiological performance [26], it was set to 0% for this study, as the goal of this study was to evaluate gait patterns [7,27,28]. The range and sensitivity of the accelerometer were ±16 g and 0.488 mg/LSB, respectively. The accelerometer data was sampled at 200 Hz. The accelerometer was small (size: 43.3 mm × 59 mm × 12 mm; total weight: 31 g), and it was positioned at the instep of both shoes of the subjects with a rubber band covered with a curing tape (Fig. 1). Foot-mounted acceleration can assess gait pattern [7] and be used to effectively measure external mechanical load [29].

2.3. Data analysis

The acceleration data were resampled at 1000 Hz by linear interpolation and then filtered with a low-pass filter using a cut-off frequency of 10 Hz [30]. Self-made MATLAB (R2021a, MathWorks Inc., USA) scripts were used to calculate ST (s), CT (s), and PA at toe-off (m/s^2) for each subject and stride based on the waveform of resultant acceleration after filtering. The CV and α were analyzed as indicators of the variability and fluctuations. The CV and α of gait parameters (ST, CT, and PA) for each subject and stage were calculated from each set of time series data for both feet. Sixty-sec time series data from 90 to 150 s after the start of each stage were used for the calculation to avoid the influence of the start and end of the run. The average values for the left and right feet were used for the subsequent analysis. The mean ± SD of the number of strides used to analyze each stage was 90.1 ± 5.6. The number of steps employed for the analysis were more than the 32–64 steps recommended in other studies [31–34]; however, the fact the number of steps were required to compute CV and α is debatable.

We analyzed gait parameters regarding the relative intensity by converting the absolute speed of each subject into four relative intensities with respect to the LT, which was determined by the intensity preceding an increase in lactate concentration of 1 mmol/l above baseline [35]. The stage in which running speed was closest to the LT was designated as "near-LT," one stage slower than "near-LT" was designated as "pre-LT," two stages slower than "near-LT" was designated as "two stages before LT," and one stage faster than "near-LT" was designated as "post-LT." Fig. 2 shows a schematic representation of LT and each stage based on relative intensity.

2.4. Statistical analysis

All statistical analyses except for sample size calculations and post-hoc power analyses were performed using R software, version 3.6.3 (The R Foundation for Statistical Computing, Vienna, Austria). The data are reported as mean ± standard error (SE). The Kolmogorov–Smirnov test was performed to confirm the normality of each dataset. If not normally distributed, a Box–Cox transformation [36] was applied to CV and α of gait parameters. Independent t-tests were used to identify group differences for individual characteristics and speed at LT (m/s). A two-way repeated measures analysis of variance (ANOVA) was used to determine the effect of group [middle-distance, long-distance] and relative intensity via LT [two stages before LT, pre-LT, near-LT, post-LT] for CV and α on gait parameters. If a significant main or interaction effect was observed, post hoc tests were performed using Shaffer's modified sequentially rejective Bonferroni procedure [37]. For each ANOVA, generalized eta squared [38,39] was calculated as measures of effect size (ES). For each *t*-test, Cohen's d was calculated as measures of ES [24]. The level of statistical significance was set at $p < .05$. Sample size

Fig. 1. Attachment of accelerometers at the instep of both shoes of the subjects with a rubber band and a curing tape.

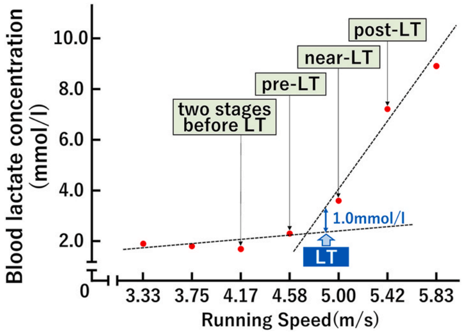

Fig. 2. Determination procedure of lactate threshold (LT) and each stage of relative intensity. This is an example of a certain subject (long-distance runner). The subject completed 7 stages and a running speed of the final stage was 5.83 m/s. Blood lactate concentrations of each stage were 1.9, 1.8, 1.7, 2.3, 3.6, 7.2, 8.9, respectively. Lactate threshold was calculated to be 4.88 m/s, which is a running speed at which lactate concentration increases 1 mmol/l above base line [35]. The closest stage to 4.88 m/s was the stage with a running speed of 5.00 m/s, therefore it was designated as "near-LT." The stage with a running speed of 4.17 m/s was designated as "two stages before LT", the stage with a running speed of 4.58 m/s was designated as "pre-LT", and the stage with a running speed of 5.42 m/s was designated as "post-LT" as well.

calculations and post-hoc power analyses were performed using G*power software, version 3.1.9.6 (Franz Faul, Universität Kiel, Germany).

3. Results

3.1. Characteristics of the subjects

No difference was noted in terms of the age of the subjects between the middle-distance and long-distance groups ($t(31) = 1.360$, $p = .184$, ES = 0.47). The subjects in the middle-distance group were significantly heavier ($t(31) = 4.073$, $p < .001$, ES = 1.42) and taller ($t(31) = 4.420$, $p < .001$, ES = 1.54) compared with those in the long-distance group. The subjects of the long-distance group were significantly faster compared with middle-distance group with respect to speed at LT (long-distance: 4.87 ± 0.082 m/s, middle-distance: 4.52 ± 0.053 m/s, $t(31) = 3.477$, $p = .002$, ES = 1.21).

Tables 2 and 3 show the results of ANOVA and post hoc tests. Effect sizes of ANOVA are shown in Table 2. For lactate concentration, significant group and intensity main effects were observed, but there was no significant interaction effect. Post hoc tests for intensity revealed that there were significant differences between all stages, except between two stages before LT and pre-LT. For RPE, a significant group effect was observed, but there were no significant intensity main effect and interaction effect. Post hoc tests for intensity indicated that there were significant differences between all stages.

3.2. Stride-to-stride variability

There were no significant effects for the CV of ST. The intensity main effect and interaction effect were significant for the CV of CT. The results of post hoc tests are as follows: Only in the middle-distance group, the CV of CT significantly declined from two stages before LT to pre-LT. Significant group main effect and intensity main effect were observed for the CV of PA. The post hoc test results were as follows: The CV of PA decreased significantly from two stages before LT to pre-LT, and the middle-distance group had smaller CV of PA compared to the long-distance group.

Table 2
Results of two-way ANOVA based on relative intensity via LT.

	Group			Intensity			Interaction Group × Intensity		
	F(1,31)	p-value	Effect size	F (3,93)	p-value	Effect size	F(3,93)	p-value	Effect size
Lactate concentration	5.263	.029	0.083	177.498	<.001	0.699	1.598	.195	0.021
RPE	0.898	.351	0.020	259.970	<.001	0.706	1.057	.371	0.010
Coefficient of variation									
ST	0.343	.563	0.008	0.276	.843	0.002	1.169	.326	0.009
CT	0.447	.509	0.011	5.231	.002	0.036	4.374	.006	0.031
PA	11.236	.002	0.214	13.429	<.001	0.074	1.738	.165	0.010
Long-range correlations α									
ST	2.049	.162	0.031	2.584	.058	0.039	0.610	.610	0.010
CT	0.392	.536	0.008	8.233	<.001	0.081	0.622	.602	0.007
PA	0.739	.397	0.015	13.988	<.001	0.129	1.898	.135	0.020

ST: stride time, CT: ground contact time, PA: peak foot acceleration at toe-off.

Table 3
Comparisons of parameters and results of post hoc tests.

	Middle-distance				Long-distance			
	Two stages before LT	pre-LT	near-LT	post-LT	Two stages before LT	pre-LT	near-LT	post-LT
Lactate concentration (mmol/l)	2.24 ± 0.16	2.47 ± 0.15	3.52 ± 0.17[ab]	5.82 ± 0.36[abc]	1.94 ± 0.23	2.01 ± 0.12	3.02 ± 0.13[ab]	5.60 ± 0.31[abc]
RPE	9.19 ± 0.37	10.94 ± 0.29[a]	12.63 ± 0.26[ab]	14.94 ± 0.34[abc]	10.00 ± 0.40	11.41 ± 0.35[a]	13.47 ± 0.24[ab]	15.41 ± 0.29[abc]
Coefficient of variation (%)								
ST	1.129 ± 0.062	1.075 ± 0.075	1.058 ± 0.057	1.086 ± 0.073	0.991 ± 0.044	1.033 ± 0.082	1.075 ± 0.083	0.999 ± 0.035
CT	1.889 ± 0.140	1.593 ± 0.092[a]	1.633 ± 0.097[a]	1.532 ± 0.067[a]	1.598 ± 0.062	1.593 ± 0.084	1.567 ± 0.069	1.582 ± 0.070
PA	5.339 ± 0.265	4.785 ± 0.225[a]	4.366 ± 0.213[a]	4.333 ± 0.146[a]	4.157 ± 0.182	3.791 ± 0.135[a]	3.828 ± 0.228[a]	3.802 ± 0.183[a]
Long-range correlations α								
ST	0.644 ± 0.042	0.621 ± 0.048	0.612 ± 0.042	0.604 ± 0.050	0.650 ± 0.089	0.593 ± 0.048	0.545 ± 0.057	0.458 ± 0.023
CT	0.761 ± 0.033	0.719 ± 0.027	0.714 ± 0.032[a]	0.667 ± 0.018[ab]	0.747 ± 0.028	0.710 ± 0.030	0.662 ± 0.028[a]	0.661 ± 0.027[ab]
PA	0.702 ± 0.026	0.640 ± 0.020[a]	0.620 ± 0.015[a]	0.592 ± 0.015[a]	0.661 ± 0.027	0.614 ± 0.019[a]	0.584 ± 0.026[a]	0.611 ± 0.019[a]

ST: stride time, CT: ground contact time, PA: peak foot acceleration at toe-off.
All values are displayed as the mean ± standard error.
[a] significantly different from two stages before LT;[b] significantly different from pre-LT;[c] significantly different from near-LT.

3.3. *Stride-to-stride fluctuations*

There were no significant group main effects and interaction effects for the α of ST, CT, and PA. Significant intensity main effects were observed for the α of CT and PA. The results of post hoc tests for intensity were as follows: The α of CT decreased significantly from two stages before LT to near-LT, with no significant difference in either parameter between near-LT and post-LT. The α of PA decreased significantly from two stages before LT to pre-LT, with no significant difference between pre-LT and post-LT.

4. Discussion

The aim of this study was to examine the relationship between LT and stride-to-stride variability and fluctuations in distance runners. Well-trained middle- and long-distance runners performed graded exercise tests to establish LT. For each of the two spatiotemporal parameters and one acceleration parameter, two indicators of variability and fluctuations (CV and α) were calculated. Changes in CV or α with intensity were not observed for ST, but significant decreases at slightly lower than LT were observed for CT and PA. There were no differences detected for any parameters between near-LT and post-LT. Thus, the decrease was not linear, but rather tended to converge. On the other hand, numerous studies have reported that the mean of spatiotemporal parameters [40,41] and peak ground reaction force [42] changed in a linear fashion with increasing running speed. This change was different from that of the CV

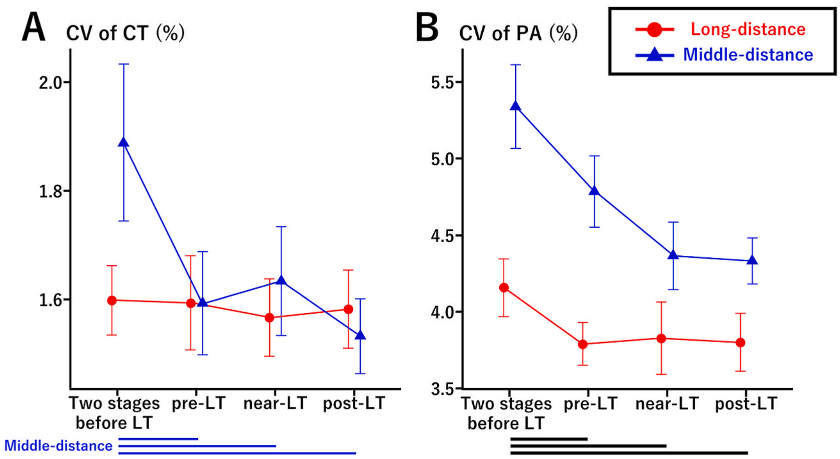

Fig. 3. The means and standard errors of (A) CV of CT, (B) CV of PA of each group at each intensity for each parameter. Black line: significant differences between paired intensities; blue line: significant differences between paired intensities for the middle-distance group.

and α observed in this study. Therefore, it appears that there were other factors that changed stride-to-stride variability and fluctuations besides biomechanical changes in response to running speed.

There was no significant change observed for the CV of ST with increasing intensity in this study. Earlier studies have shown a decreasing [6,9] or stable trend [2,10,11] for the CV of ST with increasing running speed, thus the results were not consistent. Nakayama et al. [2] compared trained runners with non-runners and reported that the CV of ST did not change with running speed for the former. The consistency in the CV of ST for trained runners has been interpreted as a byproduct of training to improve running economy [11], which is supported by the results of this study specifically targeting trained runners. From the perspective of motor learning, it has been suggested that step frequency, the reciprocal of ST, decreases in its variability with increasing experience [43]. This change is due to the nervous system learning the optimal control strategy; however, no significant change was observed in the CV of ST in this study. Therefore, there was no effect of adaptation to the experimental environment (e.g., experimental protocols, treadmill running, etc.) in this study. The increase in aerobic energy cost is caused by stride length variation and an inaccurate control of step frequency [44]. As runners have to control their step frequency very accurately to match the optimal step frequency [45], the lack of significant changes in ST in this study might be the result of the runners' ST control optimization.

With increasing intensity, the CV of PA significantly decreased from two stages before LT to pre-LT in both groups. Although the discussion should be done with caution because of the low statistical power (0.73 and 0.66 for intensity main effect and interaction effect, respectively), the CV of CT significantly decreased from two stages before LT to pre-LT only for middle-distance runners. Fig. 3 shows the mean and SE of each group at each intensity for the CV of CT and PA. In line with our hypothesis, these parameters showed a dramatic decrease at intensities slightly lower than the LT, and these changes were suggested to be generated by changes occurring around LT. While the CV of CT for long-distance runners was consistent, the CV of CT for middle-distance runners presented a significantly large variability at lower intensities, as hypothesized. Since spatiotemporal variability is associated with skill and expertise [33], it was suggested that long-distance runners had acquired a stable strike pattern at lower intensities due to their high training volume [23]. Besides, it has also been reported that runners self-optimize CT to minimize metabolic cost and CT has a narrower optimal range of metabolic cost than step frequency, inducing changes to metabolic cost with only minor alterations to CT [46]. It is possible that the different characteristics of these parameters affected the adjustment strategy of the runner when responding to each exercise intensity, resulting in different results for the CV of CT, PA, and ST in this study. Nevertheless, further studies focusing on the adaptation in motor control must be conducted to elucidate the underlying mechanisms. The parameters for which the variability changed with an increase in intensity showed a significant decrease in variability from two stages before LT to pre-LT. The decrease in CV with increasing speed of repetitive exercise was interpreted to result from a decrease in the degree of freedom of movement [47], and a decrease in the degree of freedom leads to an increase in injury risk [3,11]; therefore it is important to monitor the intensity at which the variability begins to decrease during running in order to train with less risk of injury.

The α of CT and PA significantly decreased as intensity increased, but the α of ST did not. A decrease in α indicates a reduction in the overall time dependence of a variable [6], which is reported to be caused by maladaptation to a change in the exercise environment [48] and by an increase in the frequency of motor control [5,49]. Earlier studies have shown that, as running speed increased, the α of ST had a U-shaped trend and the α of CT and peak vertical ground reaction force decreased [6,9], while others have reported that the α of ST and CT decreased [11]. These changes were partly consistent with the results of this study. The slight lack of agreement in the change of some parameters might have been due to the differences in subject characteristics and exercise intensity.

The α of PA decreased from two stages before LT to pre-LT, and α of CT decreased from pre-LT to near-LT. CT and PA have slightly different change points in α but decrease similarly with increasing intensity. The changes in one parameter with intensity do not happen in isolation, as parameters interact with each other, which reflects their inter-relatedness [6]. Some studies considered α to provide a measure of system adaptability [6]. Our study results indicated that middle- and long-distance runners, subjects of the study,

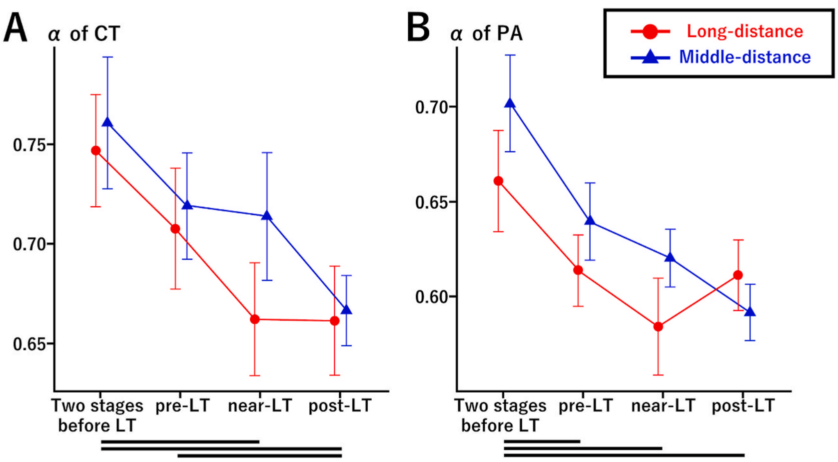

Fig. 4. The means and standard errors of (A) α of CT, (B) α of PA of each group at each intensity for each parameter. Black line: significant differences between paired intensities.

adapted to the increase in intensity by adjusting CT and PA rather than ST. Contrastingly, there was no difference in the changes between middle- and long-distance runners. Therefore, changes in the α were related to relative intensity and might have been caused by an increase in the physiological load near LT.

Fig. 4 shows the mean and SE of each group at each intensity for the α of CT and PA. In line with our hypothesis, these parameters showed a significant decline in the intensities slightly lower than the LT. It was suggested that these changes were due to the changes that occurred near LT as with the CV. Brahms et al. [7] reported that, when participants ran at a constant and all-out intensity, the α declined in the middle phase and then stabilized until reaching volitional exhaustion. This finding in conjunction with our results suggests that the change in α may indicate the start of fatigue. Additionally, muscle fiber conduction velocity, a marker of motor unit recruitment strategies [50], provides crucial details on motor control [51]. Muscle fiber conduction velocity is affected by muscle pH [52]; therefore, reduction in muscle pH has been correlated with the accumulation of lactate [53]. These discussions coupled with our results support the notion that stride-to-stride fluctuations are associated with physiological changes occurring around LT.

There are three limitations to this study. The first was that only well-trained male distance runners were included. Male and females are known to exhibit different step variability [14] and center of mass accelerations [54]. We could not include beginners in this study because the experiment protocol in this study was likely difficult for them to complete. Further studies should be performed including runners having a variety of characteristics (e.g., female runners). The second limitation was the inability to identify the physiological mechanisms that might have influenced the changes in stride-to-stride variability and fluctuations. We showed that the change point of them as exercise intensity increased nearly matched the LT, but we failed to identify a causal relationship. The CV and α of the gait parameters have been known to change at the fixed intensity during prolonged exercise [5,7,8,13,27,55,56]. To reveal the physiological, neural, and kinetic mechanisms that affect stride-to-stride variability and fluctuations, it is necessary to perform studies with a wide variety of subjects and protocols. The third limitation was that a treadmill was used in the experiment. Although some studies have reported that treadmill gait is qualitatively and quantitatively similar to overground gait [57], others have reported that gait dynamics based on treadmill running may not completely reflect the dynamics of overground running [10]. Any application of the results of this study to outdoor running should be done with caution. However, systems that sequentially calculate the α during running from accelerometer data and provide real-time information have also been developed and verified [58,59]. Thus, although these limitations, this study demonstrated the possibility of non-invasive monitoring of the LT by real-time calculation of the α. Additionally, monitoring the α only from accelerometers could be applicable to overground running, not only in a laboratory environment.

5. Conclusion

To the best of our knowledge, this is the first study to investigate the relationship between LT and stride-to-stride variability and fluctuations in distance runners. We found that some parameters related to CT and PA showed a significant decrease as the running intensity increased, whereas ST did not. This result indicated that middle- and long-distance runners adapted to the increase in intensity by adjusting CT and PA rather than ST. In line with our hypothesis, all the parameters showing significant changes with increasing intensity decreased dramatically around the LT. Besides, although the changes in the CV have a difference between middle- and long-distance runners, the changes in α were not observed between middle- and long-distance runners, which is in contrast with our hypothesis. Therefore, variations in α showed a relationship with relative intensity, which might have been caused an increase in physiological load near LT. This result may be interpreted as a variation in motor control due to changes in mobilized muscle fibers and physiological changes occurring around the LT. The α should be useful for non-invasive LT detection as it was observed that they decreased around the LT and no difference was observed between middle- and long-distance runners. In contrast, the CV of CT may be useful to classify middle- and long-distance runners because they differed between these two groups. Based on our results, further studies are needed to identify the factors that might affect stride-to-stride variability and fluctuations during distance running.

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Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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