Increases in speed do not change gait symmetry or variability in world-class race walkers

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ABSTRACT

The aim of this study was to analyse changes in gait variability and symmetry with increasing speed in race walkers. Eighteen international athletes race walked on an instrumented treadmill at speeds of 11, 12, 13 and 14 $km \cdot h^{-1}$ in a randomised order for 3 min each. Spatiotemporal and ground reaction force data were recorded for 30 s at each speed. Gait variability was measured using median absolute deviation and inter-leg symmetry was measured using the symmetry angle. There was an overall effect of speed on all absolute values except push-off force, but symmetry and variability (except flight time) did not change with increased speed, step length and step frequency. Most athletes were asymmetrical for at least one variable, but none was asymmetrical for more than half of the variables measured. Therefore, being asymmetrical or having higher variability (<5%) in a few variables is normal. Taking all findings together, practitioners should exercise caution when deciding on the need for corrective interventions and should not be concerned that increasing gait speed could increase injury risk through changes to athletes' asymmetry. Race walking coaches should test at competition speeds to ensure that flight times, and any variability or asymmetry, are measured appropriately.

199 words

INTRODUCTION

Race walking is part of the athletics programme at the Olympic Games and all other major athletics events, with competitions held over 20 km and 50 km for senior women and men. Because of World Athletics Rule 54.2, this competitive form of gait is constrained. This rule states that no visible (to the human eye) loss of contact with the ground should occur and that the knee must be fully extended from first contact with the ground until the "vertical upright position" (World Athletics, 2019). Therefore, race walkers need to maintain legal technique constantly throughout the race on both legs as violations over even short durations can lead to disqualification. As race walkers change speed throughout the race as part of their pacing strategy (Hettinga, Edwards, & Hanley, 2019), it is important to understand the effect of speed changes on variables that determine performance and could result in rules infractions.

Variability in movement has been shown to be a normal and functional feature of human movement that has been studied extensively (e.g., Glanzer, Diffendaffer, Slowick, Drogosz, Lo & Fleisig, 2019; Hamacher, Hamacher, Müller, Schega & Zech, 2017). It has been shown that experts display lower variability in outcome-related variables compared with lesser-skilled performers (Fleisig, Chu, Weber, & Andrews, 2009). In relation to running performance, Nakayama, Kudo, & Ohtsuki (2010) found that expert runners have reduced gait variability in outcome variables (i.e., the main variables that determine running speed: step length and frequency). Because of the requirements of World Athletics Rule 54.2, race walking has very specific technical demands and is considered a very stereotyped form of gait (Donà, Preatoni, Cobelli, Rodano, & Harrison, 2009) that requires methodical training to maintain a stable, consistent movement pattern (i.e., with few enough variations in flight time or knee angular motion to adopt illegal technique). Understanding movement variability in this form of gait is crucial to fully appreciate the changes in technique that could occur during a race. Some of the demands that race walkers have to encounter during a race are increased fatigue and having to maintain or change pace at different stages. It has been established previously that there are few differences in variability between junior (under 20 years of age) and senior world class race walkers (Tucker & Hanley, 2017). The effect of fatigue (i.e., distance walked) on race walking gait was also measured in the aforementioned study and found no effect on gait or kinetic variability during a 10,000 m treadmill race walk at competitive speeds. In addition, during 10,000 m treadmill running at speeds close to personal best (PB) pace, it was shown that gait and kinetic variability did not change over the distance run (Hanley & Tucker, 2018). With respect to changes in speed, the effect of speed on gait variability has been investigated previously (Beauchet et al., 2009), where it was found that gait variability decreased with increasing walking speed. Understanding the effect of changing speed on gait variability is important because race walkers vary speed throughout a race (Hettinga et al., 2019), providing a strong rationale for establishing for the first time what effect, if any, changing speed has on the consistency of key outcome-related measures (e.g., flight time, contact time) and the kinetic variables that affect these outcomes (e.g., ground reaction force (GRF) variables).

Whereas movement variability analyses can tell us about intra-limb movement consistency, symmetry scores measure inter-limb similarities. As having a dominant leg is normal, it can mean that perfectly symmetrical gait is not possible. Asymmetry happens when there is any deviation from symmetry, which itself is the exact replication of one limb's movement by the other (Exell, Irwin, Gittoes, & Kerwin, 2012). Increased gait asymmetry has been associated with injury (Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007) or decreased performance (Bell, Sanfilippo, Binkley, & Heiderscheit, 2014), and indeed some race walk coaches believe that symmetry is needed for adopting a legal and efficient technique (Salvage & Seaman, 2011). Increased asymmetry in the vertical GRF pattern has been reported with increased running speed in participants returning to sport after anterior cruciate ligament reconstruction (Thomson, Einarsson, Hansen, Bleakley, & Whiteley, 2018), whereas a study on healthy competitive sprinters at a range of speeds found no change in asymmetry across the analysed speeds (Girard, Morin, Ryu, Read & Townsend, 2019). It has been established that symmetry did not change with distance walked in a sample of elite race walkers, nor were there large differences between senior and junior race walkers (Tucker & Hanley, 2017), but these tests were conducted at a constant pace, which is unusual in race walking competitions (Hettinga et al., 2019). It is important to understand the effect of changing demands on symmetry, such as changing speed, given its link with injury and decreased performance.

There has been limited research conducted on variability and symmetry in race walking. Those investigations that have been conducted examined the effect of fatigue on variability and symmetry at a constant speed, and on differences between younger and older athletes. It is therefore necessary to analyse the effect of speed on those spatiotemporal and GRF variables that are important in race walking performances. The aim of this study was to analyse the extent of any changes in gait variability and symmetry in world-class race walkers across a range of speeds. Based on previous research (Girard et al., 2019; Hanley & Tucker, 2018), it was hypothesised that variability and symmetry scores would not change with increases in speed.

METHODS

Participants

The study was approved by an Institutional Research Ethics Committee. Eighteen international race walkers gave written informed consent. Eleven of the participants were men (25.7 ± 4.1 years, 1.77 ± 0.06 m, 64.4 ± 4.7 kg) and seven were women (25.9 ± 4.1 years, 1.68 ± 0.10 m, 56.7 ± 11.0 kg). Fifteen of the athletes had competed at the 2016 Olympic Games or 2017

World Championships; all women competed over 20 km, whereas seven of the men specialised over 20 km, and four over 50 km. The mean PB time (h:min:s) for the seven men who competed over 20 km was 1:21:59 (± 2:25), whereas for the seven women it was 1:30:14 (± 1:58). The mean PB time for the four men who specialised over 50 km was 3:55:20 (± 6:59).

Data collection

After conducting any preferred self-selected exercise routines, the participants had a 10-min warm-up / familiarisation period on the treadmill (Matsas, Taylor & Burney, 2000), and all were regular treadmill users. Each participant race walked on the instrumented Gaitway treadmill (h/p/Cosmos, Traunstein, Germany) at four speeds for 3 min each: 11, 12, 13 and 14 $km \cdot h^{-1}$, and in a randomised order. These were chosen to represent the range of speeds adopted by elite-standard race walkers in training and competition (20 km and 50 km) (Hanley, 2013). The treadmill's inclination was set at 0% during data collection (Paquette, Milner, & Melcher, 2017) because racewalking events are typically held on flat, even surfaces. The participants were all habitual treadmill users and wore their normal training clothing and footwear for indoor training sessions. The treadmill incorporated two in-dwelling piezoelectric force plates (Kistler, Winterthur, Switzerland) that recorded vertical GRFs (1000 Hz) from both feet. Data were also collected simultaneously using two 1-m OptoJump Next strips (1000 Hz) placed on opposite sides of the treadmill, which were flush with the treadmill belt. Both systems (instrumented treadmill and OptoJump Next systems) were simultaneously activated using the same triggering device (National Instruments, Austin, TX, USA). Data were collected for 30 s in the last minute of each speed condition, which allowed for the collection of 44 (± 4) steps per foot across all speeds for all participants.

Data analysis

Data from the treadmill force plates were exported from the Gaitway software and smoothed using a recursive second-order, low-pass Butterworth filter (zero phase-lag). The optimal cut-off frequency was calculated for each individual force trace using residual analysis (Winter, 2005). The mean optimal cut-off frequency was 43.7 Hz (± 2.8). For the smoothed GRF data, the mean and standard deviation (SD) of the noise occurring during the final 50 ms before ground contact (visual inspection) were calculated, and initial contact was considered to begin when the vertical force magnitude was greater than the mean plus 3 SD of the noise (Addison & Lieberman, 2015; Hanley, Tucker & Bissas, 2019). The mean plus 3 SD of the noise during the first 50 ms after toe-off were used in a similar way to identify the end of contact and the beginning of flight. The mean (± SD) of these thresholds to define these key events was 20 N (± 17). The vertical GRF variables were extracted from the treadmill force plate data whereas the OptoJump system was used to measure step length, step frequency, contact time and flight time. Results from the OptoJump Next system were extracted using specific settings (GaitIn_GaitOut) of 0_0 based on the number of light emitting diodes (LEDs) that formed the baseline and found to be optimal during a reliability study (Hanley & Tucker, 2019). The minimum threshold for flight time was set at 0.001 s (Hanley & Tucker, 2019).

Step length was defined as the distance from one footstrike to the next footstrike of the opposite foot. Contact time was defined as the time duration from initial contact to toe-off, whereas flight time was the time duration from toe-off of one foot to the initial contact of the opposite foot (Padulo, Chamari, & Ardigò, 2014). Step frequency was calculated as the reciprocal of step time (itself calculated as the sum of contact time and flight time).

The vertical GRF data variables analysed were chosen based on their importance in reducing vertical CM displacement and flight time (Hanley & Bissas, 2016), and comprised impact peak force, loading peak force, midstance force and push-off peak force (Figure 1). The impact peak was defined as the highest recorded force during the first 70 ms of contact. However, through the analysis process it was decided that impact peak could not be used in this study because a considerable number of athletes (11 out of 18) did not have an impact peak (i.e., no visible peak in the first 70 ms of contact) at lower speeds (11 and 12 $km \cdot h^{-1}$) meaning the symmetry or variability of each parameter could not be calculated. The loading peak force was identified as the next peak in the vertical GRF trace during early stance, whereas the midstance force value was measured as the minimum force occurring between the loading and push-off peaks. The push-off peak force was identified as the maximum vertical force during late stance. All kinetic variables were normalised and thus have been reported in body weights (BW).

Statistical analysis

Gait variability was measured using median absolute deviation (MAD) (Chau, Young, & Redekop, 2005; Preatoni, Ferrario, Donà, Hamill, & Rodano, 2013) where the MAD was calculated for the left and right legs separately and then averaged for each participant. The mean MAD scores were calculated as percentages of the original median value (mean of the right and left median values) to compare between groups and variables.

To detect outliers, the MAD scores were first multiplied by 1.4826 (Leys, Ley, Klein, Bernard, & Licata, 2013); the lower and upper bounds for outliers were found by multiplying the resulting value by 2.5 and subtracting from or adding to the original median value (Leys et al., 2013), as shown in Equations 1 and 2 below:

Upper bound for outliers: Original median + (MAD x 1.4826 x 2.5)

Lower bound for outliers: Original median − (MAD x 1.4826 x 2.5)

Outliers were removed before the calculation of means and SDs (absolute values) and symmetry values to reduce the chances of false positives (Leys et al., 2013); overall, 3.5% of the recorded values were removed.

For each participant, inter-leg symmetry was measured using the symmetry angle (Zifchock, Davis, Higginson, & Royer, 2008) and rectified so that all values were positive (Exell et al., 2012). The symmetry angle was calculated using Equation 3 below (Zifchock et al., 2008):

$$\text{Symmetry angle} = [(45° - \arctan(X_{left}/X_{right})/90°)] \times 100\%$$

where X was the mean value for a particular variable on each leg.

To measure any changes in variability or symmetry, one-way repeated-measures analysis of variance (ANOVA) was conducted with repeated contrast tests (Field, 2009) and Greenhouse-Geisser correction used when Mauchly's test for sphericity was violated. An alpha level of 5% was set for all statistical tests. Effect sizes (ES) for differences between speeds were calculated using Cohen's *d* (Cohen, 1988) and considered to be either trivial ($d < 0.20$), small (0.21 – 0.60), moderate (0.61 – 1.20), large (1.21 – 2.00) or very large (2.01 – 4.00) (Hopkins, Marshall, Batterham, & Hanin, 2009). On those occasions where *d* was calculated, only those instances where the effect sizes were moderate or larger have been indicated. Individual participants' inter-leg differences were considered asymmetrical if the symmetry angle was greater than 1.2% (Tucker and Hanley, 2017) and d was ≥ 1.21. Athletes were considered asymmetrical for any variable if half or more of their symmetry angles were above 1.2% (with corresponding large effect sizes) (i.e., asymmetrical at two or more of the speeds) and their mean symmetry angle was above 1.2% (averaged across all four speeds). Differences between variables at each speed for variability and symmetry were measured using independent t-tests and these scores were considered different when the alpha level was less than 5% and the effect sizes were moderate or larger.

RESULTS

There was an overall effect of speed on all variables measured ($F \geq 25.18$, $P < 0.001$) except push-off force, with significant differences between successive speeds in all spatiotemporal variables except step frequency (Figure 2). There were no differences between successive measurements of the vertical GRF variables examined (Table 1). The results for gait variability are shown in Table 2, with the results for symmetry angles shown in Table 3. There were no significant differences in variability with speed for any variable except for flight time (F = 6.79, P = 0.004), which decreased between 11 and 12 km·h^{-1} (P = 0.017, d = 0.67) and between 12 and 13 km.h^{-1} (P = 0.010, d = 0.67). There were no changes in mean symmetry angle with increasing speed.

In terms of movement variability scores, loading, midstance and push-off force scores were all greater than step length, step frequency and contact time scores at all speeds ($P \leq 0.005$, $d \geq 0.72$) (Table 2). Flight time variability was greater than that of step frequency at all speeds except 11 km·h^{-1} ($P \leq 0.001$, $d \geq 1.79$) and was also greater than that of push-off force, step length and contact time at 13 and 14 km.h^{-1} ($P \leq 0.001$, $d \geq 0.65$). With regard to symmetry angle scores, loading force was greater than step length, step frequency and contact time at all speeds ($P \leq 0.002$, $d \geq 0.84$) (Table 3). Midstance force and push-off force were greater than contact time at all speeds ($P \leq 0.017$, $d \geq 0.61$) and were also greater than step length and step frequency for all speeds except 11 km·h^{-1} ($P \leq 0.012$, $d \geq 0.66$).

The number and percentage of athletes who were considered asymmetrical for any particular variable at each speed are shown in Table 4. Table 5 shows the mean scores for symmetry angles across all four speeds for each individual race walker.

DISCUSSION

The aim of this study was to analyse changes in gait variability and symmetry across a range of speeds in world-class race walkers; it was hypothesised that variability and symmetry scores would not change with increases in speed. Despite there being an overall effect for speed on all variables except push-off force, variability and symmetry of these variables did not change with increasing speed. Therefore, neither faster nor slower speeds were associated with more (or less) variability or symmetry, supporting our hypothesis. This demonstrates that these athletes maintained their magnitude of symmetry (or asymmetry) in these variables despite changes in kinetic and spatiotemporal variables in response to increasing speed (Figure 2). This is in line with similar research on symmetry in sprinting where no changes were evident with increasing speed (Girard et al., 2019). The results from the study of Girard et al. (2019) and our study on race walking indicate that the movement variability and symmetry present are unique to the individual's motor system. These findings suggest that practitioners should not be concerned that increasing speed in either running (Girard et al., 2019) or race walking heightens the risk of injury through increasing their client's asymmetry; however, athletes recovering from injury might show increased asymmetry (Thomson et al., 2018), but this should be differentiated from the effects of increased speed alone.

Within each speed, most kinetic variables had higher symmetry angle and movement variability scores than most spatiotemporal variables, showing that kinetic variables were more likely to be asymmetrical and variable. Overall, low variability (<5%) and low symmetry angle scores (<1.2%) were found within this cohort of well-trained athletes. The only exception was flight time, which had higher scores than some other spatiotemporal and kinetic variables at speeds of 13 and 14 km·h^{-1}. Median flight time values were close to zero, especially at lower speeds, which means that they can inflate movement variability calculations in particular (Atkinson & Nevill, 1998). Therefore, it is important to be cautious when calculating movement variability at lower speeds where the mean or median flight time is close to zero (there is no flight time in cases of double support, which occurred in less than 1% of strides in this study) when using either the coefficient of variation or MAD as measures of variability.

In relation to spatiotemporal variables having lower variability and symmetry than the kinetic variables, spatiotemporal variables are outcome-related (e.g., step length and step frequency), whereas the kinetic variables are those that produce the movement pattern leading to the outcome. Step length is a determining factor in race walking speed (Hanley & Bissas, 2016) and, given the importance of spatiotemporal variables in maintaining performance outcomes, it could be that those parameters are prioritised in terms of consistency and symmetry compared with the kinetic variables when considering the constrained environment of race walking. As mentioned previously, caution should be exercised regarding the flight time variability scores at the lower speeds, but it is important to note that the recorded flight times at the higher speeds (13 and 14 km·h^{-1}) were more variable than step length and contact time. This is especially important in terms of maintaining compliance with World Athletics Rule 54.2 as rules infractions and disqualification can occur with only a few instances of increased flight times. In this study, women were closer to their PB speed for 20 km than men, although not as close as male 50 km specialists to their PB over that distance. These differences might have meant that variability and symmetry scores were affected by the relative intensity of the exercise, and a protocol that used speeds relative to PB might have been more informative on an individual basis than set speeds. Even more important is that the mean flight times at these higher speeds, which are more reflective of competition speeds, were 0.044 s at 13 $km \cdot h^{-1}$ and 0.052 s at 14 $km \cdot h^{-1}$, which was in excess of the 40 ms threshold where loss of contact is typically detected by judges (Hanley, Tucker & Bissas, 2019). Indeed, the world's best athletes race walk at speeds in excess of these measured speeds (> 15·25 $km.h^{-1}$ in men and > 14.5 $km \cdot h^{-1}$ in women) (Hettinga et al., 2019), whose flight times might be longer and with an increased risk of disqualification. Of course, it is important to develop low variability in this measure, but it is even more important that effective technique is developed and monitored by coaches at these higher speeds to maintain compliance with the rules.

It was evident throughout all speeds that variability and symmetry were present, although the influencing factor was not speed in this world-class group of race walkers. This is in line with previous research that shows that neither distance covered (Hanley & Tucker, 2018), race walking experience (Tucker & Hanley, 2017) nor gait used (whether running or race walking) affect variability and symmetry (Girard et al., 2019, Hanley & Tucker, 2018). Instead, these elements of movement consistency are based on individual motor patterns and even then an individual can be symmetrical for some variables, but not others (Tables 4 and 5). For coaches and health practitioners, the implications of this new research, alongside previous studies on the effect of distance, experience and gait mode, are that variability and asymmetry are normal to some degree, typically higher in kinetic variables (possibly so that key spatiotemporal variables are lower), consistent across speeds and that even those athletes with some asymmetry will not be symptomatic in all variables. As increasing speed did not affect variability or symmetry scores, race walk coaches who wish to assess these should use competition speeds during testing for the most meaningful values, especially with regard to flight times.

To ensure participants race walked at the target speeds in this study, an instrumented treadmill was used. This was important in maintaining the environmental constraints so that speed was the only independent variable that changed (rather than gradient or wind speed, for example). This could mean, of course, that any variability or asymmetry recorded could be lessened or increased on those surfaces used in competition, such as athletics tracks and roads, and coaches should be aware that the construction of competition surfaces (with bends or cambers, for example) could affect particular athletes. Notwithstanding that there are potential differences in overground and treadmill gait (Van Hooren et al., 2020), the treadmill also allowed for a large sample of steps to be collected at each speed per participant, and for both spatiotemporal and kinetic variables to be measured. A limitation of the treadmill used was its inability to measure shear forces, and so recommendations for future studies include the analysis of anteroposterior and mediolateral GRF variability and asymmetry, and during overground conditions.

CONCLUSIONS

Race walking is an endurance event in athletics where pace is altered because of reasons such as fatigue or tactics. This novel study examined the effects of increases in speed on variability and symmetry scores in spatiotemporal and kinetic variables and showed that these remained consistent regardless of speed and, furthermore, regardless of the underlying changes in step length, step frequency, contact time, flight time and vertical GRF. Overall, athletes had both low variability and symmetry scores and demonstrated, as shown in previous research on the effects of experience and distance covered, that they had developed consistent movement patterns. The higher values for kinetic variables suggest that these vary more within and between limbs to ensure more consistent spatiotemporal variables, and coaches should monitor their athletes for increased asymmetry during non-treadmill exercise that might arise from less controlled movements. Mean flight time was close to zero at lower race walking speeds, and hence testing for asymmetry or variability in this variable should be conducted at competitive speeds, where non-visible loss of contact is more likely to occur.

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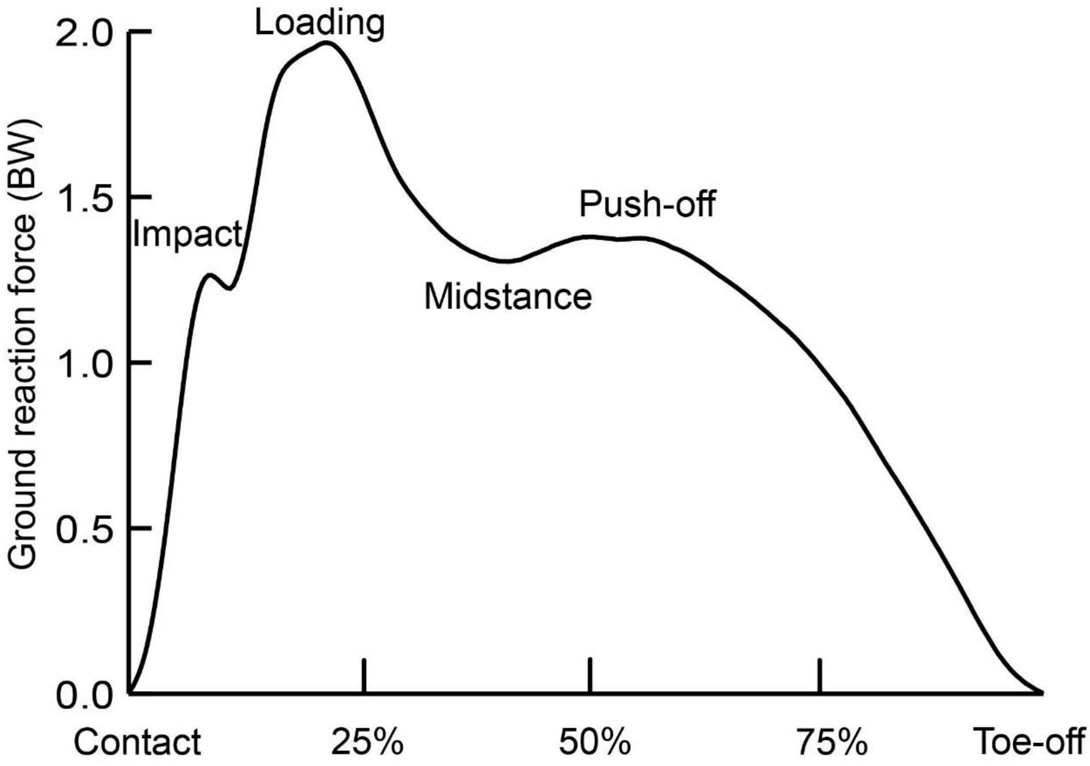

Figure 1. A typical vertical GRF trace of the race walking stance phase highlighting the key events used in this study (taken from Tucker and Hanley (2017)).

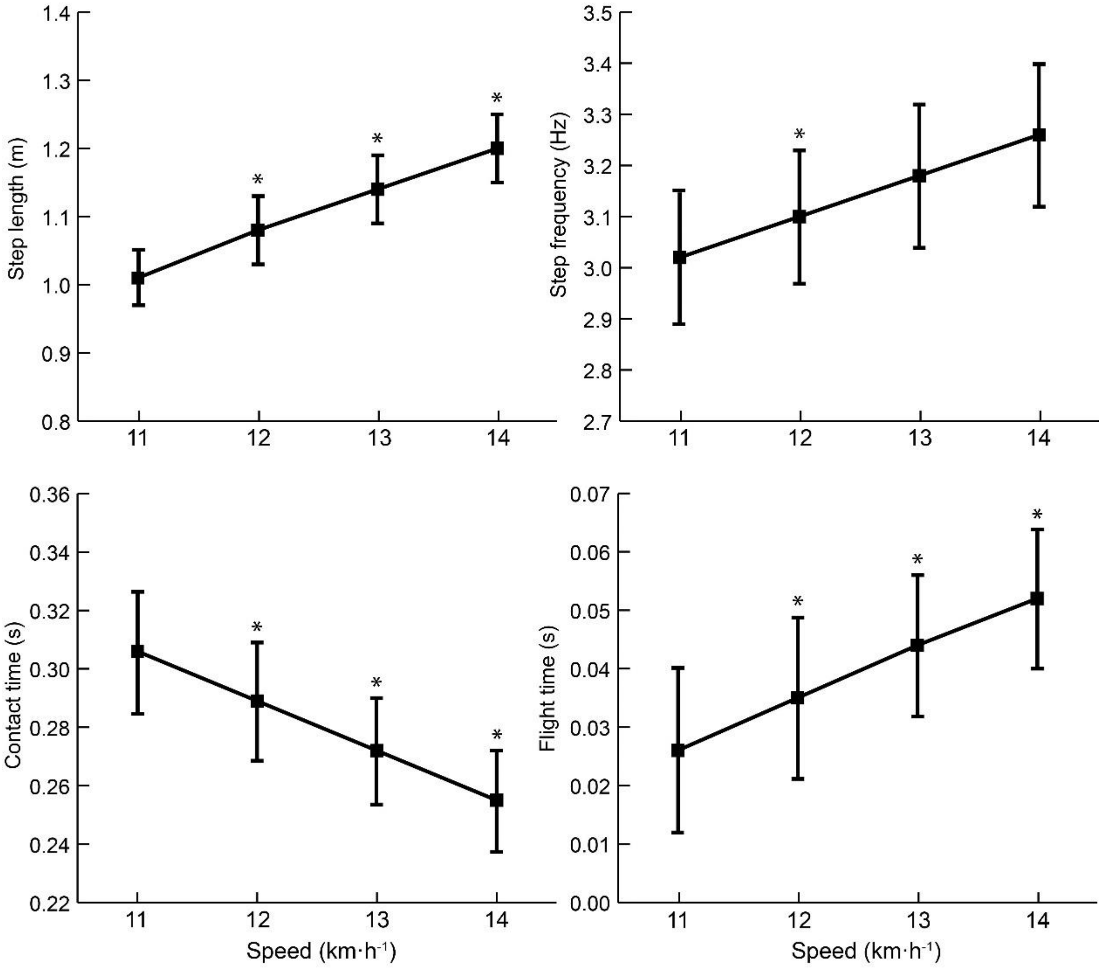

Figure 2. Changes in spatiotemporal variables with increased speed for all athletes. Results are shown as means and SD. A significant difference from the previous speed is denoted as $p < 0.01$ (*) based on repeated measures contrasts.

Table 1. Mean (± SD) values for key kinetic variables at each speed.

	11 $km.h^{-1}$	12 $km.h^{-1}$	13 $km.h^{-1}$	14 $km.h^{-1}$
Loading force (BW)	1.81 ± 0.21	1.85 ± 0.20	1.91 ± 0.19	1.97 ± 0.20
Midstance force (BW)	1.04 ± 0.32	1.14 ± 0.37	1.18 ± 0.39	1.25 ± 0.43
Push-off force (BW)	1.51 ± 0.10	1.50 ± 0.09	1.49 ± 0.09	1.51 ± 0.10

Table 2. Mean (± SD) MAD scores (%) indicating variability at each speed.

	11 $km.h^{-1}$	12 $km.h^{-1}$	13 $km.h^{-1}$	14 $km.h^{-1}$
Step length	1.34 ± 0.34	1.40 ± 0.32	1.32 ± 0.21	1.23 ± 0.30
Step frequency	1.32 ± 0.38	1.28 ± 0.41	1.33 ± 0.43	1.46 ± 0.46
Contact time	1.63 ± 0.44	1.61 ± 0.28	1.71 ± 0.42	1.64 ± 0.55
Flight time	24.91 ± 15.64	16.53 ± 8.43†	11.82 ± 5.12†	10.57 ± 4.51
Loading force	3.49 ± 1.09	3.70 ± 0.96	3.59 ± 0.92	3.48 ± 0.99
Midstance force	4.56 ± 1.33	4.38 ± 1.29	4.64 ± 1.52	4.49 ± 1.46
Push-off force	2.46 ± 0.56	2.41 ± 0.46	2.61 ± 1.16	2.73 ± 1.12

A significant difference from the previous speed is denoted as $p < 0.05$ (†) based on repeated measures contrasts.

Table 3. Mean (± SD) symmetry angle scores (%) at each speed.

	$11\ km.h^{-1}$	$12\ km.h^{-1}$	$13\ km.h^{-1}$	$14\ km.h^{-1}$
Step length	0.52 ± 0.32	0.56 ± 0.45	0.64 ± 0.43	0.55 ± 0.42
Step frequency	0.52 ± 0.38	0.49 ± 0.41	0.52 ± 0.42	0.51 ± 0.47
Contact time	0.42 ± 0.24	0.41 ± 0.26	0.38 ± 0.29	0.38 ± 0.22
Flight time	6.90 ± 5.56	4.52 ± 3.95	3.49 ± 3.42	3.09 ± 2.32
Loading force	1.88 ± 1.27	2.09 ± 1.33	1.93 ± 1.37	1.86 ± 1.46
Midstance force	1.53 ± 1.78	1.52 ± 1.10	1.45 ± 0.92	1.17 ± 1.04
Push-off force	0.97 ± 0.74	1.19 ± 0.85	1.36 ± 1.00	1.29 ± 1.04

Table 4. Number (and percentage) of athletes at each speed who were considered asymmetrical (symmetry angle > 1.2% and Cohen's *d* > 1.20).

	$11\ km.h^{-1}$	$12\ km.h^{-1}$	$13\ km.h^{-1}$	$14\ km.h^{-1}$
Step length	0 (0%)	0 (0%)	1 (6%)	0 (0%)
Step frequency	0 (0%)	2 (11%)	1 (6%)	3 (17%)
Contact time	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Flight time	5 (28%)	5 (28%)	2 (11%)	4 (22%)
Loading force	10 (56%)	9 (50%)	9 (50%)	9 (50%)
Midstance force	4 (22%)	6 (33%)	7 (39%)	5 (28%)
Push-off force	6 (33%)	7 (39%)	7 (39%)	8 (44%)

Table 5. Mean (± SD) symmetry angle scores (%) across all four speeds for each athlete (M = male; F = female). Athletes with a symmetry angle above 1.2% and asymmetrical at half or more of the speeds are indicted (*). The table is ranked by highest number of assymetries.

Athlete ID	Step length	Step frequency	Contact time	Flight time	Loading force	Midstance force	Push-off force
14 (M)	0.69 ± 0.40	1.31 ± 0.26*	0.17 ± 0.19	14.29 ± 4.02*	1.37 ± 0.47	1.34 ± 0.58	2.00 ± 0.38*
15 (M)	0.47 ± 0.08	0.28 ± 0.17	0.65 ± 0.14	5.01 ± 3.27	2.40 ± 1.39*	2.93 ± 2.71*	1.99 ± 0.40*
10 (M)	0.95 ± 0.09	0.62 ± 0.26	0.34 ± 0.19	6.19 ± 1.60*	1.72 ± 0.61*	2.39 ± 0.49*	0.76 ± 0.46
9 (M)	0.19 ± 0.15	0.61 ± 0.17	0.40 ± 0.11	2.24 ± 1.85	3.63 ± 0.49*	1.36 ± 1.14*	1.71 ± 0.32*
7 (F)	0.63 ± 0.17	1.14 ± 0.11	0.34 ± 0.13	6.80 ± 1.67	4.56 ± 0.57*	1.88 ± 0.78*	1.24 ± 0.83
11 (M)	1.08 ± 0.12	0.26 ± 0.20	0.46 ± 0.07	5.42 ± 6.73	1.91 ± 0.84*	0.93 ± 1.08	3.03 ± 0.84*
3 (F)	0.87 ± 0.10	0.15 ± 0.13	0.18 ± 0.09	1.49 ± 1.09	2.71 ± 0.27*	0.65 ± 0.51	1.33 ± 0.46*
6 (F)	0.13 ± 0.03	0.29 ± 0.08	0.06 ± 0.04	2.11 ± 0.67	2.13 ± 0.54*	1.84 ± 1.66*	0.45 ± 0.20
2 (F)	0.23 ± 0.31	0.40 ± 0.48	0.26 ± 0.21	1.25 ± 1.48	1.60 ± 0.95*	1.31 ± 0.80*	0.32 ± 0.63
16 (M)	0.28 ± 0.13	1.09 ± 0.27	0.36 ± 0.14	10.52 ± 6.09*	0.42 ± 0.21	0.47 ± 0.12	0.76 ± 0.28
17 (M)	0.96 ± 0.29	0.39 ± 0.31	0.23 ± 0.06	3.28 ± 2.40	3.77 ± 0.80*	2.48 ± 2.09	1.33 ± 0.97
12 (M)	0.52 ± 0.09	0.32 ± 0.15	0.25 ± 0.11	6.25 ± 1.98	0.80 ± 0.71	0.75 ± 0.66	1.48 ± 1.55*
13 (M)	0.35 ± 0.28	0.40 ± 0.09	0.86 ± 0.17	4.17 ± 1.83	0.95 ± 0.49	1.57 ± 1.67*	0.77 ± 0.31
8 (M)	0.25 ± 0.15	0.23 ± 0.18	0.60 ± 0.12	3.46 ± 0.43	0.81 ± 0.29	2.07 ± 0.49*	1.04 ± 0.30
4 (F)	0.27 ± 0.17	1.03 ± 0.27	0.79 ± 0.09	2.10 ± 1.57	0.81 ± 2.30	0.54 ± 0.76	2.30 ± 0.15*
5 (F)	1.47 ± 0.26	0.15 ± 0.01	0.19 ± 0.05	1.14 ± 0.48	3.27 ± 0.75*	1.24 ± 0.49	0.25 ± 0.14
1 (F)	0.44 ± 0.19	0.29 ± 0.20	0.53 ± 0.18	2.84 ± 2.47	0.70 ± 0.42	1.02 ± 0.66	0.70 ± 0.42
18 (M)	0.43 ± 0.19	0.24 ± 0.12	0.53 ± 0.19	2.42 ± 0.45	0.97 ± 0.18	0.53 ± 0.30	0.24 ± 0.20