Gait variability and symmetry in world-class senior and junior race walkers

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Running title: Variability and symmetry in race walkers

Keywords: Elite-standard athletes, gait, spatiotemporal variables, track and field

ABSTRACT

The aim of this study was to analyse gait variability and symmetry in race walkers. Eighteen senior and 17 junior athletes race walked on an instrumented treadmill (for 10 km and 5 km, respectively) at speeds equivalent to 103% of season's best time for 20 km and 10 km, respectively. Spatiotemporal and ground reaction force data were recorded at 2.5 km, and at 4.5, 6.5 and 8.5 km for a subsection of athletes. Gait variability was measured using median absolute deviation (MAD) whereas inter-leg symmetry was measured using the symmetry angle. Both groups showed low variability for step length (< 0.9%), step frequency (< 1.1%), contact time (≤ 1.2%), and vertical peak force values (< 5%), and neither variability nor symmetry changed with distance walked. Junior athletes were more variable for both step length (P = 0.004) and loading force (P = 0.003); no differences for gait symmetry were found. Whereas there was little mean asymmetry overall, individual analyses identified asymmetry in several athletes (symmetry angle ≥ 1.2%). Importantly, asymmetrical step lengths were found in 12 athletes and could result from underlying imbalances. Coaches are advised to observe athletes on an individual basis to monitor for both variability and asymmetry.

INTRODUCTION

Race walking is part of the athletics programme contested at the Olympic Games and all other major athletics championships. Competitions are held over 10 km (junior men and women), 20 km and 50 km (senior men and women). This competitive form of gait is dictated by International Association of Athletics Federations (IAAF) Rule 230.2 that 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' (IAAF, 2015). Race walkers therefore need to maintain consistently legal technique with both legs as even very brief infringements of the rules by either leg can lead to disqualification. An understanding of both gait variability and symmetry in race walkers can thus assist coaches in developing sound techniques, particularly in terms of what values are considered acceptable or potentially damaging.

Movement variability in normal and pathological gait has been researched extensively to date (e.g. Heiderscheit, Hamill, & van Emmerik, 2002; White, Agouris, Selbie, & Kirkpatrick, 1999). Relevant findings have shown that expert runners can reduce variability in achieving key performance variables (e.g. step length and frequency) (Nakayama, Kudo, & Ohtsuki, 2010), and that a function of movement variability might be to attenuate impact shocks when running and reduce the risk of injury (Bartlett, Wheat, & Robins, 2007). For example, it has been shown that participants who experience patellofemoral pain have reduced variability in lower limb joint couplings compared with healthy controls (Hamill, van Emmerik, Heiderscheit, & Li, 1999; Heiderscheit et al., 2002). Because the rules of race walking result in very particular biomechanical and coordinative demands (Preatoni, Ferrario, Donà, Hamill, & Rodano, 2010), it is considered a highly technical and rather stereotyped form of gait (Donà, Preatoni, Cobelli, Rodano, & Harrison, 2009) and so the quantification of movement variability within elite-standard performers is crucial to understand this unique form of gait. In addition, race walking is an unnatural and learned skill that takes time to develop (Hanley, Bissas, & Drake, 2014) but the existence of any variability differences between junior and senior race walkers have not yet been researched and could highlight any developmental issues that exist in less-trained athletes.

Symmetry refers to the exact replication of one limb's movement by the other, with asymmetry referring to any deviation from symmetry (Exell, Irwin, Gittoes, & Kerwin, 2012). Race walk coaches believe that legal and efficient technique requires certain symmetry of motion and therefore subjectively monitor for inter-limb discrepancies (Salvage & Seaman, 2011). Because gait movements can be achieved in a number of ways, with muscle groups compensating for others if necessary (e.g. for a weak muscle on the other leg) (Levine, Richards, & Whittle, 2012), gait asymmetry can lead to increased work demands on one side of the body. Measurements of symmetry have been previously used in both pathological gait research and in running to highlight increased injury risk (Exell et al., 2012); for example, inter-leg differences of 5.7° for peak knee extension during terminal swing and 7% for vertical peak force were found in an injured Australian Rules footballer (Schache, Wrigley, Baker, & Pandy, 2009). It has also been found that national, non-elite standard race walkers showed asymmetry between lower limbs, which could be a possible risk of injury, although this was not quantified (Donà et al., 2009). Race walkers with asymmetrical gait might also attract the attention of judges to a greater extent (Wolfe, 1998). It is thus important to quantify the degree of symmetry between lower limbs in elite-standard race walkers because of associations with injury risk, performance and the possibility of appearing to have non-legal technique to the judges' eyes.

Despite the importance of understanding both variability and symmetry in elite-standard race walking, there is little research in this area. Previous research on this topic focussed on non-linear measures of variability (Preatoni et al., 2010) or used race walking as a tool to understand variability (Donà et al., 2009), rather than studying variability in race walking with regard to athletic performance (Pavei, Cazzola, La Torre, & Minetti, 2014). Measuring the differences in variability between different skill standards has been used previously to appreciate whether increased or decreased movement variability is an indicator of better performers (Hiley, Zuevsky, & Yeadon, 2013). It might therefore be useful to examine differences between less- and more-experienced race walkers, along with symmetry analysis. The aim of this study was to analyse gait variability and symmetry in world-class race walkers, with the objectives of comparing these senior athletes with elite-standard junior race walkers and observing if changes occurred with distance race walked.

METHODS

Participants

The study was approved by the Faculty Research Ethics Committee and 35 race walkers gave written informed consent. The participants were divided into two groups: a senior group of 13 male and five female athletes (27 ± 7 yrs, 1.77 ± .08 m, 65.9 ± 10.2 kg), and a junior group of nine male and eight female athletes (19 ± 1 yrs, 1.74 ± .08 m, 60.6 ± 10.1 kg). There were no differences between groups for either stature or mass. All senior athletes had competed at the Olympic Games or World Championships, with all 13 men having competed over 20 km (personal best time: 1:23:41 ± 1:32) with nine of them also competing over 50 km (3:52:53 ± 5:52). The mean personal best time for the women over their competitive distance of 20 km was 1:31:44 (± 1:38). All junior athletes had competed at similar world-class events for their age group, e.g. World Youth Championships and World Junior Championships. The mean personal best time for the junior men over 10 km was 43:41 (± 1:10), whereas it was 49:37 (± 1:36) for the junior women.

Data collection

After a 10-min warm-up and familiarisation period (Matsas, Taylor, & McBurney, 2000), each participant race walked on a treadmill (Gaitway, Traunstein) at a pace equivalent to 103% of their most recent 10 or 20 km mean race speed (juniors and seniors, respectively) (Hanley, 2015). Senior athletes walked for 10 km, whereas juniors walked for 5 km. Each athlete race walked at a constant pace for the duration of the test. The treadmill's inclination was set at 0% during data collection (Abt et al., 2011; Vernillo et al., 2014) as race walking events are held on flat, even surfaces. 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) that recorded vertical ground reaction forces (GRF) (1000 Hz) from both feet as well as temporal data. Because of the difficulties with measuring kinematic variables on a treadmill, the force plates also recorded the position of the centre of pressure (COP) from which step length was measured. Data were collected for 30 s at 2.5 km (where 2.5 km occurred halfway through data collection), which allowed for the collection of 46 (± 2) steps per foot in the senior athletes and 45 (± 2) steps per foot in the junior athletes.

To further observe if there were any effects of distance race walked on variability or symmetry, 10 of the senior athletes (five men and five women) were analysed on three more occasions. For these athletes, data were also collected for 30 s at 4.5 km, 6.5 km and 8.5 km.

Data analysis

Step length was defined as the distance from one foot strike to the next foot strike 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 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 as reported in previous research on world-class race walkers (Hanley & Bissas, 2016) and comprised impact peak force, loading peak force, midstance force, push-off peak force, and impulse. The impact peak was defined as the highest recorded force during the first 70 ms of contact, the loading peak force was identified as the next peak in the vertical GRF trace during early stance, and the midstance force value was measured as the minimum force occurring between the loading and push-off peaks (Hanley, 2015; Watkins, 2010). The push-off peak force was itself identified as the maximum vertical force during late stance. All kinetic variables were normalised and thus have been reported in body weights (BW).

**** Figure 1 near here ****

Statistical analysis

Gait variability was measured using median absolute deviation (MAD) (Chau, Young, & Redekop, 2005; Preatoni et al., 2013) where the MAD was calculated for the left and right legs separately and then the mean calculated for each participant. The mean MAD scores were calculated as percentages of the original median value to compare between groups and variables. The MAD scores were also multiplied by 1.4826, and the median plus or minus 2.5 times the MAD used for outlier detection (Leys, Ley, Klein, Bernard, & Licata, 2013).

Outliers were removed before the calculation of means and standard deviations (absolute values) and symmetry values to reduce the chances of false positives (Leys et al., 2013); overall, 4.7% of the senior athletes' values and 4.2% of the junior athletes' values were removed.

Differences between the senior and junior race walkers for absolute values, MAD percentages and symmetry scores were measured using independent-samples *t*-tests, with adjustments made if Levene's test for equality of variances was less than 0.05 (Field, 2009). Effect sizes (ES) for differences between groups were calculated using Cohen's *d* (Cohen, 1988) and considered to be either trivial (ES: ≤ 0.20), small (0.21 – 0.60), moderate (0.61 – 1.20), large (1.21 – 2.00), or very large (> 2.01) (Hopkins, Marshall, Batterham, & Hanin, 2009). On those occasions where Cohen's *d* was calculated, only those instances where the effect sizes were moderate, large, or very large have been indicated.

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 1 below (Zifchock et al., 2008):

$$\text{Symmetry angle} = [(45° - \arctan(X_{\text{left}} / X_{\text{right}}) / 90°)] \text{ X } 100\% \qquad \text{(Equation 1)}$$

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

To determine whether a participant's symmetry angle was significant, asymmetry between legs was determined using paired-samples *t*-tests (Exell et al., 2012) provided the ES was also large (i.e. a Cohen's *d* value greater than 1.2). The percentage of athletes considered asymmetrical in each group was thus calculated as the proportion of participants whose inter-leg differences were both significant and where a large effect size was present. To measure any changes in variability or symmetry within the 10 athletes who completed 10 km on the treadmill, one-way repeated measures analysis of variance (ANOVA) was conducted with repeated contrast tests (Field, 2009), with Greenhouse-Geisser correction used if Mauchly's test for sphericity was violated. In addition, one-way ANOVA with Tukey's post-hoc tests compared variability values between variables (Field, 2009). Pearson's product moment correlation coefficient found associations between race walking speed and MAD scores and symmetry angles, with 90% confidence intervals (90% CI) calculated. An alpha level of 5% was set for all statistical tests.

RESULTS

The results for each gait variable measured in this study are shown in Table 1 for both junior and senior athletes. No distinct impact peaks were found in one senior and one junior athlete's GRF traces. Senior athletes were faster with longer steps, but no other differences were found. The results for gait variability are shown in a similar fashion in Table 2; the only differences between senior and junior athletes found were for step length and loading force. Speed was correlated with the MAD score for the impact force (r = –.456, P = 0.008, 90% CI = –0.65 to –0.20) and the loading force (r = –.334, P = 0.049, 90% CI = –0.56 to –0.06). Variability for flight time was greater than for either of the other temporal variables for both senior athletes (step frequency: $P < 0.001$, ES = 4.01; contact time: $P < 0.001$, ES = 4.07) and junior athletes (step frequency: $P < 0.001$, ES = 3.47; contact time: $P < 0.001$, ES = 3.38).

**** Table 1 near here ****

**** Table 2 near here ****

Table 3 shows the results of the symmetry analysis, with no difference found between senior and junior athletes for any variable. The percentage of athletes who were considered to be asymmetrical for any particular variable is also shown. The lowest value found for significant asymmetry was a symmetry angle of 1.2% (i.e. all symmetry angles equal to or greater than 1.2% were significant). The mean difference in left-right and right-left step lengths for those senior athletes who showed asymmetry was 21 mm (± 7) whereas for the asymmetrical junior athletes it was 32 mm (± 8). There were no correlations between speed and any other variable for symmetry. With regard to the athletes who were measured on four occasions over a 10 km race walk, there were no changes in variability or symmetry for any variable.

**** Table 3 near here ****

DISCUSSION

The aim of this study was to measure and analyse gait variability and symmetry in race walkers. The first important finding was that the senior race walkers showed low variability (< 5%) across most spatiotemporal and GRF measures. This demonstrated that these highly skilled Olympic and World Championship competitors had developed a repeatedly consistent outcome. In addition, for most measures there was little difference in variability between seniors and juniors, and thus the stable movement patterns typical of elite-standard performers (Fleisig, Chu, Weber, & Andrews, 2009; Hiley et al., 2013; Tucker, Anderson & Kenny, 2013) were demonstrated by both groups of race walkers. This showed that the junior athletes had developed similarly consistent movement outcomes, which was unsurprising given their high standard of competitive experience and that they compete under the same enforcement of IAAF Rule 230.2. However, one of the differences found was in step length variability, which could be important given step length's direct role in determining race walking speed (Hanley, Bissas, & Drake, 2013). The greater step lengths of the senior athletes combined with their lower variability showed there was still room for development within the junior athletes and that the improvement in this variable is not confined to just achieving longer steps. Whereas variations in gait movements might be beneficial, for example with regard to changing the distribution of biological stresses (Hamill et al., 1999), step length is a determining factor in race walking speed (Hanley et al., 2013) and should be maintained for optimal performance, notwithstanding that this can be achieved through variable joint patterns (Heiderscheit et al., 2002).

Variability in loading force was one of the few variables that was associated with speed (i.e. faster athletes had less variability). Loading peak force occurs between initial contact and midstance, and in gait is associated with muscle activity that prevents excessive knee flexion during this phase (Levine et al., 2012). It occurs after the impact force during which the muscles cannot respond to an external load (Watkins, 2010), and whose decreased variability also correlated with higher speeds (r = –.456). However, the wide confidence intervals found for both correlations showed there was considerable variability within the sample and this variance should be taken in account in terms of the potential role of speed on variability. The higher variability in loading force in the junior athletes could be a result of less consistent patterns of muscle activity that affect the athlete's ability to adhere to the knee straightening requirement of Rule 230.2. Achieving less variability during early stance is most likely a key developmental aim for race walkers, especially those competing over longer distances. In those senior athletes who were analysed on repeated occasions as they completed 10 km on the treadmill, no changes in variability (or symmetry) occurred over the course of the test and further showed their trained adaptations to reduce variability. In this study, 5 km and 10 km were chosen as the distances walked for junior and senior athletes, respectively, based on a compromise with coaches to avoid too strenuous a test during busy training periods. Given that athletes were tested over half of their normal competitive distances, and both groups were compared at the 2.5 km distance, it is unlikely that athletes in either group suffered to any great extent from fatigue or that any differences in variability or symmetry occurred because of the total distance covered. Future research is therefore recommended to examine the effects of longer distances on variability and symmetry over the senior competitive distances of 20 km and 50 km.

Race walkers compete on flat, even surfaces with little change in underground conditions and thus will not experience perturbations (e.g. as in cross country running) that could act as external sources of variability. This fact, combined with the need to appear consistent within the rules, means that low variability in step length and step frequency is a desirable outcome of training. Notwithstanding differences between overground and treadmill gait (e.g. Sinclair et al., 2013), treadmills therefore provide a consistent training surface for this endurance activity. The results from the treadmill testing for the spatiotemporal and GRF variables were comparable to those previously reported for overground race walking (Hanley & Bissas, 2016) and differences between treadmill and overground gait were reduced through the use of a 10-min familiarisation period (Matsas et al., 2000) and a constant speed throughout testing (Savelberg, Vorstenbosch, Kamman, van de Weijer, & Schambardt, 1998). Additionally, this study showed that variability did not change for any of the measured GRF or spatiotemporal variables over the course of 10 km, further demonstrating the stereotyped nature of race walking (Donà et al., 2009). It should be noted that in competition, race walkers typically vary pace (e.g. because of tactics or tiredness) (Hanley, 2013; Vernillo et al., 2011; Vernillo et al., 2012) and whereas left-right asymmetry might not necessarily occur, key spatiotemporal variables such as step length and frequency will change with pace (Hanley et al., 2013). Although the important temporal variables of step frequency and contact time showed low variability, flight time was considerably more variable in both groups (> 6%) and this is important with regard to compliance with IAAF Rule 230.2. This is because the detection of visible loss of contact requires only a few instances of increased flight times to be considered non-legal by judges and lead to disqualification. However, the mean flight times in this study (0.053 s) were greater than the 40 ms threshold above which loss of contact is typically detected (Knicker & Loch, 1990) and would most likely be considered illegal regardless of the variability found. Race walkers develop low variability through consistent training, but this still needs to be monitored by coaches to ensure it is legal and efficient technique that is being developed.

In general, the senior race walkers were symmetrical for the gait variables measured (< 2.5%), with no differences found between those athletes and the juniors. In this study, acceptable asymmetry was found to be below 1.2% as calculated using the symmetry angle, and could be used as a practically useful reference for coaches and future gait studies. However, the individual nature of asymmetry (Dufek, Bates, Stergiou, & James, 1995; Exell et al., 2012) was demonstrated by the percentage of athletes in each group displaying asymmetry (e.g. more than half the athletes in both groups were asymmetrical for impact force and impulse). The key spatiotemporal gait variable of step length showed very little mean asymmetry (0.33 ± 0.27% and 0.42 ± 0.40% for seniors and juniors, respectively), but the relatively large variance found was because 12 of the total 35 athletes did not have symmetrical step lengths. The mean differences in left-right steps in the asymmetrical athletes of just over 2 cm for seniors and 3 cm for juniors are important from a competitive point of view as not only could they result in movement inefficiency, but also the asymmetrical step lengths could attract the attention of judges who are often advised to look for athletes who appear different from the others (USATF, 2008). Even though such large individual step length asymmetries might be noticeable to a coach, their underlying causes are less likely to be detectable. For example, differences in step lengths could be a result of the asymmetries in flight time, a key component of step length given its very short duration in elite-standard race walking (Hanley & Bissas, 2016). Race walk coaches should therefore monitor their athletes for imbalances between legs during training and competition, and obtain the services of biomechanists who can evaluate symmetry in important factors not readily observed, such as GRF variables and muscle activity (via electromyography).

Completely symmetrical gait is rare given there are always some strength or mobility differences between left and right legs, especially given normal human right- or left-dominance. If a particular muscle cannot be used fully in a movement (e.g. it is weak or injured), its function can be taken over by others (Levine et al., 2012) but could mean workload imbalances occur. Future research is recommended to examine the inter-leg differences in muscle activity patterns and magnitudes, as well as the variability and symmetry in overground race walking, including during competition to take into account typical variations in pace. Although there were no differences between juniors and seniors for stature, lower limb length might have differed between groups. As step length is associated with lower limb length (Svedenhag & Sjödin, 1994) and could have affected the interpretation of results, future research should measure and examine the effect of lower limb length on variability. Although the instrumented treadmill was limited by its inability to measure shear forces and remove systematic noise (and hence future measurements of differences and variability in anteroposterior impulses would be particularly beneficial), its usage in this study did prevent any conscious or unconscious targeting of the force plates by the participants and allowed for predetermined race walking speeds to be set and maintained. It also allowed for a large sample of successive GRF traces to be collected that made their analysis particularly robust when removing outliers. Nonetheless, further studies that examine the differences between overground and treadmill race walking (similar to those already conducted on running (Sinclair et al., 2013)) will be particularly useful in understanding variability and symmetry in this abnormal but highly technical form of gait. Future research will also be useful in quantifying intersegmental variability to understand how the consistent outcomes found in this study are produced.

CONCLUSIONS

Race walking is a skilled endurance event where competitors train to maintain a consistent, legal technique so that it leads to both low gait variability and asymmetry. This was the first study to examine the magnitudes of variability and symmetry in elite-standard race walkers, and compared more experienced senior competitors with younger, junior athletes. Both groups demonstrated very little variability in either GRF or spatiotemporal variables, indicating that these athletes had developed a stereotyped, consistent gait pattern; however, the greater variability in step length amongst the junior athletes might be an area for improvement combined with the development of increased step length itself. Whereas both groups displayed symmetrical gaits overall, individual athletes showed asymmetry for some variables and highlighted the need for coaches to observe each of their athletes independently. Two of the most important variables to monitor are step length and flight time, not just because of their importance in achieving higher race walking speeds, but also because of the requirements of IAAF Rule 230.2. It is recommended that strength and conditioning programmes are developed by coaches that take into account the repetitive, consistent gait patterns of race walking alongside the need for balanced development of both sides of the body.

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Table 1. Mean (± *s*) values and Cohen's *d* values for key spatiotemporal and kinetic variables in elite-standard senior and junior race walkers. Between-group effects were significant at $P < 0.05$ (shown in bold).

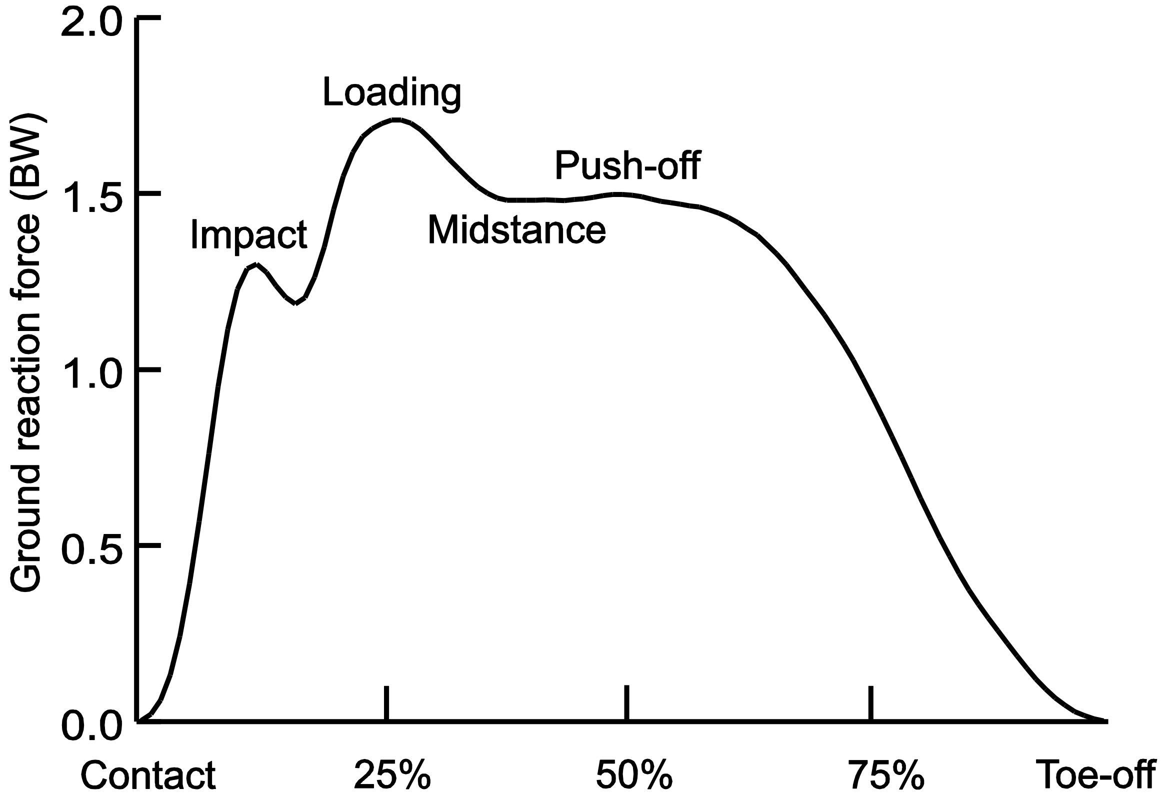
	Senior	Junior	*P*	*d*
Speed ($km \cdot h^{-1}$)	12.98 ± 0.66	12.26 ± 0.85	**0.009**	**0.94**
Step length (m)	1.14 ± 0.07	1.09 ± 0.07	**0.043**	**0.71**
Step frequency (Hz)	3.17 ± 0.12	3.13 ± 0.12	0.360	0.31
Contact time (s)	.263 ± .021	.267 ± .019	0.578	0.19
Flight time (s)	.053 ± .016	.053 ± .011	0.969	0.01
Impact force (BW)	1.60 ± 0.35	1.59 ± 0.28	0.884	0.05
Loading force (BW)	1.86 ± 0.19	1.86 ± 0.12	0.978	0.01
Midstance force (BW)	1.57 ± 0.35	1.50 ± 0.28	0.547	0.21
Push-off force (BW)	1.64 ± 0.15	1.59 ± 0.10	0.296	0.36
Impulse (BW·s)	0.31 ± 0.01	0.31 ± 0.02	0.852	0.06

Table 2. Mean (± *s*) MAD percentages and Cohen's *d* values for key spatiotemporal and kinetic variables in elite-standard senior and junior race walkers. Between-group effects were significant at $P < 0.05$ (shown in bold).

	Senior (%)	Junior (%)	*P*	*d*
Step length	0.67 ± 0.12	0.82 ± 0.16	**0.004**	**1.06**
Step frequency	1.03 ± 0.24	1.09 ± 0.28	0.490	0.24
Contact time	0.99 ± 0.17	1.20 ± 0.44	0.066	0.64
Flight time	6.28 ± 1.79	6.94 ± 2.79	0.412	0.28
Impact force	3.70 ± 1.36	4.89 ± 2.66	0.124	0.56
Loading force	2.16 ± 0.38	2.77 ± 0.67	**0.003**	**1.12**
Midstance force	3.68 ± 1.64	4.73 ± 3.23	0.246	0.41
Push-off force	1.89 ± 0.47	2.49 ± 1.19	0.063	0.67
Impulse	0.70 ± 0.13	0.76 ± 0.14	0.184	0.46

Table 3. Mean (± *s*) symmetry angles for key spatiotemporal and kinetic variables in elite-standard senior and junior race walkers. Between-group effects were significant at $P < 0.05$.

	Senior (%)	Junior (%)	*P*	% asymmetrical (senior / junior)
Step length	0.33 ± 0.27	0.42 ± 0.40	0.432	39 / 29
Step frequency	0.27 ± 0.26	0.48 ± 0.34	0.052	22 / 24
Contact time	0.39 ± 0.42	0.52 ± 0.59	0.457	28 / 24
Flight time	2.03 ± 1.93	3.24 ± 2.73	0.138	28 / 53
Impact force	2.48 ± 2.46	2.85 ± 2.57	0.678	65 / 56
Loading force	1.38 ± 1.14	0.77 ± 1.01	0.103	50 / 6
Midstance force	1.98 ± 2.22	1.66 ± 1.31	0.607	33 / 35
Push-off force	1.24 ± 1.11	1.83 ± 1.19	0.135	50 / 65
Impulse	0.84 ± 0.75	0.82 ± 0.66	0.929	61 / 71


Ground reaction force (BW)
2.0
1.5
1.0
0.5
0.0
Loading
Push-off
Impact
Midstance
Contact
25%
50%
75%
Toe-off