Bilateral asymmetry of running gait in competitive, recreational and novice runners at different speeds

Shiwei Mo[1], Fannie O.Y. Lau[2], Alan K.Y. Lok[1], Zoe Y.S. Chan[1], Janet H. Zhang[1], Gary Shum[3], Roy T.H. Cheung[1*]

[1] Gait & Motion Analysis Laboratory, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong SAR

[2] Department of Orthopaedics & Traumatology, The Chinese University of Hong Kong, Hong Kong SAR

[3] School of Sport, Health and Wellbeing, Plymouth Marjon University, Plymouth, United Kingdom

Corresponding authors

* Roy T.H. Cheung

Telephone: +852 2766 6739

Fax: +852 2330 8656

Email: roy.cheung@polyu.edu.hk

Postal address: Gait & Motion Analysis Laboratory, ST004, G/F, Core S, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Abstract

The mechanisms and underlying causes of bilateral asymmetry among healthy runners of different levels remain unclear. This cross-sectional laboratory study aimed to investigate the effects of running speed and running experience or competitive level on bilateral symmetry during running. Eleven competitive runners, 9 recreational runners and 11 novice runners were recruited in this study. They ran on an instrumented treadmill for 3 minutes at each of 5 fixed speeds (8, 9, 10, 11 and 12 km/h) in a randomized order. Bilateral asymmetry was evaluated and quantified using symmetry index (SI) of temporal and kinetic parameters. Overall, SI ranged between 0.8% for stride time and 21.4% for vertical average loading rate. Significant speed effects were observed on SI of flight time (p = 0.012), which was significantly higher at 8 km/h than that of the other 4 speeds (p = 0.023, 0.005, 0.023 and 0.028, respectively). Group-by-speed interactions were detected on SI in time to peak vertical ground reaction force (p = 0.032) and vertical average loading rate (p = 0.002). The competitive runners presented linear reduction in the SI with increasing speed from 8 to 12 km/h (R^2 > 0.94); for the recreational runners, SI changed nonlinearly and presented a roughly U-shaped trend across speeds (R^2 > 0.88); and for the novice runners, changes of SI across speed were inconsistent and dependent on parameters of interest (R^2 > 0.64). Bilateral asymmetry was affected by both running speed and runners' running experience or competitive level. The competitive runners were found to run with a more symmetrical manner with a greater running speed, the recreational runners demonstrated the most symmetrical pattern at the critical speed, whereas the novice runners showed inconsistent trends.

Keywords: Symmetry index; Competitive level; Running experience; Vertical average loading rate

1. Introduction

Running-related injuries are very common among distance runners and there was a tendency that runners developed a running-related injury on a particular leg. Bilateral asymmetry between legs during running was considered a risk factor (Zifchock, Davis, & Hamill, 2006; Zifchock, Davis, Higginson, McCaw, & Royer, 2008) when one leg being exposed to more loading than the other. For example, stress on the Achilles tendon of the preferred leg was significantly greater than that of the non-preferred leg for healthy recreational runners (Furlong & Egginton, 2018); loading of the injured leg was higher than that of the uninjured leg for the recreational runners with unilateral tibial stress fracture (Zifchock et al., 2006); stance time was longer in the injured leg when compared with the uninjured side for well-trained athletes with a running-related injury history (Gilgen-Ammann, Taube, & Wyss, 2017).

Brughelli, Cronin, Mendiguchia, Kinsella, and Nosaka (2010) examined the bilateral asymmetry of running kinetics and kinematics of both injured and uninjured players during running. A compensation mechanism, in which the horizontal force was significantly less in the injured leg than that of the uninjured leg, was observed in injured players. The horizontal force was also found to be significantly greater in the uninjured leg of the injured runners when compared to either legs of healthy players. Robadey, Staudenmann, Schween, Gehring, Gollhofer, and Taube (2018) found that the injured leg exhibited significantly smaller values for the parameters of interest (e.g., step and stance times) when compared with the contralateral uninjured leg during overground running. Moreover, a prospective study found that the injured novice runners exhibited lower bilateral asymmetry in peak impact force and contact time when compared to their uninjured counterparts (Bredeweg, Buist, & Kluitenberg, 2013; Gilgen-Ammann et al., 2017). On contrary, two previous retrospective studies reported no differences in symmetry index (SI) (Zifchock et al., 2006) and symmetry angle (Zifchock et al., 2008) between the injured and uninjured runners. Haugen, Danielsen, McGhie, Sandbakk, and Ettema (2018) also reported no bilateral asymmetry in running kinematics between the injured and uninjured sprinters. Such findings (Haugen et al., 2018; Zifchock et al., 2006; 2008) could be a result of a compensatory mechanism, for example, the uninjured leg might afford more loads than the injured side, thereby minimizing bilateral differences prior to suffering from a running-related injury.

Asymmetrical gait pattern has been reported extensively in previous studies in running (Bredeweg et al., 2013; Brughelli et al., 2010; Cavanagh, Pollock, & Landa, 1977; Furlong & Egginton, 2018; Gilgen-Ammann et al., 2017; Hanley & Tucker, 2018; Karamanidis, Arampatzis, & Brüggemann, 2003; Munro, Miller, & Fuglevand, 1987; Robadey et al., 2018; Williams, Cavanagh, & Ziff, 1987; Zifchock et al., 2006; 2008). Significant bilateral asymmetry was reported in various parameters of interest including stance time, peak impact force and hip internal rotation velocity (Karamanidis et al., 2003; Zifchock et al., 2006; 2008) and the asymmetrical level varied greatly across parameters of interest (Furlong & Egginton, 2018; Karamanidis et al., 2003; Zifchock et al., 2006).

The extent of bilateral asymmetry might be further affected by runners' competitive level or running experience. Zifchock et al. (2006) found that the between-subject variability of SI was between 69% and 81% of the mean among the female recreational runners; Pappas, Paradisis, and Vagenas (2015) reported that the between-subject variability of asymmetry index was from 0% to 31.6% among the male recreational runners. Such considerable between-subject variations might result from different competitive levels or running experience because movement patterns became more consistent and stable with practice (Fujii, Kudo, Ohtsuki, & Oda, 2009), and the well-trained runners exhibited lower running variability than non-runners (Nakayama, Kudo, & Ohtsuki, 2010). However, previous studies mainly focused to compare the bilateral asymmetry between injured and uninjured runner within specific runner groups, such as elite competitive runners (Gilgen-Ammann et al., 2017), recreational runners (Zifchock et al., 2006), or novice runners (Bredeweg et al., 2013).

Only one previous study by Cavanagh et al. (1977) investigated the bilateral asymmetry of both competitive (mean 3-mile time for 5 runners: 15:16.7; mean marathon time for 3 runners: 2:34:40) and elite runners (mean 3-mile time for 5 runners: 13:10.2; mean marathon time for 9 runners: 2:15:52). They found that the elite runners exhibited a significantly more bilaterally symmetrical running gait pattern, which might contribute to lower metabolic and mechanical costs (Beck, Azua, & Grabowski, 2018; Ellis, Howard, & Kram, 2013). However, Cavanagh et al. only recruited runners in competitive level. Therefore, the effect of runners' competitive level or running experience on bilateral asymmetry during running remains largely unknown.

Lower limbs act as paired oscillators during running. Theoretically, running gait would become more symmetrical with speed increasing because perfect phasing of gait could be more achievable at a faster speed. However, findings from previous studies were contradictory. Karamanidis et al. (2003) found that bilateral asymmetry did not change across speeds or stride frequencies; Bredeweg et al. (2013) reported that the male recreational runners demonstrated no differences in bilateral asymmetry during running at 9 km/h and 10 km/h, whereas the female recreational runners presented significantly smaller symmetry angle at 9 km/h compared to 8 km/h; Furlong and Egginton (2018) reported lower bilateral asymmetry at preferred running speed than non-preferred running speeds (± 10% from preferred running speed). Limited test speeds were adopted in the aforementioned studies (Bredeweg et al., 2013; Furlong & Egginton, 2018; Karamanidis et al., 2003). Thus, the effect of running speed on bilateral asymmetry is still not well understood and it remains inconclusive how bilateral asymmetry changes across running speed.

Giakas and Baltzopoulos (1997) claimed that the intra-limb variability must be less than the inter-limb difference, or bilateral asymmetry should be considered non-significant. Exell, Irwin, Gittoes, and Kerwin (2012) found that the athletes are highly individual in their bilateral asymmetries during sprint running and when incorporating intra-limb variability, some athletes displayed large asymmetry values in averaged right and left values which were not significant due to larger relative variability within each side.

The primary objective of this study was to compare bilateral asymmetry incorporating intra-limb variability in runners with different competitive levels or running experience. We also investigated the effect of running speed on bilateral asymmetry and explored the relationship between the two factors. It was hypothesized that runners with higher competitive level or more running experience would display less bilateral asymmetry. We also hypothesized that there would be a nonlinear relationship between bilateral asymmetry and running speed.

2. Methods

2.1. Participants

Participants were recruited from local running clubs. Respondents were screened to include those who aged between 18 and 40 years, had some treadmill running experience, and did not have any known running-related injuries during the past six months. Respondents were excluded if they had leg length discrepancy of more than 3 cm (Resende, Kirkwood, Deluzio, Cabral, & Fonseca, 2016), or had any known diseases that would prevent their participation in strenuous physical activities. Eventually, this study recruited 31 participants (13 females and 18 males). The experimental procedures were reviewed and approved by the institutional review board. All participants provided written informed consent before data collection.

The participants were categorized into either competitive, recreational or novice runners according to their age, gender, race performance (i.e., 10 km, half-marathon, or marathon) and years of running practice. Their running performance was quantified using an age-graded score, which was computed using an online calculator (www.howardgrubb.co.uk/athletics/wmalookup06.html), and based on the World Masters Association Age Grading Performance Tables, runners who achieved an age-graded score of greater than 60% were classified as competitive runners (Clermont, Benson, Osis, Kobsar, & Ferber, 2019); runners with age-graded score of less than 60% were categorized as recreational runners (Clermont et al., 2019); and runners who had either never participated in any running race or performed regular running practice (i.e., at least 3 times per week, 30 minutes per time, and minimum weekly running mileage of 20 km) for less than 24 months at the time of participation were defined as novice runners (Baltich, Emery, Whittaker, & Nigg, 2017). Consequently, 11 competitive runners (4 females and 7 males), 9 recreational runners (4 females and 5 males), and 11 novice runners (5 females and 6 males) completed this study.

2.2. Experimental procedures

All participants were instructed to run on an instrumented treadmill (Advance Mechanical Technology Inc., MA, USA) at five fixed speeds (8, 9, 10, 11 and 12 km/h) in a random order. The slope of the treadmill was set at 0°. Before testing, they had 10 minute for warm-up and familiarizing themselves with experimental settings. During running, they were required to run for 3 minutes at each fixed speed and kinetic data of the last 30 seconds for each running speed were recorded at 1,000 Hz. All participants wore their own running shoes and were allowed to rest for 5 minutes between each run.

2.3. Data processing

The kinetic data were processed using MATLAB R2018a (MathWorks Inc., Natick, MA). Data were firstly low-pass filtered using a fourth-order Butterworth filter at 50 Hz (Zifchock et al., 2006). The initial contact and toe-off were then detected from the vertical ground reaction force (GRF) with a threshold of 60 N (Riley, Dicharry, Franz, Della Croce, Wilder, & Kerrigan, 2008). The kinetic data were segmented for each running speed condition; the middle 30 right and 30 left footfalls were analyzed.

Temporal parameters (i.e., stride, step, stance and flight times and duty factor) were calculated based on the identified initial contacts and toe-offs. Duty factor was defined as the percentage of stance time relative to stride time (Bonnaerens et al., 2019). Kinetic parameters including peak vertical GRF, peak braking and propulsion forces, time to the peaks, vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR) were calculated from the vertical and anteroposterior GRFs. Both VALR and VILR were calculated between 20% and 80% of the period between the initial contact and the vertical impact peak (Blackmore, Willy, & Creaby, 2016). VALR and VILR were the average slope and the steepest slope of the vertical GRF within that period, respectively. When the vertical impact peak was undiscernible, VALR and VILR were calculated using a period between the initial contact and the time point of 13% stance (Blackmore et al., 2016).

SI was used to quantify the level of bilateral asymmetry in previous studies (Karamanidis et al., 2003; Zifchock et al., 2006). In the current study, SI was calculated for all the selected temporal and kinetic parameters using the following formula:

$$SI = \frac{|X_{right} - X_{left}|}{0.5 \times (X_{right} + X_{left})} \times 100$$

where SI was presented in percentage, X_{right} was the value of the right leg, and X_{left} was the value of the left leg. An SI value of zero indicated perfect symmetry between right and left legs, and a higher value indicated a higher level of bilateral asymmetry.

2.5. Statistical analysis

One-way analysis of variance (ANOVA) and independent samples *t* tests were performed to compare demographics between competitive, recreational and novice runners. Repeated measures ANOVA were performed to determine the effects of competitive level or running experience and running speed on bilateral asymmetry during running. If indicated, the least significant difference post-hoc pairwise comparisons were performed. A *p* value less than 0.05 was considered to be statistically significant. All statistical analysis were performed using SPSS version 25.0 (SPSS IBM Inc., Chicago, IL, USA).

To determine the magnitude of intra-limb variability relative to the that of bilateral asymmetry, paired t-tests were conducted to detect if there were any significant differences ($p < 0.05$) between right (X_{right}) and left (X_{left}) values for each parameter of interest. In order to highlight the magnitude of intra-limb variability relative to the magnitude of bilateral asymmetry, parameters that displayed a significant difference between right and left values were considered to be significantly asymmetrical, when the magnitude of the intra-limb variability was less than the magnitude of the between-limb difference (Exell et al., 2012).

To explore the relationship between bilateral asymmetry and running speed, different trend lines were used to fit the scatter plots of the mean SI for those parameters indicating significances for each group. An appropriate continuous regression model for the SI with respect to the speed was identified for each parameter and group. The expression of SI for each parameter as continuous functions of speed was calculated as below:

$\mathrm{SI}_{(i,j)} = \mathrm{f}_{(i,j)}(\mathrm{Speed})$ where i represents competitive, recreational or novice runners; j represents the parameter indicating statistical significances.

3. Results

Participant characteristics of each group were summarized in Table 1. No statistical differences were observed in age, height, mass, and body mass index among competitive, recreational and novice runners (*p*s > 0.05). Compared to the recreational runners (47.2% ± 15.7%), the age-graded score for the competitive runners (71.8% ± 6.4%) was significantly greater (*p* < 0.001), indicating higher competitive level. Regarding to running practice, the competitive runners also had a significantly greater weekly running mileage (*p* = 0.022).

Right and left values of all selected parameters were presented for each testing speed and group in the Supplementary Table A. SI values of all the parameters for each group and speed condition and those parameters that exhibited significant bilateral asymmetry relative to intra-limb variability were presented in the Supplementary Table B. Overall, SI ranged between 0.8% ± 0.2% and 21.4% ± 9.4%, regardless of runners' competitive level, running speed and parameters of interest. The temporal parameters (e.g., stride time, step time, stance time and duty factor) presented relatively low level of bilateral asymmetry with SI of less than 3.1% but SI for flight time was 5.0% ± 4.1%. With regard to running kinetics, SI was 3.4% ± 1.5% for peak vertical GRF, 7.1% ± 3.2% for time to peak vertical GRF; the level of bilateral asymmetry was relatively higher for the anteroposterior GRF variables with SI of 12.7% ± 4.3% for peak braking force and 13.6% ± 4.9% for peak propulsion force; overall, VALR and VILR exhibited the highest level of bilateral asymmetry and SI was 17.3% ± 7.7% and 14.7% ± 7.9%, respectively.

For the competitive runners, peak propulsion force at 9 km/h (X_{right} = 0.16 ± 0.07 s; X_{left} = 0.15 ± 0.07 s; *p* = 0.040) and time to peak propulsion force at 10 km/h (X_{right} = 0.173 ± 0.013 s; X_{left} = 0.171 ± 0.015 s; *p* = 0.016) demonstrated significant bilateral asymmetry with SI of 12.1% ± 4.0% and 3.0% ± 1.2%, respectively. Regardless of running speed, they also exhibited significant bilateral asymmetry for stride time (X_{right} = 0.687 ± 0.04 s; X_{left} = 0.690 ± 0.04 s; *p* = 0.038; SI = 0.8% ± 0.2%), flight time (X_{right} = 0.120 ± 0.02 s; X_{left} = 0.122 ± 0.02 s; *p* = 0.002; SI = 3.4% ± 2.4%), duty factor (X_{right} = 32.6% ± 2.4%; X_{left} = 32.3% ± 2.5%; *p* = 0.009; SI = 3.0% ± 1.4%), peak vertical GRF (X_{right}= 2.68 ± 0.44 BW/s; X_{left} = 2.71 ± 0.42 BW/s; *p* = 0.029; SI = 3.3% ± 1.6%) and time to peak propulsion force (X_{right} = 0.174 ± 0.017 s; X_{left} = 0.171 ± 0.018 s; *p* = 0.018; SI = 3.6% ± 1.9%).

For recreational runners, significant bilateral asymmetry was reported for step (10 km/h: X_{right} = 0.335 ± 0.026 s; X_{left} = 0.329 ± 0.025 s; p = 0.028; 11 km/h: X_{right} = 0.325 ± 0.026 s; X_{left} = 0.320 ± 0.027 s; p = 0.031) and flight times at 10 and 11 km/h (10 km/h: X_{right} = 0.104 ± 0.015 s; X_{left} = 0.099 ± 0.016 s; p = 0.036; 11 km/h: X_{right} = 0.107 ± 0.014 s; X_{left} = 0.102 ± 0.012 s; p = 0.011) and peak propulsion force at 9 km/h (X_{right} = 0.18 ± 0.06 s; X_{left} = 0.17 ± 0.06 s; p = 0.013), and VALR at 10 km/h exhibited a marginal significance level (X_{right} = 47.9 ± 12.3 BW/s; X_{left} = 51.0 ± 14.3 BW/s; p = 0.051). The corresponding SIs varied between 2.5% ± 1.1% for step time and 15.0% ± 4.4% for VALR. They presented significant (or marginal significant) bilateral asymmetry for step time ($p < 0.001$; SI = 3.0% ± 1.5%), flight time ($p < 0.001$; SI = 6.1% ± 4.3%), peak vertical GRF (p = 0.014; SI = 3.9% ± 1.5%), VALR (p = 0.002; SI = 17.1% ± 7.8%) and VILR (p = 0.001; SI = 13.5% ± 7.8%) regardless of running speed.

Novice runners showed significant (or marginal significant) bilateral asymmetry for time to peak vertical GRF at 9 km/h (X_{right} = 0.108 ± 0.014 s; X_{left} = 0.106 ± 0.011 s; p = 0.016; SI = 6.9% ± 2.9%), VALR at 10 km/h (X_{right} = 62.5 ± 15.9 BW/s; X_{left} = 57.4 ± 12.7 BW/s; p = 0.047; SI = 17.1% ± 9.5%) and VILR at 8 km/h (X_{right} = 57.2 ± 19.9 BW/s; X_{left} = 53.9 ± 17.8 BW/s; p = 0.036; SI = 13.7% ± 3.2%) at 10 km/h (X_{right} = 76.0 ± 20.6 BW/s; X_{left} = 73.1 ± 16.6 BW/s; p = 0.051, SI = 15.0% ± 5.5%). Significant (or marginal significant) bilateral asymmetry, regardless of running speed, was detected for stance time (p = 0.057; SI = 3.2% ± 1.4%), time to peak vertical GRF (p = 0.004; SI = 6.8% ± 3.3%) and VILR (p = 0.002; SI = 14.5% ± 5.9%).

Effects of running experiences and speed on SI were observed for flight time, time to peak vertical GRF and VALR (Figure 1). Scatter plots of mean SI and estimated trend lines across speeds for each group are presented in Figure 2. Significant speed effects were observed on SI of flight time (p = 0.012, observed power = 0.80). Post-hoc pairwise comparisons revealed significantly higher SI of flight time at 8 km/h (6.8% ± 4.8%) than the other 4 speeds (SI = 4.8% ± 3.3%, 4.2% ± 3.4%, 4.5% ± 3.9% and 4.6% ± 4.4%, respectively; p = 0.023, 0.005, 0.023 and 0.028, respectively) and no statistical differences between the other 4 speeds. SI of flight time changed linearly across speeds and reduced with increase of speed for the competitive runners (R^2 = 0.949, Figure 2a), whereas it changed nonlinearly across speeds and displayed roughly U-shaped trends for both the recreational (R^2 = 0.947) and novice runners (R^2 = 0.644).

Group-by-speed interactions were detected for SI of time to peak vertical GRF (p = 0.032, observed power = 0.84, Figure 2b) and VALR (p = 0.002, observed power = 0.96, Figure 2c). For the competitive runners, SI changed across speeds in a linear trend (R^2 = 0.947 for time to peak vertical GRF and 0.940 for VALR). For the recreational runners, it changed across speeds in a roughly U-shaped trend for both time to peak vertical GRF (R^2 = 0.993) and VALR (R^2 = 0.883). While speed increased, the SIs decreased in the beginning until reaching their respective local critical speeds, then reversed towards increase with further increase in speed. For the novice runners, SI of time to peak vertical GRF linearly increased with speeds (R^2 = 0.780), whereas SI of VALR appeared to be unchanged across speeds (R^2 = 0.933).

4. Discussion

The purpose of this cross-sectional study was to investigate effects of runners' competitive level or running experience and speed on bilateral asymmetry during running. We found significant group-by-speed interactions on SI of time to peak vertical GRF and VALR, and speed effects on SI of flight time. Bilateral asymmetry changed across speed differently among competitive, recreational and novice runners, which is partially consistent to our hypotheses.

In this study, significant differences between right and left sides were observed for most of the parameters of interest. However, we did not observe that a particular side consistently scored higher in spite of the fact that limb preference was frequently reported among different physical activities (Serrien, Ivry, & Swinnen, 2006). This may be because we simply compared right and left legs rather than based on limb preference (e.g., dominant vs. non-dominant legs). Accordingly, only 25-45% of individuals were found to be right leg preference in lower limb actions (Cuk, Leben-Seljak, & Stefancic, 2001). The participants with right leg preference and the participants with left leg preference may be group together, thereby would minimize or eliminate the difference due to limb preference.

SI values of the present study varied greatly from 0.8% (stride time) to 21.4% (VALR), but they were still within the range of 54.7% reported by Karamanidis et al. (2003). Karamanidis et al. (2003) found that the kinematics asymmetry varied from 3.0% for knee angle at initial contact to 54.7% for hip joint velocity; Williams et al. (1987) reported that SI ranged between 3.9% for peak vertical GRF and 28.3% for peak change in lateral velocity; Zifchock et al. (2006) detected a bilateral asymmetry level between 3.1% for peak vertical GRF and 49.8% for peak lateral GRF. Moreover, for some parameters of interest, including peak vertical GRF (3.4% ± 1.5%), VALR (17.3% ± 7.7%) and VILR (14.7% ± 7.9%), the asymmetrical levels detected in the present study were similar to those reported in a previous study (Zifchock et al., 2006).

The magnitude of bilateral asymmetry was found to be varied across the parameter of interest regardless of runners' competitive level or running experience and running speed. Overall, the asymmetrical level was lower (SI < 5.0%) in temporal variables (e.g., stride, step, stance and flight time and duty factor) and vertical GRF. This may be because these parameters are gross outcome measures, which usually exhibit minor differences between legs (Bredeweg et al., 2013; Zifchock et al., 2006). Furlong and Egginton (2018) also demonstrated a lower bilateral asymmetry for the gross outcome measures (e.g., stance time < 5% and vertical GRF < 3%) when compared to that of the kinetic outcome measures (e.g., peak hip moment > 15%). Similar to that of our results, the peak vertical GRF exhibited lower bilateral asymmetry compared with the anteroposterior GRF (e.g., peak braking and propulsion forces), VALR and VILR (SI > 12.5%), Zifchock et al. (2006) detected a higher bilateral asymmetry for peak mediolateral GRFs (e.g., lateral = 49.8% and medial = 37.5%) when compared with peak vertical GRF (3.1%). The temporal parameters and vertical GRF parameters tend to be more symmetrical than other biomechanical parameters such as vertical loading rates.

SI for the identified parameters with significant bilateral asymmetry ranged between 0.8% ± 0.2% (stride time) and 3.6% ± 1.9% (time to peak propulsion force) for competitive runners, between 3.0% ± 1.5% (step time) and 17.1% ± 7.8% (VALR) for recreational runners, and between 3.2% ± 1.4% (stance time) and 14.5% ± 5.9% (VILR) for novice runners. Comparing bilateral asymmetry of the three groups, it revealed that competitive runners exhibited a lower asymmetry level than the other two groups. This was consistently to the finding in the study by Cavanagh et al. (1977) who reported that bilateral asymmetry was lower for elite runners than competitive runners who had lower competitive level. In addition, Clark (2009) found that the athletes showed significantly lower inter-limb joint stiffness regulation than non-athletes during sprint running. Boyer, Silvernail, and Hamill (2014) stated that kinematic waveforms of low-limb joints and segments were different between runners with different running volumes. The lower asymmetrical level of the competitive runners observed in the present study may be contributed by their relatively more years of running experience and weekly running mileage, which would reduce inter-limb differences. Additionally, Carpes, Bini, and Mota (2008) found that well-trained subjects revealed a lower level of bilateral asymmetry during multi-joint leg-press exercise and better perception of bilateral asymmetry compared to their counterparts who just started a training regimen. Therefore, the improved perception of bilateral asymmetry due to long-term running practice may also contribute to the current finding. Finally, although bilateral asymmetry was found to be associated to running experience, running practice was not the only method of improving running symmetry. For example, Cavagna (2006) stated that take-off symmetry could be improved by an increase of the running speed.

For the recreational runners, SI changed across speed nonlinearly and presented a roughly U-shaped trend. A recent study (Furlong & Egginton, 2018) also demonstrated nonlinear changes of bilateral asymmetry across speed among RRs and reported a minimum bilateral asymmetry at preferred running speed compared to non-preferred running speeds (± 10% from preferred running speed). However, only 3 speeds were investigated in that study. Similar U-shape trend across speed was previously highlighted on other gait parameters, such as stride interval variability (Jordan, Challis, & Newell, 2006), and metabolic costs (Hamill, Derrick, & Holt, 1995). For example, Jordan et al. (2006) found that the stride interval variability reached minimum at preferred running speed and increased when either running slower or faster; the oxygen consumption was found to be the minimum at preferred stride frequency and increased with both increase and decrease of stride frequency (Hamill et al., 1995). Based on these findings and the minimum principles in motor control (Engelbrecht, 2001), the recreation runners may display the minimum bilateral asymmetry during running at a certain critical speed. In the present study, the averaged race speed calculated based on the runners' self-reported best race time (10 km: n=1; half-marathon: n=1; full marathon: n=7) was 10.0 ± 1.4 km/h (95% confidence interval: 9.1-11.0 km/h), which was close to previously reported preferred running speed (10.1-11.3 km/h) for the recreational runners (Beck et al., 2018; Furlong & Egginton, 2018). We therefore speculated that the critical speed, which was 10 km/h (Figure 2), may be close to the preferred running speed of the recreation runners in the current study. Since fixed rather than relative speeds (i.e., preferred and non-preferred running speeds) were employed in this study, further evidences are required to support this speculation.

In addition, asymmetric gait increased metabolic and mechanical costs (Beck et al., 2018; Ellis et al., 2013), which suggests that the recreational runners could optimize speed and determine a critical speed (e.g., preferred running speed) for lowering bilateral asymmetry and improve running economy. However, the relationship between SI and running speed for the novice runners appeared to change across parameters of interest. Such inconsistency was also reported in previous study, e.g., symmetry angle was not different in bilateral asymmetry of male novice runners running at 9 and 10 km/h, while significantly smaller of female novice runners running at 9 km/h compared to 8 km/h (Bredeweg et al., 2013). It seems that the novice runners are incapable to do such optimization during running because they had short duration to learn or strengthen their running movements due to lack of running experience. A longitudinal study will be required to verify this assumption.

For competitive runners, SI decreased linearly with increasing speed, which indicates a more symmetrical gait at faster speed. This could be explained from a theoretical aspect that the lower limbs act as pair oscillators, phase would be closer to a perfect in-phase or out-phase at fast speed, which therefore induce a more symmetrical running gait. However, to ensure all runners could finish the test, the fastest speed in this study was only set at 12 km/h regardless of their competitive levels or running experience. Testing speed for runners of competitive level could reach 20 km/h (Munro et al., 1987), whereas the fastest speed in the current study was only set at 12 km/h. Similarly, we calculated the race speed of each runner based on their self-reported best race time (half-marathon: n=1; full marathon: n=10). The average race speed was 14.1 ± 1.8 km/h (95% confidence interval: 13.1-15.2 km/h), which was faster than the maximum testing speed (12 km/h) in the present study as well as previously reported preferred running speed (approximately 11.3 km/h) for competitive runners (Beck et al., 2018). Considering that the race speed is usually a little bit faster than that during their daily regular practice, 12 km/h may closely approach the preferred speed of the competitive runners recruited for this study. So, it is unknown whether SI would increase further with a greater running speed for the competitive runners. To explicitly gain insights into the speed effect on bilateral asymmetry, faster speed with wider range, e.g., ± 10% and ± 20% from preferred running speed could be investigated in future studies. This is one of limitations of this study, which should be addressed in the future.

4.1. Limitations of the present study

One of the strengths of this study is to compare bilateral asymmetry of runners with different competitive level or running experience across a wide range of running speed. This provided an explicit understanding of underlying causes of bilateral asymmetry during running in healthy runners. Nonetheless, four limitations should be highlighted. Firstly, fixed speeds from 8 to 12 km/h were employed for all participants regardless of their competitive levels or running experience. Although running at the same speed, their physiological intensity levels may be quite different. Speed of 12 km/h may be fast enough for the novice runners but not for the competitive runners because testing speed previously reached up to 20.3 km/h for the competitive runners (Cavagna, 2006). Relative rather than fixed testing speeds are suggested in the future, e.g., speed range could be individually determined based on preferred speed (± 10% and 20% from preferred running speed). Additionally, all running trials were performed on an instrumented treadmill for obtaining continuous kinetic data.

Although running kinetics were similar between treadmill and overground running (Riley et al., 2008), bilateral asymmetries were reported to be different between the two conditions (Robadey et al., 2018). The current results may therefore not be generalizable to overground running. In this study, all participants wore their own running shoes, which may present different features. Future study could eliminate this effect. Finally, inter-limb differences may refer to three aspects: right vs. left, dominant vs. non-dominant, and stronger vs. weaker. Because leg preference has not been tested, this study only focused on right-left differences.

5. Conclusions

In summary, this study demonstrated that bilateral asymmetry was simultaneously affected by running speed and runners' competitive level or running experience. For the competitive runners, bilateral asymmetry appeared to decrease linearly with speed increasing from 8 to 12 km/h. For the novice runners, changes of bilateral asymmetry across speed were inconsistent and dependent on the parameter of interest. For recreational runners, it changed nonlinearly across different running speeds in a roughly U-shaped trend, and a critical running speed with the lowest bilateral asymmetry was demonstrated and this suggested an improved running economy.

Conflict of interest

None.

Acknowledgements

None.

References

Baltich, J., Emery, C. A., Whittaker, J. L., & Nigg, B. M. (2017). Running injuries in novice runners enrolled in different training interventions: a pilot randomized controlled trial. *Scandinavian Journal of Medicine and Science in Sports, 27*(11), 1372-1383. https://doi.org/10.1111/sms.12743

Beck, O. N., Azua, E. N., & Grabowski, A. M. (2018). Step time asymmetry increases metabolic energy expenditure during running. *European Journal Applied Physiology, 118*(10), 2147-2154. https://doi.org/10.1007/s00421-018-3939-3

Blackmore, T., Willy, R. W., & Creaby, M. W. (2016). The high frequency component of the vertical ground reaction force is a valid surrogate measure of the impact peak. *Journal of Biomechanics, 49*(3), 479-483. https://doi.org/10.1016/j.jbiomech.2015.12.019

Bonnaerens, S., Fiers, P., Galle, S., Aerts, P., Frederick, E. C., Kaneko, Y., Derave, W., & De Clercq, D. (2019). Grounded running reduces musculoskeletal loading. *Medicine and Science in Sports and Exercise, 51*(4), 708-715. https://doi.org/10.1249/MSS.0000000000001846

Boyer, K. A., Silvernail, J. F., & Hamill, J. (2014). The role of running mileage on coordination patterns in running. *Journal of Applied Biomechanics, 30*(5), 649-654. https://doi.org/10.1123/jab.2013-0261

Bredeweg, S. W., Buist, I., Kluitenberg, B. (2013). Differences in kinetic asymmetry between injured and noninjured novice runners: a prospective cohort study. *Gait & Posture, 38*(4), 847-852. https://doi.org/10.1016/j.gaitpost.2013.04.014

Brughelli, M., Cronin, J., Mendiguchia, J., Kinsella, D., & Nosaka, K. (2010). Contralateral leg deficits in kinetic and kinematic variables during running in Australian rules football players with previous hamstring injuries. *The Journal of Strength and Conditioning Research, 24*(9), 2539-2544. https://doi.org/10.1519/JSC.0b013e3181b603ef

Carpes, F. P., Bini, R. R., & Mota, C. B. (2008). Training level, perception and bilateral asymmetry during multijoint leg-press exercise. *Brazilian Journal of Biomotricity, 2*(2), 51-62.

Cavagna, G. A. (2006). The landing-take-off asymmetry in human running. *Journal of Experimental Biology, 209*(Pt 20), 4051-4060. https://doi.org/10.1242/jeb.02344

Cavanagh, P. R., Pollock, M. L., & Landa, J. (1977). A biomechanical comparison of elite and good distance runners. *Annals of the New York Academy of Sciences, 301*(1), 328-345. https://doi.org/10.1111/j.1749-6632.1977.tb38211.x

Clark, R. A. (2009). The effect of training status on inter-limb joint stiffness regulation during repeated maximal sprints. *Journal of Science and Medicine in Sport, 12*(3), 406-410. https://doi.org/10.1016/j.jsams.2007.12.003

Clermont, C. A., Benson, L. C., Osis, S. T., Kobsar, D., & Ferber, R. (2019). Running patterns for male and female competitive and recreational runners based on accelerometer data. *Journal of Sports Sciences, 37*(2), 204-211. https://doi.org/10.1080/02640414.2018.1488518

Cuk, T., Leben-Seljak, P., & Stefancic, M. (2001). Lateral asymmetry of human long bones. *Variability and Evolution, 9*, 19-23.

Ellis, R. G., Howard, K. C., & Kram, R. (2013). The metabolic and mechanical costs of step time asymmetry in walking. *Proceedings of the Royal Society B: Biological Sciences, 280*(1756), 20122784. https://doi.org/10.1098/rspb.2012.2784

Engelbrecht, S. E. (2001). Minimum principles in motor control. *Journal of Mathematical Psychology, 45*(3), 497-542. https://doi.org/10.1006/jmps.2000.1295

Exell, T. A., Irwin, G., Gittoes, M. J. & Kerwin, D. G. (2012). Implications of intra-limb variability on asymmetry analyses. *Journal of Sports Sciences, 20*(4), 403-409. https://doi.org/10.1080/02640414.2011.647047

Fujii, S., Kudo, K., Ohtsuki, T, & Oda, S. (2009). Tapping performance and underlying wrist muscle activity of non-drummer, drummers, and the world's fastest drummer. *Neuroscience Letters, 459*(2), 69-73. https://doi.org/10.1016/j.neulet.2009.04.055

Furlong, L. M., & Egginton, N. L. (2018). Kinetic asymmetry during running at preferred and nonpreferred speeds. *Medicine and Science in Sports and Exercise, 50*(6), 1241-1248. https://doi.org/10.1249/MSS.0000000000001560

Giakas, G., & Baltzopoulos, V. (1997). Time and frequency domain analysis of ground reaction forces during walking: an investigation of variability and symmetry. *Gait & Posture, 5*(3), 189-197. https://doi.org/10.1016/S0966-6362(96)01083-1

Gilgen-Ammann, R., Taube, W., & Wyss, T. (2017). Gait asymmetry during 400- to 1000-m high-intensity track running in relation to injury history. *International Journal of Sports Physiology and Performance, 12*(Suppl. 2), S2157-S2160. https://doi.org/10.1123/ijspp.2016-0379

Hamill, J., Derrick, T. R., & Holt, K. G. (1995). Shock attenuation and stride frequency during running. *Human Movement Science, 14*(1), 45-60. https://doi.org/10.1016/0167-9457(95)00004-C

Hanley, B., & Tucker, C. B. (2018). Gait variability and symmetry remain consistent during high-intensity 10,000 m treadmill running. *Journal of Biomechanics, 79*, 129-134. https://doi.org/10.1016/j.jbiomech.2018.08.008

Haugen, T., Danielsen, J., McGhie, D., Sandbakk, Ø., & Ettema, G. (2018). Kinematic stride cycle asymmetry is not associated with sprint performance and injury prevalence in athletic sprinters. *Scandinavian Journal of Medicine and Science in Sports, 28*(3), 1001-1008. https://doi.org/10.1111/sms.12953

Jordan, K., Challis, J. H., & Newell, K. M. (2006). Long range correlations in the stride interval of running. *Gait & Posture, 24*(1), 120-125. https://doi.org/10.1016/j.gaitpost.2005.08.003

Karamanidis, K., Arampatzis, A., & Brüggemann, G. P. (2003). Symmetry and reproducibility of kinematic parameters during various running techniques. *Medicine and Science in Sports and Exercise, 35*(6), 1009-1016. https://doi.org/10.1249/01.MSS.0000069337.49567.F0

Munro, C. F., Miller, D. I., & Fuglevand, A. J. (1987). Ground reaction forces in running: a reexamination. *Journal of Biomechanics, 20*(2), 147-155. https://doi.org/10.1016/0021-9290(87)90306-x

Nakayama, Y., Kudo, K., & Ohtsuki, T. (2010). Variability and fluctuation in running gait cycle of trained runners and non-runners. *Gait & Posture, 31*(3), 331-335. https://doi.org/10.1016/j.gaitpost.2009.12.003

Pappas, P., Paradisis, G., & Vagenas, G. (2015). Leg and vertical stiffness (a)symmetry between dominant and non-dominant legs in young male runners. *Human Movement Science, 40*, 273-283. https://doi.org/10.1016/j.humov.2015.01.005

Resende, R. A., Kirkwood, R. N., Deluzio, K. J., Cabral, S., & Fonseca, S. T. (2016). Biomechanical strategies implemented to compensate for mild leg length discrepancy during gait. *Gait & Posture, 46*, 147-153. https://doi.org/10.1016/j.gaitpost.2016.03.012

Riley, P. O., Dicharry, J., Franz, J., Della Croce, U., Wilder, R. P., & Kerrigan, D. C. (2008). A kinematics and kinetic comparison of overground and treadmill running. *Medicine and Science in Sports and Exercise, 40*(6), 1093-1100. https://doi.org/10.1249/MSS.0b013e3181677530

Robadey, J., Staudenmann, D., Schween, R., Gehring, D., Gollhofer, A., & Taube, W. (2018). Lower between-limb asymmetry during running on treadmill compared to overground in subjects with laterally pronounced knee osteoarthritis. *PLoS One, 13*(10), e0205191. https://doi.org/10.1371/journal.pone.0205191

Serrien, D. J., Ivry, R. B., & Swinnen, S. P. (2006). Dynamics of hemispheric specialization and integration in the context of motor control. *Nature Reviews Neuroscience, 7*(2), 160-166. https://doi.org/10.1038/nrn1849

Williams, K. R., Cavanagh, P. R., & Ziff, J. L. (1987). Biomechanical studies of elite female distance runners. *International Journal of Sports Medicine, 8*(Suppl. 2), 107-118.

Zifchock, R. A., Davis, I., & Hamill, J. (2006). Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. *Journal of Biomechanics, 39*(15), 2792-2797. https://doi.org/10.1016/j.jbiomech.2005.10.003

Zifchock, R. A., Davis, I., Higginson, J., McCaw, S., & Royer, T. (2008). Side-to-side differences in overuse running injury susceptibility: a retrospective study. *Human Movement Science, 27*(6), 888-902. https://doi.org/10.1016/j.humov.2008.03.007

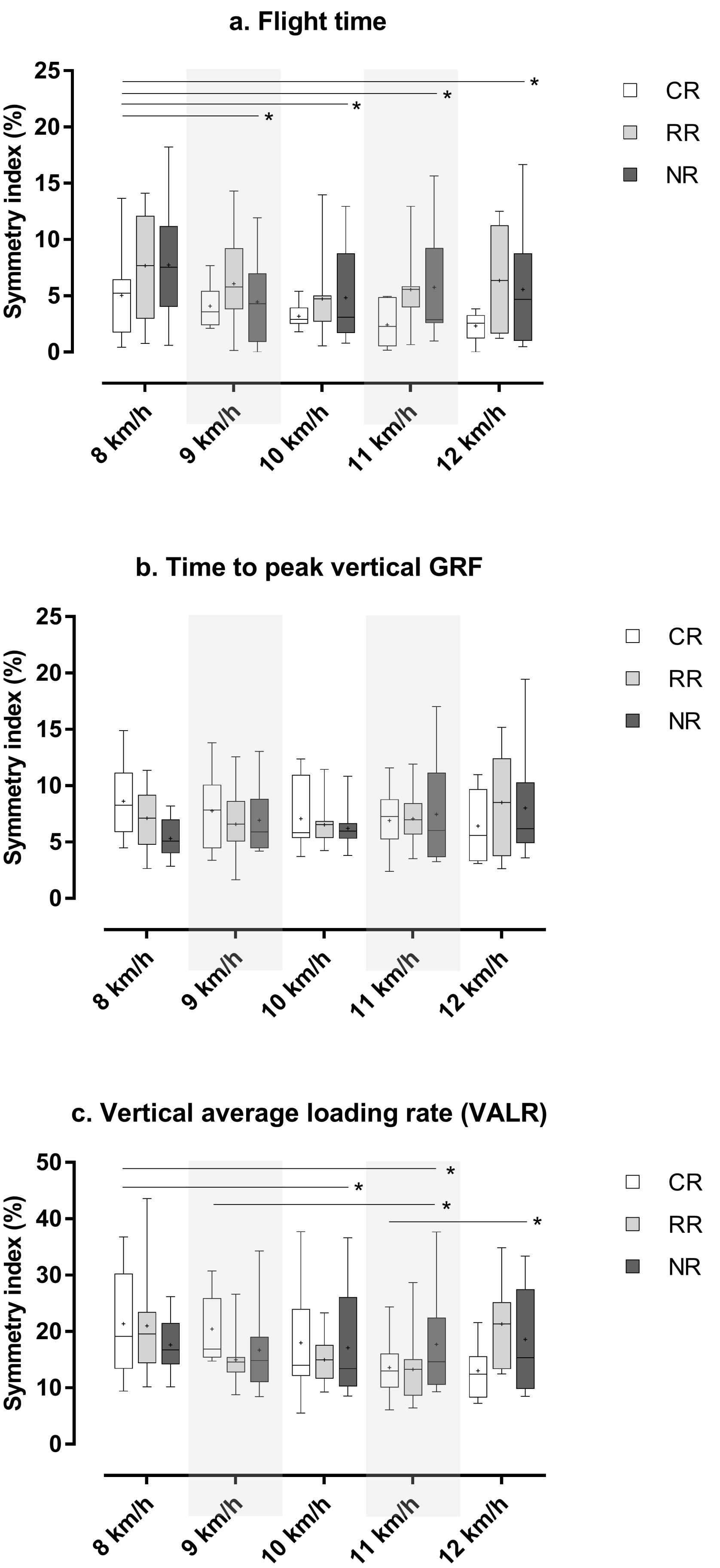
Figure legends

Figure 1.

Symmetry index of flight time (a), time to peak vertical ground reaction force (b), and vertical average loading rate (c) for competitive runners (CR), recreational runners (RR), and novice runners (NR) at each speed condition (8, 9, 10, 11, and 12 km/h). +, mean value of symmetry index for each group at each speed condition; *, significant speed effects ($p < 0.05$).

Figure 2.

Estimated R^2 and equations of using running speed to predict symmetry index (SI) of (a) flight time, (b) time to peak vertical ground reaction force (GRF), and (c) vertical average loading rate (VALR) for competitive runners (CR), recreational runners (RR), and novice runners (NR).


a. Flight time
Symmetry index (%)
0
5
10
15
20
25
*
*
*
*
CR
RR
NR
8 km/h
9 km/h
10 km/h
11 km/h
12 km/h
b. Time to peak vertical GRF
Symmetry index (%)
0
5
10
15
20
25
CR
RR
NR
8 km/h
9 km/h
10 km/h
11 km/h
12 km/h
c. Vertical average loading rate (VALR)
Symmetry index (%)
0
10
20
30
40
50
*
*
*
*
CR
RR
NR
8 km/h
9 km/h
10 km/h
11 km/h
12 km/h

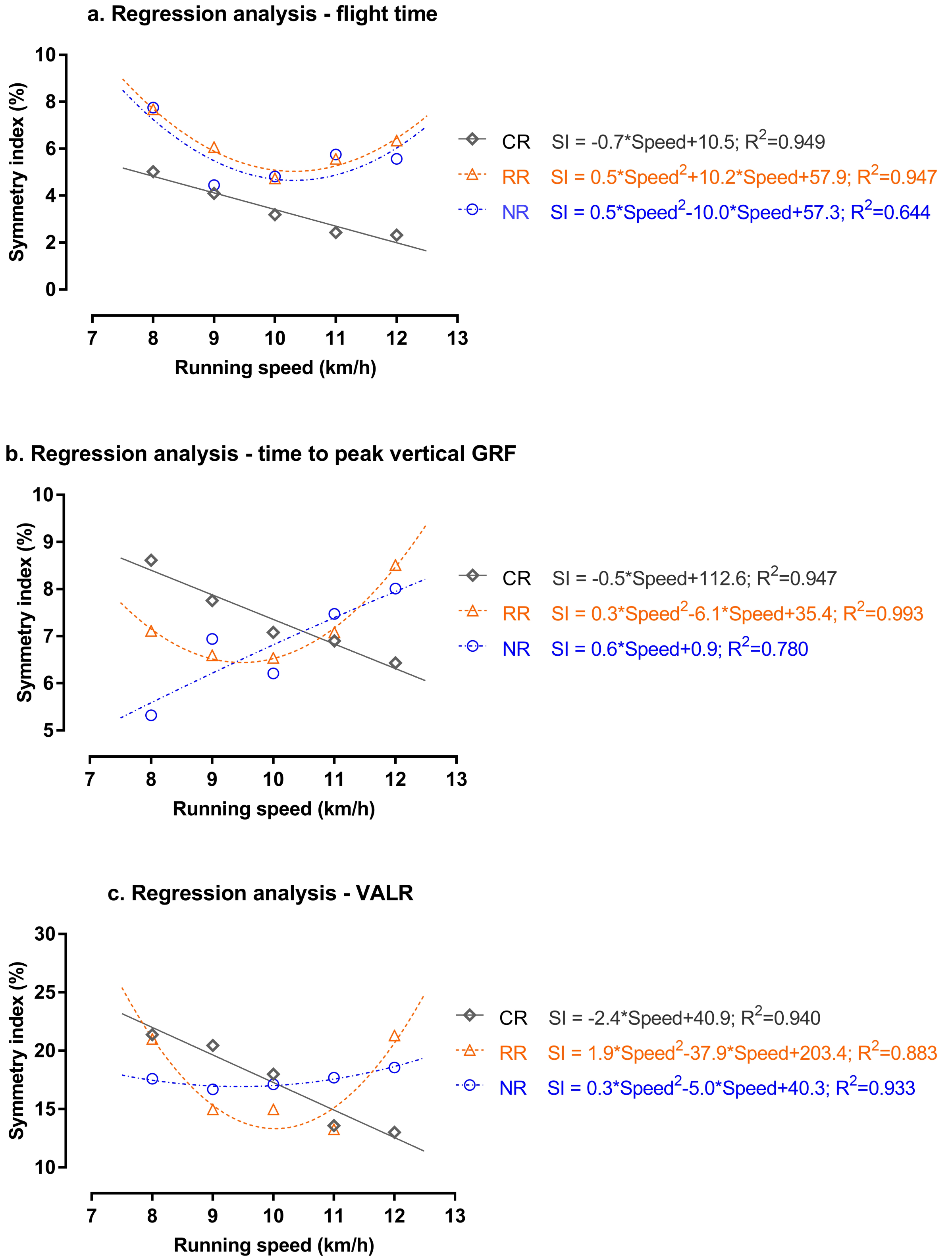

a. Regression analysis - flight time
Symmetry index (%)
Running speed (km/h)
CR SI = -0.7*Speed+10.5; R^2=0.949
RR SI = 0.5*Speed^2+10.2*Speed+57.9; R^2=0.947
NR SI = 0.5*Speed^2-10.0*Speed+57.3; R^2=0.644
b. Regression analysis - time to peak vertical GRF
Symmetry index (%)
Running speed (km/h)
CR SI = -0.5*Speed+112.6; R^2=0.947
RR SI = 0.3*Speed^2-6.1*Speed+35.4; R^2=0.993
NR SI = 0.6*Speed+0.9; R^2=0.780
c. Regression analysis - VALR
Symmetry index (%)
Running speed (km/h)
CR SI = -2.4*Speed+40.9; R^2=0.940
RR SI = 1.9*Speed^2-37.9*Speed+203.4; R^2=0.883
NR SI = 0.3*Speed^2-5.0*Speed+40.3; R^2=0.933

Table 1.

Participant characteristics. Results are presented in mean (standard deviation).

	Competitive runner	Recreational runner	Novice runner	Statistical results
Number of participants (Female/Male)	11 (4 / 7)	9 (4 / 5)	11 (5 / 6)	
Age (years)	31.7 (4.1)	35.2 (7.4)	29.1 (4.3)	F = 3.3; p = 0.052
Height (m)	1.69 (0.10)	1.72 (0.10)	1.67 (0.10)	F = 0.6; p = 0.564
Mass (kg)	58.3 (10.9)	63.8 (11.7)	62.8 (10.7)	F = 0.7; p = 0.500
Body mass index (kg/m^2)	20.2 (1.8)	21.4 (1.9)	22.5 (2.7)	F = 2.9; p = 0.072
Age-graded performance (%) ^	71.8 (6.4)	47.2 (15.7)	Not applicable	t = 6.8; ***p* < 0.001**
Running experience (year) ^	9.3 (3.9)	6.2 (2.9)	Not applicable	t = 2.0; p = 0.067
Weekly running mileage (km) ^	55.5 (25.8)	31.1 (14.5)	Not applicable	t = 2.5; ***p* = 0.022**
Self-reported race time (minute)				
10 km	(N=0)	55.9 (N=1)	63.0 (N=1)	
Half-marathon	83.0 (N=1)	122.0 (N=1)	(N=0)	
Marathon	183.1 (23.7) (N=10)	264.4 (42.1) (N=7)	(N=0)	

^, independent samples (competitive runner vs. recreational runner) t-test;
Bold, indicating significant differences (p < 0.05).

Table A — Mean (standard deviation) right and left value for all parameters of interest for competitive runners (CR), recreational runners (RR) and novice runners (NR) at each test speeds (8, 9, 10, 11, and 12 km/h), and results of paired t-tests.

		8 km/h		**p**	**9 km/h**		**p**	**10 km/h**		**p**	**11 km/h**		**p**	**12 km/h**		**p**	**Overall**		**p**
	Group	X_{Right}	X_{Left}		X_{Right}	X_{Left}		X_{Right}	X_{Left}		X_{Right}	X_{Left}		X_{Right}	X_{Left}		X_{Right}	X_{Left}	
Stride time (s)	**CR**	0.71 (0.04)	0.71 (0.04)	0.32	0.70 (0.04)	0.70 (0.04)	0.34	0.69 (0.04)	0.69 (0.03)	0.37	0.67 (0.04)	0.67 (0.04)	0.34	0.66 (0.04)	0.66 (0.04)	0.36	0.687 (0.04)	0.690 (0.04)	**0.038**
	RR	0.69 (0.05)	0.69 (0.05)	0.35	0.68 (0.05)	0.68 (0.05)	0.17	0.66 (0.05)	0.66 (0.05)	0.17	0.64 (0.05)	0.64 (0.05)	0.35	0.63 (0.06)	0.63 (0.06)	0.45	0.661 (0.06)	0.661 (0.06)	1.00
	NR	0.71 (0.03)	0.71 (0.03)	0.68	0.70 (0.04)	0.70 (0.04)	0.15	0.69 (0.04)	0.69 (0.04)	0.34	0.67 (0.04)	0.67 (0.04)	0.19	0.65 (0.04)	0.65 (0.04)	0.59	0.682 (0.04)	0.682 (0.04)	0.45
	Overall	0.703 (0.04)	0.705 (0.04)	0.30	0.693 (0.04)	0.694 (0.04)	0.63	0.682 (0.04)	0.682 (0.04)	0.36	0.663 (0.05)	0.664 (0.05)	0.28	0.646 (0.05)	0.647 (0.05)	0.31			
Step time (s)	**CR**	0.36 (0.02)	0.36 (0.02)	0.67	0.35 (0.02)	0.35 (0.02)	0.93	0.35 (0.02)	0.35 (0.02)	0.79	0.34 (0.02)	0.34 (0.02)	0.65	0.33 (0.02)	0.33 (0.02)	0.41	0.344 (0.02)	0.345 (0.02)	0.43
	RR	0.35 (0.03)	0.34 (0.03)	0.08	0.34 (0.03)	0.34 (0.03)	0.06	0.34 (0.03)	0.33 (0.03)	**0.028**	0.32 (0.03)	0.32 (0.03)	**0.031**	0.31 (0.03)	0.31 (0.03)	0.14	0.333 (0.03)	0.328 (0.03)	**<0.001**
	NR	0.35 (0.02)	0.36 (0.02)	0.49	0.35 (0.02)	0.35 (0.02)	0.74	0.34 (0.02)	0.34 (0.02)	0.88	0.33 (0.02)	0.34 (0.02)	0.94	0.32 (0.02)	0.32 (0.02)	0.40	0.341 (0.02)	0.341 (0.02)	0.75
	Overall	0.352 (0.02)	0.352 (0.02)	0.92	0.348 (0.02)	0.346 (0.02)	0.16	0.342 (0.02)	0.340 (0.02)	0.21	0.332 (0.02)	0.332 (0.02)	0.63	0.324 (0.02)	0.322 (0.02)	0.28			
Stance time (s)	**CR**	0.25 (0.02)	0.25 (0.02)	0.45	0.24 (0.01)	0.24 (0.01)	0.13	0.22 (0.01)	0.22 (0.02)	0.31	0.21 (0.01)	0.21 (0.02)	0.83	0.20 (0.01)	0.20 (0.01)	0.92	0.224 (0.02)	0.223 (0.02)	0.13
	RR	0.26 (0.04)	0.26 (0.04)	0.50	0.24 (0.03)	0.24 (0.03)	0.40	0.23 (0.02)	0.23 (0.03)	0.57	0.22 (0.02)	0.22 (0.03)	0.89	0.21 (0.02)	0.21 (0.03)	0.67	0.231 (0.03)	0.230 (0.03)	0.25
	NR	0.27 (0.02)	0.27 (0.02)	0.67	0.26 (0.03)	0.26 (0.02)	0.14	0.24 (0.02)	0.24 (0.02)	0.50	0.23 (0.02)	0.23 (0.02)	0.25	0.22 (0.02)	0.22 (0.02)	0.20	0.246 (0.03)	0.244 (0.03)	0.057
	Overall	0.260 (0.03)	0.259 (0.03)	0.52	0.248 (0.03)	0.245 (0.03)	**0.020**	0.233 (0.02)	0.232 (0.02)	0.18	0.220 (0.02)	0.219 (0.02)	0.44	0.208 (0.02)	0.207 (0.02)	0.35			

Flight time (s)	**CR**	0.108 (0.013)	0.110 (0.017)	0.22	0.113 (0.018)	0.115 (0.019)	0.22	0.122 (0.011)	0.124 (0.013)	0.12	0.127 (0.013)	0.129 (0.014)	0.21	0.131 (0.014)	0.133 (0.014)	0.09	0.120 (0.02)	0.122 (0.02)	**0.002**
	RR	0.091 (0.021)	0.087 (0.021)	0.09	0.101 (0.017)	0.095 (0.018)	0.07	0.104 (0.015)	0.099 (0.016)	**0.036**	0.107 (0.014)	0.102 (0.012)	**0.011**	0.108 (0.018)	0.105 (0.014)	0.23	0.102 (0.02)	0.098 (0.02)	**<0.001**
	NR	0.080 (0.019)	0.081 (0.018)	0.76	0.089 (0.018)	0.091 (0.018)	0.18	0.099 (0.010)	0.100 (0.013)	0.59	0.102 (0.010)	0.105 (0.010)	0.23	0.106 (0.011)	0.106 (0.012)	0.80	0.095 (0.02)	0.097 (0.02)	0.18
	Overall	0.093 (0.02)	0.093 (0.02)	0.87	0.101 (0.02)	0.101 (0.02)	0.96	0.109 (0.02)	0.108 (0.02)	0.74	0.113 (0.02)	0.113 (0.02)	0.93	0.116 (0.02)	0.115 (0.02)	0.65			
Duty factor (%)	**CR**	35.1 (2.0)	34.6 (2.2)	0.23	34.2 (1.8)	33.7 (2.3)	0.09	32.5 (1.4)	32.1 (1.7)	0.13	31.1 (1.4)	30.9 (1.4)	0.43	30.1 (1.4)	30.1 (1.4)	0.70	32.6 (2.4)	32.3 (2.5)	**0.009**
	RR	37.1 (2.9)	36.9 (3.5)	0.50	35.7 (2.9)	35.3 (2.9)	0.37	34.7 (2.1)	34.5 (2.3)	0.57	33.8 (1.9)	33.8 (1.9)	0.99	33.0 (2.2)	32.9 (2.1)	0.60	34.9 (2.7)	34.7 (2.8)	0.20
	NR	38.6 (2.7)	38.8 (2.4)	0.65	37.3 (2.8)	36.9 (2.4)	0.27	35.6 (1.8)	35.3 (1.6)	0.52	34.7 (1.6)	34.3 (1.6)	0.27	33.7 (1.6)	33.4 (1.6)	0.26	36.0 (2.7)	35.7 (2.7)	0.10
	Overall	37.0 (2.9)	36.7 (3.2)	0.32	35.7 (2.8)	35.3 (2.8)	**0.025**	34.2 (2.2)	34.0 (2.3)	0.13	33.2 (2.2)	32.9 (2.2)	0.23	32.3 (2.3)	32.1 (2.3)	0.20			
Peak vertical GRF (BW)	**CR**	2.57 (0.45)	2.60 (0.42)	0.42	2.62 (0.45)	2.66 (0.43)	0.17	2.67 (0.43)	2.68 (0.41)	0.50	2.76 (0.45)	2.78 (0.42)	0.51	2.78 (0.47)	2.81 (0.45)	0.26	2.68 (0.44)	2.71 (0.42)	**0.029**
	RR	2.42 (0.47)	2.46 (0.50)	0.24	2.51 (0.51)	2.53 (0.45)	0.54	2.54 (0.53)	2.57 (0.53)	0.24	2.55 (0.48)	2.60 (0.49)	0.14	2.58 (0.47)	2.61 (0.48)	0.43	2.52 (0.47)	2.55 (0.47)	**0.014**
	NR	2.23 (0.36)	2.19 (0.35)	0.08	2.34 (0.37)	2.33 (0.33)	0.90	2.42 (0.36)	2.39 (0.34)	0.20	2.47 (0.39)	2.46 (0.36)	0.53	2.49 (0.41)	2.49 (0.38)	0.93	2.39 (0.38)	2.37 (0.36)	0.08
	Overall	2.40 (0.44)	2.41 (0.44)	0.58	2.49 (0.44)	2.50 (0.41)	0.24	2.54 (0.44)	2.55 (0.43)	0.73	2.60 (0.44)	2.61 (0.43)	0.33	2.62 (0.45)	2.64 (0.44)	0.26			
Peak braking force (BW)	**CR**	0.29 (0.08)	0.29 (0.09)	0.80	0.33 (0.09)	0.34 (0.09)	0.78	0.36 (0.10)	0.35 (0.09)	0.43	0.35 (0.08)	0.34 (0.09)	0.26	0.39 (0.09)	0.37 (0.10)	0.21	0.34 (0.09)	0.34 (0.09)	0.20
	RR	0.28 (0.07)	0.29 (0.07)	0.07	0.30 (0.08)	0.31 (0.09)	0.21	0.33 (0.06)	0.33 (0.06)	0.89	0.35 (0.06)	0.35 (0.06)	0.43	0.39 (0.07)	0.38 (0.07)	0.79	0.33 (0.08)	0.33 (0.07)	0.25
	NR	0.24 (0.06)	0.24 (0.05)	0.46	0.28 (0.05)	0.28 (0.06)	0.30	0.30 (0.04)	0.29 (0.04)	0.43	0.32 (0.06)	0.31 (0.05)	0.68	0.34 (0.05)	0.34 (0.05)	0.93	0.30 (0.06)	0.29 (0.06)	0.18

	Overall	0.27 (0.07)	0.27 (0.07)	0.72	0.30 (0.08)	0.31 (0.08)	0.68	0.33 (0.07)	0.32 (0.07)	0.35	0.34 (0.07)	0.33 (0.07)	0.11	0.37 (0.07)	0.36 (0.08)	0.21			
Peak propulsion force (BW)	**CR**	0.15 (0.06)	0.14 (0.07)	0.12	0.16 (0.07)	0.15 (0.07)	**0.040**	0.20 (0.07)	0.19 (0.07)	0.14	0.25 (0.06)	0.25 (0.07)	0.80	0.25 (0.08)	0.26 (0.08)	0.47	0.20 (0.08)	0.20 (0.09)	0.10
	RR	0.13 (0.05)	0.13 (0.05)	1.00	0.18 (0.06)	0.17 (0.06)	**0.013**	0.20 (0.06)	0.20 (0.07)	0.44	0.22 (0.05)	0.22 (0.06)	0.54	0.23 (0.07)	0.24 (0.07)	0.45	0.19 (0.07)	0.19 (0.07)	0.78
	NR	0.16 (0.05)	0.16 (0.05)	0.80	0.18 (0.06)	0.17 (0.06)	0.12	0.21 (0.05)	0.20 (0.04)	0.16	0.24 (0.06)	0.23 (0.06)	0.45	0.24 (0.06)	0.24 (0.06)	0.74	0.21 (0.06)	0.20 (0.06)	0.07
	Overall	0.15 (0.05)	0.14 (0.06)	0.18	0.17 (0.06)	0.16 (0.06)	**0.001**	0.20 (0.06)	0.20 (0.06)	0.057	0.24 (0.06)	0.24 (0.06)	0.85	0.24 (0.07)	0.24 (0.07)	0.60			
Time to peak vertical GRF (s)	**CR**	0.101 (0.009)	0.099 (0.010)	0.68	0.099 (0.008)	0.096 (0.009)	0.68	0.094 (0.009)	0.092 (0.010)	0.68	0.088 (0.009)	0.086 (0.008)	1.00	0.084 (0.008)	0.083 (0.008)	0.17	0.093 (0.011)	0.092 (0.011)	0.28
	RR	0.104 (0.011)	0.102 (0.009)	0.59	0.101 (0.009)	0.098 (0.008)	1.00	0.098 (0.010)	0.096 (0.009)	0.35	0.094 (0.009)	0.092 (0.008)	0.35	0.087 (0.014)	0.088 (0.012)	1.00	0.097 (0.011)	0.096 (0.011)	0.54
	NR	0.113 (0.011)	0.113 (0.009)	1.00	0.108 (0.014)	0.106 (0.011)	**0.016**	0.104 (0.013)	0.102 (0.011)	0.28	0.100 (0.103)	0.097 (0.012)	0.17	0.093 (0.012)	0.091 (0.010)	0.28	0.104 (0.014)	0.102 (0.013)	**0.004**
	Overall	0.106 (0.011)	0.106 (0.012)	0.42	0.103 (0.011)	0.100 (0.010)	**0.038**	0.099 (0.011)	0.097 (0.010)	**0.021**	0.094 (0.011)	0.093 (0.002)	0.40	0.088 (0.012)	0.087 (0.011)	0.39			
Time to peak braking force (s)	**CR**	0.053 (0.010)	0.049 (0.018)	0.46	0.054 (0.009)	0.052 (0.014)	0.42	0.055 (0.006)	0.052 (0.011)	0.21	0.051 (0.009)	0.049 (0.010)	0.72	0.051 (0.007)	0.050 (0.011)	0.68	0.054 (0.009)	0.051 (0.013)	0.16
	RR	0.056 (0.020)	0.054 (0.023)	0.76	0.055 (0.020)	0.053 (0.020)	0.51	0.052 (0.021)	0.052 (0.021)	0.59	0.050 (0.021)	0.051 (0.020)	0.59	0.046 (0.021)	0.049 (0.019)	0.27	0.052 (0.020)	0.052 (0.018)	0.87
	NR	0.063 (0.013)	0.067 (0.006)	0.11	0.062 (0.012)	0.066 (0.006)	0.11	0.064 (0.004)	0.065 (0.004)	0.68	0.059 (0.012)	0.060 (0.007)	0.64	0.059 (0.007)	0.055 (0.012)	0.28	0.061 (0.010)	0.063 (0.009)	0.11
	Overall	0.057 (0.014)	0.058 (0.017)	0.89	0.058 (0.014)	0.058 (0.015)	1.00	0.058 (0.013)	0.057 (0.014)	0.31	0.054 (0.014)	0.054 (0.013)	0.89	0.052 (0.014)	0.052 (0.013)	0.69			
Time to peak propulsion force (s)	**CR**	0.190 (0.014)	0.189 (0.014)	0.76	0.182 (0.012)	0.181 (0.014)	0.28	0.173 (0.013)	0.171 (0.015)	**0.016**	0.163 (0.011)	0.161 (0.012)	0.34	0.158 (0.011)	0.156 (0.012)	0.44	0.174 (0.017)	0.171 (0.018)	**0.018**
	RR	0.198 (0.026)	0.195 (0.027)	0.20	0.187 (0.023)	0.183 (0.021)	0.59	0.179 (0.017)	0.177 (0.018)	1.00	0.170 (0.018)	0.168 (0.021)	0.35	0.162 (0.019)	0.160 (0.018)	0.35	0.179 (0.024)	0.177 (0.024)	0.09

	NR	0.211 (0.020)	0.212 (0.021)	1.00	0.199 (0.020)	0.198 (0.019)	0.34	0.190 (0.018)	0.188 (0.016)	0.34	0.179 (0.019)	0.178 (0.019)	0.22	0.169 (0.017)	0.168 (0.016)	0.72	0.190 (0.024)	0.188 (0.024)	0.13
	Overall	0.200 (0.022)	0.199 (0.023)	0.42	0.190 (0.020)	0.188 (0.020)	0.15	0.180 (0.018)	0.178 (0.018)	**0.050**	0.172 (0.018)	0.169 (0.019)	0.059	0.163 (0.016)	0.161 (0.016)	0.23			
VALR (BW/s)	**CR**	46.1 (13.2)	47.3 (13.9)	0.74	54.9 (11.5)	56.5 (11.7)	0.67	62.2 (17.0)	63.4 (15.5)	0.55	64.6 (13.3)	64.1 (16.3)	0.88	74.3 (13.3)	76.0 (16.0)	0.44	60.4 (16.3)	61.5 (17.1)	0.41
	RR	39.5 (12.8)	42.5 (11.1)	0.31	44.7 (11.2)	47.5 (11.6)	0.11	47.9 (12.3)	51.0 (14.3)	0.051	54.9 (12.7)	57.8 (14.0)	0.16	58.4 (14.8)	62.1 (17.3)	0.27	49.1 (14.0)	52.2 (15.0)	**0.002**
	NR	45.0 (17.1)	42.3 (14.6)	0.056	54.1 (18.7)	50.9 (16.6)	0.11	62.5 (15.9)	57.4 (12.7)	**0.047**	63.8 (17.1)	59.7 (14.3)	0.18	70.6 (17.3)	67.9 (16.4)	0.43	59.2 (18.8)	55.6 (16.9)	0.14
	Overall	43.8 (14.4)	44.1 (13.2)	0.82	51.6 (14.6)	51.9 (13.7)	0.86	58.2 (16.3)	57.7 (14.7)	0.71	61.5 (14.7)	60.7 (14.7)	0.63	68.4 (16.2)	69.1 (17.0)	0.68			
VILR (BW/s)	**CR**	60.1 (15.6)	61.3 (15.2)	0.70	68.1 (12.5)	71.8 (14.3)	0.37	76.0 (17.3)	77.9 (17.2)	0.37	78.9 (14.4)	79.3 (20.3)	0.88	88.2 (16.0)	91.0 (19.4)	0.30	74.3 (17.6)	76.3 (19.4)	0.13
	RR	51.0 (15.1)	53.4 (14.1)	0.42	58.2 (13.7)	58.4 (14.3)	0.81	61.9 (16.8)	62.2 (16.8)	0.83	67.6 (17.6)	69.0 (17.3)	0.57	70.6 (19.5)	73.9 (20.6)	0.33	61.8 (17.4)	63.4 (17.6)	**0.001**
	NR	57.2 (19.9)	53.9 (17.8)	**0.036**	66.5 (20.6)	63.9 (18.3)	0.14	76.0 (18.7)	71.2 (14.2)	0.051	76.4 (20.6)	73.1 (16.6)	0.27	83.7 (20.3)	82.0 (18.7)	0.58	72.0 (21.4)	68.8 (19.1)	**0.002**
	Overall	56.4 (17.0)	56.4 (15.8)	0.98	64.7 (16.2)	65.1 (16.3)	0.79	71.9 (18.3)	71.0 (16.8)	0.46	74.7 (17.8)	74.1 (18.1)	0.74	81.5 (19.4)	82.8 (20.1)	0.44			

GRF, ground reaction force;
BW, body weight;
VALR, vertical average loading rate;
VILR, vertical instantaneous loading rate;
Bold, indicating significant difference ($p < 0.05$).

Table A — Mean (standard deviation) value of symmetry index (%) of all parameters of interest for competitive runners (CR), recreational runners (RR) and novice runners (NR) at each test speeds (8, 9, 10, 11, and 12 km/h), results of two-way (3 groups by 5 speeds) repeated measures analysis of variance (ANOVA), and showing parameters that exhibited significant asymmetry (*) relative to intra-limb variability.

		Running speed						Repeated measures ANOVA		
Parameter	**Group**	**8 km/h**	**9 km/h**	**10 km/h**	**11 km/h**	**12 km/h**	**Overall**	**Interaction**	**Speed effect**	**Group effect**
Stride time	**CR**	0.8 (0.2)	0.9 (0.3)	0.8 (0.3)	0.9 (0.2)	0.9 (0.2)	0.8 (0.2) *	F = 1.18; *p* = 0.32; power = 0.52	F = 1.37; *p* = 0.25; power = 0.41	F = 1.96; *p* = 0.16; power = 0.37
	RR	0.9 (0.2)	0.9 (0.3)	0.8 (0.2)	0.9 (0.2)	1.1 (0.3)	0.9 (0.2)			
	NR	0.9 (0.3)	1.0 (0.2)	1.1 (0.2)	1.0 (0.2)	1.0 (0.3)	1.0 (0.2)			
	Overall	0.9 (0.2)	0.9 (0.3)	0.9 (0.2)	0.9 (0.2)	1.0 (0.3)	0.9 (0.2)			
Step time	**CR**	3.3 (2.1)	2.9 (1.2)	2.3 (0.5)	2.7 (1.1)	2.2 (0.7)	2.7 (1.3)	F = 2.18; *p* = 0.06; power = 0.71	F = 0.55; *p* = 0.63; power = 0.15	F = 0.46; *p* = 0.64; power = 0.12
	RR	2.8 (1.3)	3.3 (1.6)	2.8 (1.5) *	2.5 (1.1) *	3.5 (2.0)	3.0 (1.5) *			
	NR	2.7 (0.6)	2.7 (0.7)	3.0 (0.6)	3.4 (1.7)	3.6 (1.9)	3.1 (1.3)			
	Overall	2.9 (1.4)	2.9 (1.2)	2.7 (0.9)	2.9 (1.4)	3.1 (1.7)	2.9 (1.3)			
Stance time	**CR**	3.2 (1.5)	2.9 (1.5)	2.5 (1.3)	3.6 (1.4)	2.6 (1.0)	3.0 (1.4)	F = 1.47; *p* = 0.20; power = 0.52	F = 1.06; *p* = 0.37; power = 0.27	F = 0.09; *p* = 0.91; power = 0.06
	RR	3.0 (2.0)	3.1 (1.3)	3.1 (1.0)	3.1 (1.2)	3.4 (1.2)	3.1 (1.3)			
	NR	3.0 (1.1)	3.0 (1.3)	3.3 (1.9)	3.3 (1.3)	3.1 (1.3)	3.2 (1.4) ^			
	Overall	3.1 (1.5)	3.0 (1.3) *	3.0 (1.4)	3.4 (1.3)	3.0 (1.2)	3.1 (1.3)			
Flight time	**CR**	5.0 (3.9)	4.1 (1.8)	3.2 (1.0)	2.4 (1.9)	2.3 (1.2)	3.4 (2.4) *	F = 0.68; *p* = 0.66; power =0.25	F = 3.97; ***p* = 0.012**; power = 0.80	F = 3.06; *p* = 0.06; power = 0.55
	RR	7.7 (5.2)	6.1 (4.3)	4.7 (4.0) *	5.6 (3.7) *	6.4 (4.8)	6.1 (4.3) *			
	NR	7.8 (5.2)	4.4 (3.6)	4.8 (4.3)	5.8 (4.9)	5.6 (5.3)	5.7 (4.7)			
	Overall	6.8 (4.8)	4.8 (3.3)	4.2 (3.4)	4.5 (3.9)	4.6 (4.4)	5.0 (4.1)			

Duty factor	**CR**	3.1 (1.5)	2.9 (1.4)	2.6 (1.3)	3.6 (1.5)	2.6 (1.0)	3.0 (1.4) *	F = 1.11; *p* = 0.37; power = 0.40	F = 1.45; *p* = 0.24; power = 0.36	F = 0.07; *p* = 0.94; power = 0.06
	RR	3.0 (2.0)	3.1 (1.4)	3.0 (1.0)	3.2 (1.1)	3.3 (1.3)	3.1 (1.3)			
	NR	3.0 (1.1)	3.0 (1.4)	3.2 (1.8)	3.3 (1.3)	3.0 (1.3)	3.1 (1.3)			
	Overall	3.0 (1.5)	3.0 (1.3) *	2.9 (1.4)	3.4 (1.3)	3.0 (1.2)	3.1 (1.3)			
Peak vertical GRF	**CR**	3.7 (2.5)	3.6 (1.8)	2.9 (1.1)	3.1 (1.3)	3.1 (0.9)	3.3 (1.6) *	F = 0.89; *p* = 0.50; power = 0.31	F = 2.23; *p* = 0.10; power = 0.51	F = 0.80; *p* = 0.46; power = 0.17
	RR	4.3 (1.2)	3.7 (1.7)	3.3 (1.2)	3.5 (1.5)	4.4 (1.7)	3.9 (1.5) *			
	NR	3.6 (1.5)	3.3 (1.1)	3.4 (1.5)	3.1 (0.9)	3.1 (1.0)	3.3 (1.2)			
	Overall	3.8 (1.9)	3.5 (1.5)	3.2 (1.3)	3.2 (1.2)	3.5 (1.3)	3.4 (1.5)			
Peak braking force	**CR**	14.4 (5.7)	13.7 (5.1)	12.7 (5.0)	11.8 (4.1)	13.8 (5.2)	13.3 (3.5)	F = 1.03; *p* = 0.42; power = 0.46	F = 1.29; *p* = 0.28; power = 0.39	F = 1.09; *p* = 0.35; power = 0.22
	RR	12.5 (4.6)	12.8 (3.0)	10.2 (2.0)	10.5 (1.7)	11.1 (3.3)	14.3 (5.0)			
	NR	14.0 (4.2)	11.5 (3.2)	13.1 (5.3)	13.9 (4.8)	13.9 (3.9)	13.3 (4.3)			
	Overall	13.7 (4.8)	12.7 (3.9)	12.1 (4.5)	12.2 (4.0)	13.1 (4.3)	12.7 (4.3)			
Peak propulsion force	**CR**	12.7 (3.7)	12.1 (4.0) *	10.6 (2.6)	10.1 (4.3)	12.1 (2.4)	11.5 (3.5)	F = 0.68; *p* = 0.71; power = 0.30	F = 2.23; *p* = 0.07; power = 0.64	F = 3.07; *p* = 0.06; power = 0.55
	RR	15.9 (4.9)	12.4 (2.0) *	13.4 (6.2)	13.8 (3.6)	15.8 (5.4)	14.3 (4.6)			
	NR	15.8 (6.3)	13.7 (6.0)	15.0 (5.9)	15.5 (6.5)	15.6 (4.3)	15.1 (5.7)			
	Overall	14.8 (5.2)	12.7 (4.4) *	13.0 (5.3)	13.1 (5.4)	14.4 (4.3)	13.6 (4.9)			
Time to peak vertical GRF	**CR**	8.6 (3.6)	7.8 (3.2)	7.1 (3.0)	6.9 (2.7)	6.4 (2.9)	7.4 (3.1)	F = 2.20; ***p* = 0.032**; power = 0.84	F = 0.89; *p* = 0.47; power = 0.28	F = 0.17; *p* = 0.85; power = 0.07
	RR	7.1 (2.9)	6.6 (3.2)	6.5 (2.1)	7.1 (2.7)	8.5 (4.5)	7.2 (3.1)			
	NR	5.3 (1.6)	6.9 (2.9) *	6.2 (1.8)	7.5 (4.2)	8.0 (4.6)	6.8 (3.3) *			
	Overall	7.0 (3.1)	7.1 (3.0) *	6.6 (2.3) *	7.2 (3.2)	7.6 (4.0)	7.1 (3.2)			

Time to peak braking force	**CR**	10.9 (6.4)	12.1 (7.4)	9.3 (6.2)	11.8 (6.7)	9.6 (5.9)	10.7 (6.4)	F = 0.53; *p* = 0.83; power = 0.24	F = 1.78; *p* = 0.14; power = 0.53	F = 1.95; *p* = 0.16; power = 0.37
	RR	10.4 (6.1)	11.9 (6.2)	11.0 (5.9)	11.9 (8.7)	8.8 (3.7)	10.8 (6.2)			
	NR	8.4 (5.8)	6.6 (3.1)	6.0 (2.1)	8.6 (5.1)	7.0 (6.3)	7.3 (4.7)			
	Overall	9.9 (6.0)	10.1 (6.2)	8.6 (5.3)	10.7 (6.8)	8.4 (5.5)	9.5 (6.0)			
Time to peak propulsion force	**CR**	3.4 (1.4)	4.2 (2.2)	3.0 (1.2) *	3.6 (2.5)	3.7 (2.1)	3.6 (1.9) *	F = 0.61; *p* = 0.77; power = 0.27	F = 1.60; *p* = 0.18; power = 0.48	F = 0.67; *p* = 0.52; power = 0.15
	RR	4.0 (2.3)	5.1 (2.9)	3.9 (1.3)	4.7 (2.2)	4.3 (1.7)	4.4 (2.1)			
	NR	3.5 (1.6)	3.6 (1.8)	3.9 (1.1)	4.2 (2.2)	4.0 (2.6)	3.9 (1.9)			
	Overall	3.6 (1.7)	4.3 (2.3)	3.6 (1.3) *	4.1 (2.3) ^	4.0 (2.1)	3.9 (2.0)			
VALR	**CR**	21.4 (9.4)	20.4 (6.2)	18.0 (9.2)	13.6 (4.9)	13.0 (4.7)	17.3 (7.7)	F = 3.21; ***p* = 0.002**; power = 0.96	F = 3.46; ***p* = 0.010**; power = 0.85	F = 0.02; *p* = 0.98; power = 0.05
	RR	21.0 (11.1)	15.0 (5.0)	15.0 (4.4) ^	13.3 (6.8)	21.3 (7.8)	17.1 (7.8) *			
	NR	17.6 (4.9) ^	16.7 (7.4)	17.1 (9.5) *	17.7 (8.8)	18.6 (8.8)	17.5 (7.7)			
	Overall	19.9 (8.5)	17.5 (6.5)	16.8 (8.1)	15.0 (7.1)	17.4 (7.8)	17.3 (7.7)			
VILR	**CR**	18.2 (9.7)	18.8 (10.7)	12.8 (6.2)	17.0 (13.3)	12.1 (4.6)	15.8 (9.5)	F = 1.86; *p* = 0.07; power = 0.76	F = 0.62; *p* = 0.65; power = 0.20	F = 0.48; *p* = 0.62; power = 0.12
	RR	15.6 (9.3)	10.3 (1.6)	12.1 (5.6)	12.3 (7.1)	17.4 (11.3)	13.5 (7.8) *			
	NR	13.7 (3.2) *	13.7 (5.6)	15.0 (5.5) ^	15.8 (7.0)	14.4 (8.1)	14.5 (5.9) *			
	Overall	15.9 (7.8)	14.5 (7.9)	13.4 (5.7)	15.2 (9.6)	14.5 (8.2)	14.7 (7.9)			

GRF, ground reaction force;
VALR, vertical average loading rate;
VILR, vertical instantaneous loading rate;
Bold, indicating significant difference ($p < 0.05$);
*, significant difference between right and left values ($p < 0.05$);
^, difference between right and left values with a marginal significance level ($p = 0.05 \sim 0.06$).

Declarations of interest: none