Constant low-to-moderate mechanical asymmetries during a treadmill graded exercise test

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Abstract

This study describes asymmetry in key mechanical variables during a treadmill-based, running graded exercise test (GXT). Twenty-one recreationally trained male runners completed a continuous, maximal GXT on an instrumented treadmill, starting at 9 km.h\(^{-1}\) with speed increases of +0.5 km.h\(^{-1}\) every 30 s, for the determination of ventilatory threshold (VT), respiratory compensation point (RCP), and maximal oxygen uptake (MAX). Ground reaction forces were recorded continuously and subsequently averaged from 10 consecutive steps corresponding to VT, RCP and MAX intensity stages (13.4±1.2 km.h\(^{-1}\), 16.0±1.6 km.h\(^{-1}\) and 18.2±1.5 km.h\(^{-1}\), respectively). Asymmetry scores were assessed from the “symmetry angle” (SA) formulae, where a score of 0%/100% indicates perfect symmetry/asymmetry; these were then compared between the three intensity stages. There was no influence of exercise intensity on SA scores for any of the sixteen biomechanical variables (P > 0.222). The group mean SA scores did not exceed 1.5% for spatio-temporal variables (contact time, aerial time, frequency and step length). There were larger mean SA scores for mean loading rate (3.7±2.7%) and most spring-mass model variables (vertical stiffness: 2.2±1.6% and leg stiffness: 1.7±1.4%). The SA scores were ~1.0–3.5% for braking and propulsive phase durations, peak forces, and resulting impulses. Lower extremities behave similarly at submaximal and maximal intensities during GXT, indicating that runners maintained relatively even strides as intensity increased. However, practitioners must be careful not to infer the presence of asymmetry during GXT based on a single variable, given the lower SA scores for spatio-temporal parameters.

Key words: symmetry angle scores; asymmetry, running mechanics, incremental test, instrumented treadmill.
Highlights

- Our comprehensive list of sixteen mechanical variables provides a mechanical norm of expected asymmetry during treadmill graded exercise testing for recreationally trained runners.

- The stride pattern across submaximal and maximal exercise intensities remains consistent between limbs, with mechanical asymmetries being more individual-specific than intensity stage-dependent.

- Low to moderate asymmetry is a natural phenomenon in recreationally trained runners during treadmill graded exercise testing; notwithstanding, asymmetry scores appear inconsistent between mechanical parameters.
**Introduction**

A graded exercise test (GXT), performed on a treadmill, is commonly used to determine aerobic fitness in runners. In addition to ‘gold standard’ maximal oxygen uptake, direct gas exchange measurement also allows determination of two characteristic ventilatory breakdowns corresponding to the ventilatory threshold (VT) and the respiratory compensation point (RCP) (Bentley et al. 2007). Despite these routine physiological measurements, adjustments in the stride pattern occurring during GXT are rarely explored, with any such studies to date only considering basic spatio-temporal variables (e.g., contact time, aerial time, step length and step frequency; Gonzalez-Mohino et al. 2016). However, determination of kinetics and spring-mass model characteristics, from continuous ground reaction forces (GRF) recorded on an instrumented treadmill, could provide a more detailed understanding of the biomechanical adjustments occurring during GXT.

During sub-maximal constant-speed running, GRF traces can be used as a primary descriptive component in the analysis of bilateral leg differences, or asymmetry. The effect of running at faster speeds on lower limb asymmetry in ‘fresh’ conditions is well documented, with equivocal outcomes of increased (Belli et al. 1995), unchanged (Karamanidis et al. 2003; Furlong and Egginton, 2018; Girard et al. 2019) or decreased (Bredeweg et al. 2013; Mo et al. 2020) differences reported. Regardless, the magnitude of lower limb asymmetry varies greatly depending on the variable of interest measured, with asymmetries observed for spatio-temporal variables typically lower than those established from kinetics and spring-mass model characteristics (Herzog et al. 1987). For instance, in the antero-posterior direction, peak braking as opposed to push-off forces display four times larger deviations from symmetry when sprinting repeatedly on a treadmill (Girard et al. 2020). However, the possibility that specific changes in landing patterns (as opposed to propulsion patterns) also develop with speed changes during GXT requires exploration.

Alteration in the magnitude of lower limb asymmetry with fatigue development is another issue yielding inconsistent literature findings. For example, Radzak et al. (2017) found increased knee joint
asymmetries (i.e., knee internal rotation and knee stiffness) when participants were tested at a constant speed of ~14.4 km.h\(^{-1}\) after completion of an exhaustive incremental treadmill test. However, there were only small effects of slower running speeds on lower limb asymmetry for the majority of mechanical variables measured (i.e., kinetics and spring-mass model characteristics) during repeated treadmill sprints (Girard et al. 2017; Girard et al. 2020). Accordingly, the outcomes reported in the current literature appear equivocal, with a recent systematic review (Heil et al. 2020) concluding that the influence of exercise-induced fatigue on lower limb asymmetries is not explicit, likely due to discrepancies in study designs, loading protocols, tasks/procedures, and participants’ training background between studies. For instance, studies of exhaustive running typically record mechanical variables from both legs, and report the average between legs (Rabita et al. 2011), or they record data from a single leg, and assume the contralateral leg exhibits identical stride biomechanics (Slawinski et al. 2005). Additionally, running at fixed as opposed to relative exercise intensities have often been employed to determine lower limb asymmetries (Bredeweg et al. 2013; Mo et al. 2020), which leaves it unclear as to the level of fatigue accumulated (if any) in such trials. In this context, one advantage of conducting GXT on an instrumented treadmill is to allow investigation of how the magnitude of lower limb asymmetry may change over the progression of an increasing physical load. A GXT exercise model likely offers the possibility to compare biomechanical asymmetries in runners with a different training background tested at consistent relative physiological landmarks, which include both submaximal and maximal exercise intensity stages.

When collectively considering the two factors presented above (i.e., the impact of running speed, and the impact of fatigue on lower limb asymmetries), it is important to note that alterations in these two variables (speed and/or fatigue) likely influence the stride pattern of a runner (Girard et al. 2019; Rabita et al. 2015), Interestingly, Read et al. (2019) reported that the magnitude of lower limb asymmetry can be driven by alterations in stride patterns due to more pronounced changes of neuromuscular control on one side of the body, presenting the question of how lower limb asymmetries change in response to changes in fatigue and running speed. Accordingly, our intention was to characterize biomechanical
asymmetries during treadmill GXT. We hypothesized that mechanical variables, and in particular, kinetics and spring-mass model characteristics, will become more asymmetrical at later exercise intensity stages (i.e., when fatigue is accumulated from continuous increments in running speed).

Methods

Participants

Twenty-one recreationally trained male runners (age: 38.5±5.0 years; stature: 1.75±0.06 m; body mass: 75.1±7.9 kg) provided written informed consent to participation. Training volume (running and swimming and/or cycling) for the 3 months preceding testing was ~9 h.wk⁻¹, with an average running distance of ~35 km per week and 5-km and 10-km personal bests of ~22 min and ~45 min. Participants had no known history of cardiovascular, neurological or orthopedic problems, and were injury free for the 3 months leading up to data collection. The study was approved by Anti-Doping Laboratory Ethics Committee in Qatar (IRB Application Number 2017000201), and conducted according to the principles outlined in the Declaration of Helsinki.

Procedures

Each participant completed a continuous GXT, starting at 9 km.h⁻¹, with speed increases of 0.5 km.h⁻¹ every 30 s. The test ended with voluntary exhaustion of the participants. Verbal encouragement was only given by the researcher guiding the runners throughout the session. Participants were all given the same model of neutral running shoes (Pearl Izumi N2v2, Colorado, US) to complete this test. They ran on a single-belt, instrumented treadmill (ADAL 3D-WR, Medical Development – HEF Tecmachine, France) allowing continuous GRF measurement, while uninterrupted breath-by-breath gas exchange recordings were simultaneously obtained. Briefly, the treadmill was mounted on a highly rigid metal frame, set at 0° grade incline, fixed to the ground through four piezoelectric force transducers (KI 9077b; Kistler, Winterthur, Switzerland) and installed on a special engineered concrete slab to ensure maximal rigidity.
of the supporting ground. Testing was conducted in an indoor facility maintained at \( \sim 24^\circ C \) and 45% of relative humidity.

**Running mechanics**

Data were continuously sampled at 1,000 Hz, and after appropriate filtering (Butterworth-type 30 Hz low-pass filter), instantaneous data of vertical and antero-posterior GRF were averaged for each support phase (vertical force above 30 N) (Morin et al. 2010). These data were determined by measurement of the main spatio-temporal variables: contact time (s), aerial time (s), step frequency (Hz) and step length (m). Peak braking and peak push-off forces (BW), duration of braking and push-off phases (s) along with braking and push-off impulses (N.s) were obtained. Finally, vertical mean loading rate (LR) was calculated as the mean value of the time-derivate of vertical force signal within the first 50 ms of the support phase, and expressed in BW.s\(^{-1}\) (Giandolini et al. 2013).

A linear spring-mass model of running was used to investigate the main mechanical integrative variables characterizing the lower limb behavior during running (McMahon and Cheng, 1990). Vertical stiffness (kN.m\(^{-1}\)) was calculated as the ratio of peak vertical force (N) to the maximal vertical downward displacement of center of mass (m), which was determined by double integration of vertical acceleration of center of mass over time during ground contact. Leg stiffness (kN.m\(^{-1}\)) was calculated as the ratio of peak vertical forces to the maximum leg spring compression [maximal vertical downward displacement + \( L_0 - \sqrt{L_0^2 - (0.5 \times \text{running speed} \times \text{contact time})^2} \), in m]. Initial leg length (\( L_0 \), great trochanter to ground distance in a standing position) was determined from participant’s stature as \( L_0 = 0.53 \times \text{stature} \) (Morin et al. 2005).

**Symmetry angle**

For each participant, inter-leg symmetry was measured using the symmetry angle (SA) equation (Zifchock et al. 2008):

\[
\text{Symmetry angle (SA)} = \]
\[
\left| \frac{45^\circ - \left( \tan^{-1} \left[ \frac{\text{left}}{\text{right}} \right] \right)}{90^\circ} \right| \times 100
\]

but if
\[
\left( 45^\circ - \tan^{-1} \left[ \frac{\text{left}}{\text{right}} \right] \right) > 90^\circ
\]

then
\[
\left| \frac{45^\circ - \left( \tan^{-1} \left[ \frac{\text{left}}{\text{right}} \right] - 180^\circ \right)}{90^\circ} \right| \times 100
\]

The SA is an arctan function of the ratio of two bilateral values, where a SA score of 0% indicates perfect symmetry and 100% indicates perfect asymmetry.

**Physiological measurements**

The following gas exchanges data were measured using a breath-by-breath gas analyzer (A JaegerTM Oxycon Mobile, Carefusion, Hoechberg, Germany), which was calibrated before each test using the manufacturers’ recommendations: \( \dot{V}O_2 \), carbon dioxide production (\( \dot{V}CO_2 \)) and minute ventilation (\( \dot{V}E \)). Data were first averaged every 15 s for the purpose of VT and RCP determination (*see below*) and subsequently expressed as 30-s means for each stage. The highest value for \( \dot{V}O_2 \) over 30 s was determined. The metabolic cart was suspended from the ceiling, so participants did not have to support the additional weight of the system when running.

The criteria of an increase in \( \dot{V}E/\dot{V}O_2 \) with no increase in \( \dot{V}E/\dot{V}CO_2 \) and departure from the linearity of \( \dot{V}E \) was used to determine VT. A disproportionate increase in both \( \dot{V}E/\dot{V}O_2 \) and \( \dot{V}E/\dot{V}CO_2 \) was used to determine RCP (Davis, 1985). All assessments of VT and RCP were made by visual inspection of graphs, time plotted against each relevant respiratory variable. All assessments were done independently by two experienced exercise physiologists. Each physiological variable corresponding to VT, RCP, and the speed associated with attainment of maximal \( \dot{V}O_2 \) or maximal load (\( \dot{V}O_2\text{MAX} \)) was expressed in absolute terms, while \( \dot{V}O_2 \) and heart rate at VT and RCP were also expressed in relative terms.
**Statistical analysis**

Values are presented as mean ± SD and 95% confidence interval (CI_{95%}). For the sixteen biomechanical variables, the effect of exercise intensity was determined by a single factor ANOVA for repeated measures (VT, RCP vs. \( \dot{V}O_{2\text{MAX}} \)). A Bonferroni post-hoc multiple comparison was performed if a significant main effect was observed. For each ANOVA, partial eta-squared (\( \eta^2 \)) was calculated as measures of effect size. Values of 0.01, 0.06 and above 0.14 were considered as small, medium and large, respectively (Nozourian and Plonsky, 2018). All statistical calculations were performed using SPSS statistical software V.26.0 (IBM Corp., Armonk, USA). The significance level was set at P < 0.05.

**Results**

There was no influence of exercise intensity on SA scores for the sixteen variables tested (P > 0.222; Figures 1–3). Consequently, group mean and the range of SA scores are subsequently presented in the text below as pooled values, corresponding to the average of VT, RCP and \( \dot{V}O_{2\text{MAX}} \) intensity stages. This averaging procedure offers, for a given mechanical variable, material benchmark for expected asymmetry magnitudes during GXT.

Mean SA scores did not exceed 1.5% for spatio-temporal variables: contact time (0.7±0.5% [CI_{95%} 0.6–0.8]; range: 0.3–1.6), aerial time (1.3±1.1% [CI_{95%} 1.1–1.6]; range: 0.4–2.8) as well as step frequency and step length (0.6±0.5% [CI_{95%} 0.5–0.7]; range: 0.2–1.6) (Figure 1).

Mean SA scores were larger for mean loading rate (3.7±2.7% [CI_{95%} 3.1–4.4]; range: 0.6–8.7) and most spring-mass model variables: peak vertical force (1.8±1.4% [CI_{95%} 1.4–2.1]; range: 0.2–3.8), maximal downward vertical displacement (3.0±2.6% [CI_{95%} 2.3–3.6]; range: 0.4–7.4), leg compression (1.8±1.4% [CI_{95%} 1.4–2.2]; range: 0.4–4.1), vertical stiffness (2.2±1.6% [CI_{95%} 1.8–2.6]; range: 0.3–5.2) and leg stiffness (1.7±1.4% [CI_{95%} 1.4–2.1]; range: 0.2–4.2) (Figure 2).

Mean SA scores were ~1–3.5% for duration of braking (1.6±1.5% [CI_{95%} 1.2–2.0]; range: 0.1–4.2) and push-off (1.2±1.2% [CI_{95%} 0.9–1.5]; range: 0.3–3.7) phases, peak braking (3.4±2.3% [CI_{95%} 2.8–4.0];
range: 1.0–7.8) and push-off (2.3±1.8% [CI95% 1.8–2.8]; range: 0.1–5.9) forces, as well as braking (2.6±1.9% [CI95% 2.1–3.1]; range: 0.6–6.3) and push-off (2.5±1.8% [CI95% 2.0–3.0]; range: 0.2–6.8) impulses (Figure 3).

*** Insert Figure 1–3 about here ***

Changes in spatio-temporal variables, kinetics and spring-mass model characteristics at intensities corresponding to the speed associated with VT, RCP and VO2MAX during GXT are displayed in Table 1.

Running speed at VT, RCP and VO2MAX intensity stages was 13.4±1.2 km.h\(^{-1}\), 16.0±1.6 km.h\(^{-1}\) and 18.2±1.5 km.h\(^{-1}\), respectively. Maximal oxygen uptake was 48.2±6.2 ml.min\(^{-1}\).kg\(^{-1}\).

*** Insert Table 1 about here ***

Discussion

Constant asymmetry between the three intensity stages

As treadmill belt speed increased across the three intensity stages, our main observation was that SA scores did not differ for any of the biomechanical variables studied. This occurred despite noticeable adjustments in most biomechanical variables between the two submaximal intensities (VT and RCP), while runners further altered their stride pattern at faster speeds when nearing exhaustion (VO2MAX). Previously, unchanging group mean asymmetry values were reported for the same sixteen variables as treadmill speed varied between 10 and 25 km.h\(^{-1}\) (Girard et al. 2019). Whereas treadmill speed increased progressively and continuously until exhaustion in the present study, Girard et al. (2019) implemented a discontinuous testing protocol where individuals ran at seven speeds for 60 s with 90 s of rest between efforts. Accordingly, the reader needs to be cognizant that accumulated fatigue, not only faster running speeds per se, may have at least partially influenced the magnitude of mechanical alterations observed here during GXT. Despite large adjustments in most running mechanical variables mainly due to the increase in belt speed, our most remarkable finding was that lower extremities behave similarly at submaximal and maximal intensities during GXT.
SA scores are inconsistent between variables

To our knowledge, this study is the first to present normative asymmetry values for running mechanics at characteristic submaximal and maximal intensities during treadmill GXT. Here, the magnitude of SA scores differed across the variable of interest, regardless of exercise intensity, confirming that biomechanical asymmetry is a natural phenomenon during maximal incremental testing. Overall, kinetics and spring-mass model characteristics’ SA scores exceeded those of the spatio-temporal variables at the three intensity stages, in agreement with observations made during submaximal constant speed running (Pappas et al. 2015; Tucker and Hanley, 2017; Girard et al. 2019; Mo et al. 2020) or repeated treadmill sprints (Girard et al. 2017; Girard et al. 2020). A qualitative inspection indicates that asymmetry does not appear to be a fixed trait with respect to SA scores, such that values ranged from as low as 0.6% (step frequency and step length), up to 3.7% (mean loading rate). Similarly, Mo et al. (2020) reported that vertical mean loading rate is the biomechanical variable that exhibited the largest inter-limb difference for speeds ranging from 8 to 12 km.h⁻¹. Nonetheless, no direct between-studies comparison is possible here since different indices (SA score vs. symmetry index) were used to quantify asymmetry (Bishop et al. 2016). To this end, we conclude that different biomechanical variables should not be used interchangeably to assess asymmetry during GXT, implying that practitioners must be careful not to infer the presence of asymmetry based on a single variable.

Individual responses

As with previous studies (Tucker and Hanley, 2017; Girard et al. 2019), our data demonstrate considerable inter-individual variability, with the range of responses for most individuals contained in approximately twice the magnitude of the mean value for a given variable. Remarkably, individual athletes did not necessarily exhibit consistent asymmetry values during GXT. For instance, when considering aerial time, participant #8 was the least symmetrical at both VT and RCP, yet was more symmetrical at VO₂MAX. Being asymmetrical at submaximal intensities but symmetrical at maximal intensity, is not uncommon for a given variable, reinforcing the individual nature of this biomechanical
trait. These observations agree with previous reports that show small effects between running at preferred and non-preferred speeds on kinetic asymmetry, where several large individual-specific responses were also found (Furlong and Egginton, 2018). Whereas inter-limb differences are often considered significant if the asymmetry score is greater than a fixed cut-off threshold (i.e., 15% for injury predisposition; Zifchock et al. 2008), others postulate that asymmetry for a given parameter is meaningful only if the inter-limb variability exceeds the intra-limb variability (Exell et al. 2012a; Exell et al. 2012b). Therefore, using a ‘fixed cut-off’ threshold to quantify asymmetries is an arbitrary approach that should be discouraged, since lower limb asymmetry during GXT is more athlete-specific than intensity-dependent.

**Mechanical alterations across intensity stages**

By modelling the lower limb as a linear mass-spring system, mechanical spring constants can be used to describe the resistance of vertical center of mass excursion and leg compression to a corresponding vertical force, respectively known as vertical and leg stiffness (McMahon and Cheng, 1990). For the first time during GXT, we demonstrated that the center of mass underwent significantly smaller vertical displacement along with no change for both leg compression and peak vertical force as running speed increased across the three intensity stages. Despite relatively similar SA scores, this resulted in progressively higher vertical stiffness but unchanged leg stiffness values. Such outcomes are in agreement with spring-mass model characteristics changes previously reported during running stages associated with the onset of blood lactate accumulation (Bitchell et al. 2019). Another unique aspect of this study was to continuously monitor braking and propulsive phase durations, peak forces, and resulting impulses in the antero-posterior direction. As with SA scores, adjustments occurring during the braking and push-off phases (i.e., shorter phases along with larger peak forces resulting in greater impulses) were of relatively similar magnitudes across the three intensity stages. Future studies quantifying surface EMG activity, ideally coupled with 3-D analysis of individual joints, would be required to verify how SA scores can be maintained during treadmill GXT.

**Practical implications**
Our novel data indicate that for spatio-temporal variables, presenting the lowest SA scores, it may be acceptable to collect unilateral data during GXT. However, spring-mass model characteristics and variables derived from the antero-posterior force signal displayed much larger asymmetry. Collection of these data, at both submaximal (VT, RCP) and maximal (VO_{2MAX}) intensities, from just one side of the body would therefore be inappropriate during incremental running. Additionally, the individual nature of mechanical asymmetry supports the notion of an athlete-specific step characteristic reliance, and thereby, the necessity for individual and separate (submaximal vs. maximal intensity stages) analyses. Making the distinction between a general trend drawn from the group mean of all tested athletes and the diversity of the features that can be found within a particular individual is paramount when quantifying asymmetries.

**Conclusion**

Our comprehensive list of sixteen variables provides a mechanical norm of expected asymmetry during treadmill GXT. We observed constant low-to-moderate SA scores between VT, RCP and VO_{2MAX} for spatio-temporal variables, kinetics and spring-mass model characteristics. Lower extremities behave in a similar manner as belt speed increased during GXT, indicating that recreationally trained runners maintained relatively even strides across intensity stages. Despite the overall group mean similarity for SA scores with faster belt speeds, individual responses were much more varied and should therefore be considered by the practitioner.

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Disclosure statement

No potential conflict of interest was reported by the authors.
References


Figure legends

Figure 1 – Symmetry angle scores (expressed as %) for spatio-temporal variables and vertical impact loading rate at intensities corresponding to the speed associated with the ventilatory threshold (VT), respiratory compensation point (RCP) and attainment of maximal oxygen uptake ($\dot{V}O_{2\text{MAX}}$) during the graded exercise test.

Contact time (A), aerial time (B), step frequency (C), step length (D), and mean loading rate (E).

Values are mean±SD (n=21).

Figure 2 – Symmetry angle scores (expressed as %) for spring-mass model characteristics at intensities corresponding to the speed associated with the ventilatory threshold (VT), respiratory compensation point (RCP) and attainment of maximal oxygen uptake ($\dot{V}O_{2\text{MAX}}$) during the graded exercise test.

Vertical stiffness (A), leg stiffness (B), maximal downward vertical displacement (C), leg compression (D) and peak vertical force (E).

Values are mean±SD (n=21).

Figure 3 – Symmetry angle scores (expressed as %) for antero-posterior force production variables at intensities corresponding to the speed associated with the ventilatory threshold (VT), respiratory compensation point (RCP) and attainment of maximal oxygen uptake (MAX) during the graded exercise test.

Braking phase duration (A), push-off phase duration (B), peak braking force (C), peak push-off force (D), braking impulse (E), and push-off impulse (F).

Values are mean±SD (n=21).