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Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals☆

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ABSTRACT

Although normal gait is often considered symmetrical in healthy populations, differences between limbs during walking suggest that limbs may be used preferentially for braking or propulsion. The purpose of this study was to evaluate kinematic and kinetic variables, at both rested state and following a two-stage treadmill fatiguing run, for asymmetry between limbs. Kinematic (240 Hz) and kinetic (960 Hz) running data were collected bilaterally for 20 physically active individuals at both rested and fatigued states. Symmetry angles were calculated to quantify asymmetry magnitude at rested and fatigued states. Paired *t*-tests were used to evaluate differences between right and left limbs at rested and fatigued states, as well as rested and fatigued states symmetry angles. Variables that have been previously associated with the development of overuse injuries, such as knee internal rotation, knee stiffness, loading rate, and adduction free moment, were found to be significantly different between limbs at both rested and fatigued states. Significant differences in vertical stiffness were found, potentially indicating functional asymmetry during running. Symmetry angle was used to investigate changes in percentage of asymmetry at rested and fatigued states. Small (1–6%), but significant decreases in vertical stiffness, loading rate, and free moment symmetry angles indicate that these variables may become more symmetrical with fatigue. Knee internal rotation and knee stiffness became more asymmetrical with fatigue, increasing by 14% and 5.3%, respectively. The findings of the current study indicate that fatigue induced changes in gait may progress knee movement pattern asymmetry.

1. Introduction

Normal gait is often considered to be symmetrical, which has influenced data collection methodology. Bilateral data collection may complicate the interpretation of results, especially when pooling limbs since combining data from right and left limbs will magnify effect size but negate the assumption of independent observations [1]. To satisfy this assumption, the researcher is required to choose one limb to be representative of both limbs [1]. However, symmetry of gait, the perfect congruence between right and left measures, may not occur in healthy populations [2]. Statistically significant differences in kinematic and kinetic measures between limbs have been observed, contradicting the assumption of gait symmetry [3–5]. Previous findings indicate that separate limbs are used by individuals more heavily for stabilization, propulsion, or braking during walking [3–5]. While differences could be attributed to limb dominance, as is established within the upper extremity, lower extremity (LE) differences have been reported despite controlling for dominance [3,6].

Upper extremity dominance is identified as the limb preferred for writing tasks, a learned neuromuscular skill; LE dominance has been categorized based on the limb's role in either stabilization or mobilization. For example, the leg used for kicking a ball is the mobilization limb and the stance leg is the stabilization limb. Arguments have been made for both mobilization and stabilization limbs to be considered dominant [4]. Both functions require precise neuromuscular adaption and modulation for successful

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task execution. Although definitions of LE dominance are not standardized, asymmetry appears to be present in normal gait [3–5]. Evaluations of the neuromuscular modulation of the LE may help quantify asymmetry relative to gait.

Measures of stiffness can be used to assess neuromuscular modulation of the entire LE [7]. The leg acts as a spring absorbing shock during braking and returning energy during propulsion according to the spring-mass model [7]. The nervous system can modulate the stiffness of the leg spring, via musculoskeletal changes in joint excursions, to maintain ideal center of mass excursion despite changes in running surface [7] and velocity [8]. Vertical stiffness (K_{vert}), the ratio of maximum vertical ground reaction force (GRF) over center of mass displacement [7], provides a measure to evaluate neuromuscular modulation symmetry.

Research evaluating asymmetry has largely examined walking [3–6]. Imbalances in propulsion measures have been shown to increase as walking velocity increases [5], indicating a potential for greater asymmetry in running. Biomechanical asymmetry not detrimental during walking could potentially become pathological or injurious in running due to the increased kinetic demands placed upon the musculoskeletal system. Populations affected by LE overuse injuries have demonstrated significant differences between the injured and non-injured limbs [9], but symmetry angles quantifying variation between limbs were not significantly different than controls [9,10]. Researchers have suggested that evaluations following fatiguing exercise are necessary, due to the potential for asymmetry becoming more pronounced with fatigue [10]. As a growing body of research appears to contradict the assumption of gait symmetry, there remains a need to evaluate differences between limbs of healthy individuals in conditions more physically demanding than walking [2–4,6,9–11]. Therefore, the purpose of this study was to evaluate asymmetry of kinetic and kinematic variables in both rested and fatigued state running. We hypothesized that there would be significant differences between limbs at rested and fatigued states. We also hypothesized that the effects of fatigue will enhance the magnitude of asymmetry.

2. Material and methods

Twenty healthy participants (14 Males, 6 Females), without previous LE surgeries, volunteered to participate (Table 1). Prior to data collection, participants completed an informed consent form approved by the University Institutional Review Board and a brief medical history questionnaire evaluated by a Certified Athletic Trainer (ATC). Only participants placed in the low risk group according to American College of Sports Medicine (ACSM) Risk Stratification Categories were included [12]. Participants wore their own non-standardized personal running shoes [13]. Skinfold measurements for body composition were obtained in duplicate by the same researcher with Lange calipers (Cambridge Scientific Industries, Inc., Cambridge, MD) [14].

The data collection procedure involved: 1) biomechanical gait collection at rested state, 2) fatigue inducing exhaustive protocol, 3) biomechanical gait collection at fatigued state. Prior to biomechanical analysis, participants completed a self-directed warm-up and familiarization on the 18-m runway to ensure consistent running velocity ($4.0 m \cdot s^{-1} \pm 10\%$). Speedtrap II (Brower Timing Systems, Draper, UT) infrared sensors were placed four meters apart on the middle third of the runway to collect velocity. Kinematic data were collected using a modified Vicon Plug-in-Gait model utilizing 27 retroreflective markers fixed to the LE and thorax skin (Fig. 1). A static calibration trial to determine joint centers was obtained utilizing medial anatomical markers [15]. A three-dimensional motion capture system including thirteen cameras and Vicon Nexus Software (Vicon, Inc., Centennial, CO) were used to capture, reduce, and analyze kinematic data (240 Hz). Kinetic data (960 Hz) were recorded using an AMTI force platform (Advanced Medical Technology Incorporated, Boston, MA) embedded flush within the runway and time synchronized with kinematics. Joint moments were calculated using inverse dynamics and reported as external moments. Data were processed using a fourth order, low-pass Butterworth filter with a 10 Hz cutoff. Three successful trials per limb were recorded from nonconsecutive steps [16]. During the rested state, participants were allowed to walk back to the start position following each trial. Differentiated Ratings of Perceived Exertion (RPE) from Borg's scale were collected prior to, at midpoint, and at completion of trials [17].

Table 1
Descriptive statistics of participant demographics.

	Mean ± SD
Age (years)	20.80 ± 2.48
Height (m)	1.74 ± 0.99
Body Mass (kg)	70.68 ± 11.10
Body Fat (%)	13.54 ± 8.94
VO_2max ($mL\,kg^{-1}\,min^{-1}$)	47.74 ± 8.67

Following rested state, participants underwent a speed blinded exhaustive protocol on a Quinton Medtrack T65 Treadmill (Cardiac Science, Corp. Bothell, WA) to elicit fatigue. Metabolic data were collected using a metabolic cart containing an Oxygen Analyzer and Carbon Dioxide Analyzer (AEI Technologies, Naperville, IL) via open circuit indirect calorimetry. Head support and mouthpiece with a two-way non-rebreather valve (Hans Rudolph, Kansas City, MO) were individualized and connected to the metabolic cart.

The exhaustive protocol began with completion of the Modified Åstrand Protocol Graded Exercise Test (GXT) to determine VO_{2max} [17]. The GXT was terminated at the point of volitional exhaustion and VO_{2max} was confirmed based upon meeting one of the following criteria: respiratory exchange ratio greater than 1.15, $RPE \geq 17$, or plateau in maximal oxygen output with increased work rate [17]. Participants were then given a three-minute, self-selected pace walking recovery at 1% grade with the breathing apparatus removed. The breathing apparatus was then refitted and treadmill speed was increased to a speed predicted to elicit 80% VO_{2max} at 1% grade as determined by the ACSM equations for estimating oxygen consumption [17]. Metabolic data were collected and speed adjustments were made, if needed, to elicit the prescribed oxygen consumption ($80 \pm 5\%$ VO_{2max}). The breathing apparatus was then removed. Participants continued running while the grade increased 2.5% every three minutes until volitional exhaustion. Differentiated RPE measures [17] were collected following the completion of the GXT, prior to the start of the exhaustive run, and following the exhaustive run.

Onset of fatigued state trials (gait) began as soon as possible following completion of the exhaustive protocol. Retro-reflective makers were replaced as needed and a new static calibration trial was taken. Fatigued state trials and RPE ratings were repeated using the same procedure as rested state trials, with the addition of participants running continuously between trials.

2.1. Statistical analysis

Data were analyzed using SPSS 21.0 with an a priori alpha level set at $p \leq 0.05$. Discrete variables for each trial were obtained and trial means were used for analysis. Two-way, repeated measures ANOVA (Limb & Condition) assessed asymmetry and the effects of fatigue. Paired *t*-tests assessed differences in biomechanical variables between legs at rested state and fatigued stated [4]. Rested and fatigued state symmetry angles (SA) were calculated to quantify asymmetry magnitude according the methods of Zifchock