Gender Differences in the Variability of Lower Extremity Kinematics During Treadmill Locomotion

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ABSTRACT. The authors examined whether there were gender differences in the variability of basic gait parameters (stride length, stride time) and 3-dimensional (3D) rotations of the hip, knee, and ankle joints during treadmill locomotion of 18 men and 15 women at 4 different gait speeds (walking at 5 km/hr, running at 8, 10, and 12 km/hr). The authors used 2-way analyses of variance to assess the data. No gender differences in the mean values or variability of basic gait parameters were detected. However, the women exhibited lower variability than did the men for 6 individual joint rotations: (a) transverse plane rotations of the ankle joint at 8, 10, and 12 km/hr, (b) transverse plane rotations of the hip and knee joints at 12 km/hr, and (c) sagittal plane rotations of the ankle joint at 12 km/hr. When collapsed across all 3D lower extremity rotations, the data showed that the women had lower variability than did the men at 12 km/hr. Reduced variability may result in more localized mechanical stress on anatomical structures and could therefore be a risk factor for injury in women at high gait speeds. The results also suggested that gender differences in variability may not be consistent across different levels of the motor system.

Keywords: gender, kinematics, running, variability

Researchers have widely used measures of motion variability to gain insight into the control of movement. Their general view is that motion variability within limits is a normal and functional characteristic of the neuromotor system that affords it greater flexibility and increases its ability to adapt to the demands of the task being performed, to changes in the environment, or to both (Bassingthwaighte, Liebovitch, & West, 1994; Holt, Jeng, Ratcliffe, & Hamill, 1995; Neuringer, 2004; Neuringer, Kornell, & Olufs, 2001; Newell, Vaillancourt, & Sosnoff, 2006; Yates, 1987). Conversely, excessively high or low motion variability may indicate a degree of system dysfunction (Vaillancourt & Newell, 2002). Even for such highly stereotypical and repeatable actions such as gait, differences in the vari-

ability of various walking measures have provided insights into the control mechanisms underlying walking and have enabled researchers to discriminate between different participant groups on the basis of neurological disorders, the normal aging process, or both (Hausdorff, Ashkenazy, et al., 2001; Hausdorff, Rios, & Edelberg, 2001; Heiderscheit, 2000). For example, Hausdorff, Cudkowicz, Firtion, Wei, and Goldberger (1998) and Hausdorff et al. (1997) reported that healthy elderly individuals, Parkinson's disease patients, and individuals with Huntington's disease display increased variability in stride-to-stride fluctuations in comparison with those of young individuals. This gait feature may be associated with increased risk of falls (Hausdorff, Rios, et al., 2001). Other researchers have reported a loss of movement variability in joint-coupling measures for individuals with unilateral patellofemoral pain during cutting maneuvers (Hamill, van Emmerik, Heiderscheit, & Li, 1999). Hamill et al. speculated that the decreased variability in joint coupling within the painful limb during cutting movements may reflect such individuals' reduced capacity to adapt to the requirements of the task and may increase their risk of injury.

Movement variability is affected by the nature of the task and the level of the system at which researchers assess the motor output (Newell & Slifkin, 1998). Van Emmerik, Wagenaar, Winogrodzka, and Wolters (1999) highlighted the relevance of assessing change at different levels of the neuromotor system. They reported lower variability at the joint level between individuals with Parkinson's disease and

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healthy controls, but not for basic gait parameters. The U-shaped relationship between walking speed and the standard deviation of relative phase for ankle–hip and ankle–knee illustrates the influence of task constraints on movement variability (Diedrich & Warren, 1995). Researchers have also reported higher values for the same measures for running at low speeds than for walking. The graphs decreased and flattened out with increased running speed up to 3.6 m/s. Researchers have also reported U-shaped relationships between gait speed and the strength of long-range correlations (a measure of the structure of variability) in stride intervals and for walking (Hausdorff et al., 1996; Jordan, Challis, & Newell, 2007) and running (Jordan, Challis, & Newell, 2006). The reduced strength in a long-range correlation at preferred gait speeds indicates that the stride interval in any particular stride is less dependent on the stride interval from preceding strides and therefore that preferred walking speed is less constrained and more readily adaptable than are other walking speeds. Nonpreferred gait speeds may therefore produce a biological stress that reduces the dynamical degrees of freedom that are necessary for adaptive control of locomotion (West & Scafetta, 2003).

In most studies of gender differences in gait, investigators have focused on changes in the average (mean) values of various kinematic and kinetic variables. For example, they have found changes in structural measures such as the Q-angle (Horton & Hall, 1989; Woodland & Francis, 1992) and differences between genders in measures of active range of hip motion (Simoneau, Hoenig, Lepley, & Papanek, 1998). In addition, male and female participants of similar ages differed in their lower extremity joint kinematics during walking, landing, and side-step cutting maneuvers (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; Kerrigan, Todd, & Della Croce, 1998; McLean, Neal, Myers, & Walters, 1999; Pollard, Davis, & Hamill, 2004). During running, women reportedly use less knee flexion and have higher knee valgus angles, greater quadriceps activation, and lower hamstrings activation than do men (Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001). Women also have higher peak hip adduction moments, hip internal rotation, and knee abduction than men have (Ferber, Davis, & Williams, 2005).

Because measures of variability provide additional insight into system functioning and organization (Davids, Bennett, & Newell, 2006; Dingwell & Marin, 2006; Hausdorff, Ashkenazy, et al., 2001; Hausdorff, Rios, et al., 2001), researchers' reliance on the assessment of average values to differentiate between populations may mean that they overlook important differences. For example, in the only study of variability in gait-related parameters between genders that we know of, Pollard, Heiderscheit, van Emmerik, and Hamill (2005) reported less variability in lower extremity joint coupling for women during unanticipated side-step cutting maneuvers in response to a visual cue during running. Those authors suggested that lower variability may be an injury risk factor because of greater localized mechanical

stress on anatomical structures, which may contribute in the longer term to degenerative changes from overuse.

Our purpose in the present study was to determine whether there are gender differences in the variability of basic gait parameters and in three-dimensional (3D) hip, knee, and ankle kinematics during treadmill locomotion at a range of gait speeds. We hypothesized that women would exhibit lower variability in 3D motion of the hip, knee, and ankle than would men during running and that those differences would be most evident at the highest running speed.

Method

Participants

Thirty-three volunteers (15 women and 18 men) participated in the study. The age, height, and weight ($M \pm SD$) of the women were 21.6 ± 2.1 years, 169.6 ± 7.5 cm, and 62.9 ± 11.3 kg, respectively. The age, height, and weight of the men were 24.6 ± 6.4 years, 180.2 ± 8.5 cm, and 75.5 ± 11.1 kg, respectively. Participants were not trained runners but were physically active, had normal vision, and were free from any neurological or musculoskeletal conditions that may have affected their gait on the day of testing. The Griffith University Human Research Ethics Committee approved the experiment, and all participants provided written informed consent before participating.

Data Collection Procedures

Each participant attended the laboratory once. After a period of familiarization with treadmill locomotion, we fitted participants with electromagnetic sensors. Then they performed static and dynamic calibration trials and completed treadmill locomotion trials for walking and running.

We conducted all testing on a 4,200-mm-long and 1,600-mm-wide custom wooden-framed motorized treadmill (Payne Engineering, Sydney, Australia). We made kinematic measurements with an eight-channel Polhemus (Colchester, VT) Liberty electromagnetic tracking system (ETS). The Polhemus system reportedly has a static accuracy of 0.762 mm along each sensor axis and 0.15° root mean square for sensor orientation, with a reported resolution of 0.038 mm for position and 0.0012° for orientation. We sampled data at 240 Hz per sensor by using AIM-3D Version 1.4 software (Advanced Motion Measurement, Phoenix, AZ). The ETS transmitter was approximately 600 mm above the right edge of the treadmill belt. We firmly secured six-degrees-of-freedom electromagnetic sensors to the pelvis, right and left thighs, shank, and foot with purpose-made mounting straps. We took particular care to attach the sensors as rigidly as possible to the underlying segments. We used an additional calibration sensor embedded in an acrylic pointer to identify the location of anatomical landmarks (ALs) during static trials. We obtained the locations of 28 ALs by sequentially placing the tip of the pointer on each AL during separate static trials in which the participant was standing. We subsequently used that information to compute the static transformation matrixes for determining the location

of each AL in the technical coordinate system of the underlying segment. After the static calibration trials, participants also performed dynamic calibration trials. Those trials enabled us to determine the functional hip joint center. In the dynamic trials, participants rotated the hip joint at least three times through the largest range possible about all three primary axes. To define neutral angles, we also collected a trial while the participant stood in anatomical position.

After the calibration trials, each participant completed approximately 3 min of treadmill locomotion at a walking speed of 5.5 km/hr and at running speeds of 8, 10, and 12 km/hr. During that period, we recorded 30 s of gait data. We randomized the order in which we presented the gait speeds to minimize fatigue and learning effects. All participants wore running shorts and their own running shoes. We checked their shoes before testing to ensure that they were in good condition and provided adequate support.

Data Analysis Procedures

We analyzed all data with custom Matlab software (MathWorks, Natick, MA). Mills, Morrison, Lloyd, and Barrett (2007) provide a full mathematical description of the steps one should follow to compute the location of ALs in the global coordinate system, and we therefore describe them in this article only briefly. We first defined each AL within its respective segment technical coordinate system by using the position and orientation of the pointer and the respective segment sensor from the static calibration

trials. We subsequently computed ALs for the calibration and gait trials in the global coordinate system by using the aforementioned static transformation matrix and the sensor position and orientation data from the dynamic calibration and gait trials. We estimated the functional hip joint centers (HJCs) for the left and right hip joints by using the method described by Leardini et al. (1999). We defined *leg length* for each participant as the distance between the functional HJC and the midpoint between the lateral and medial malleoli with the participant standing in anatomical position, and we averaged the lengths across the left and right legs.

We computed all 3D angles by using a joint coordinate system (Grood & Suntay, 1983), and we defined segmental coordinate systems in accordance with recommended conventions (Wu et al., 2002). We first expressed motion of the moving frame in the coordinate system of the fixed frame by using a singular value decomposition method (Soderkvist & Wedin, 1993), and we extracted Cardan angles from the resulting rotation matrix by using Matlab functions SODER and CARDAN (Reinschmidt & van den Bogert, 1997). We subtracted from each waveform 3D angles obtained from a static trial in which the participant stood in anatomical position.

We defined *foot-contact events* from the peak vertical acceleration of the heel of each foot (see Figure 1A). We extracted 10 *gait cycles*, defined by right and left foot contact events from each trial, and we temporally normalized them to 101 data points. We computed *gait speed*, which corre-

sponded with treadmill belt speed, from the minimum value of the horizontal velocity of the heel marker during stance (see Figure 1B). We obtained *stride time* from the interval between successive peaks in the peak vertical acceleration of the left and right heels, respectively, and the corresponding *stride length* from the product of gait speed and stride time.

We used the coefficient of variation (*CV*) to quantify the variability of stride time. We quantified the variability of the 3D rotations for the hip, knee, and ankle by using the coefficient of multiple determination (*CMD*). The *CMD* is a waveform similarity statistic ranging between 0 and 1; a *CMD* of 1.0 indicates perfect waveform repeatability (i.e., low variability; Kadaba et al., 1989). The *CMD* is the square of the coefficient of multiple correlation (*CMC*), and it reflects the variance that multiple waveforms share.

Statistical Analysis

We used a mixed general linear model to assess the effects of gender (between factor: man vs. woman) and gait speed (within factor: 5.5, 8, 10, and 12 km/hr) on the depen-

dent measures. We used leg length as a covariate and a priori contrasts to compare means by gender. We expressed effect size as partial eta squared (η_p^2), and we accepted significance at $p < .05$. We performed all statistical analyses with SPSS for Windows Version 13.0.

Results

Leg lengths ($M \pm SD$) were 0.806 ± 0.036 m and 0.803 ± 0.044 m for men and women, respectively. We detected no significant main or interaction effects in any analysis.

In Figure 2, we present interaction plots for the basic gait parameters that were assessed. All *CVs* were below 2%. Gait speed had a significant main effect on actual speed, $F(3, 29) = 170.9$, $\eta_p^2 = .885$, and on stride length, $F(3, 29) = 8.55$, $\eta_p^2 = .228$. We detected no significant gender differences for any of the basic gait parameters that we assessed. However, the gender difference in *CV* at the 10-km/hr running speed condition approached significance, $p = .051$.

Representative 3D joint angles for the hip, knee, and ankle for a woman who was running at the highest speed

(12 km/hr) are displayed in Figure 3. The greatest range of motion and the highest *CMDs* were typically associated with rotations in the sagittal plane.

Interaction plots for the *CMDs* associated with each 3D lower extremity rotation are displayed in Figure 4. We detected a main gender effect for internal–external (IE) ankle rotations in the transverse plane (ankle IE): *CMDs* were significantly greater for women ($.899 \pm .015$) than for men ($.857 \pm .013$), $F(1, 29) = 4.40$, $\eta_p^2 = .132$. We also detected a main speed effect for abduction–adduction (AA) ankle rotations in the frontal plane (ankle AA): *CMDs* increased with increased gait speed, $F(3, 29) = 4.49$, $\eta_p^2 = .134$. A priori contrasts revealed significantly higher *CMDs* for women than for men for hip IE, knee IE, ankle flexion–extension (FE), and ankle IE at 12, 8, and 10 km/hr.

The interaction plot for *CMDs* collapsed across all 3D joint rotations is displayed in Figure 5. A priori contrasts

revealed a significantly higher *CMD* for women than for men at the 12-km/hr speed condition.

Discussion

Researchers have traditionally equated motor variability with system noise and viewed motor variability as a system property that the motor system should minimize for optimal motor performance (Harris & Wolpert, 1998; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). More recent, alternative suggestions are that investigators should consider (a) variability in the human motor system to be highly functional (Bassingthwaite et al., 1994; Davids et al., 2006; Holt et al., 1995; Newell, Deutsch, & Morrison, 2000; Newell & Slifkin, 1998; Yates, 1987) and (b) decreased variability in the system to be a reflection of loss of flexibility and adaptive control (Newell & Slifkin; Newell et al., 2006). Our aim in the current study was to examine whether there are gender differences in measures

that reflect variability in motor output during locomotion. On the basis of previous results that indicated that women exhibit reduced coordination variability in cutting maneuvers in comparison with men (Pollard et al., 2005), we hypothesized that women would exhibit reduced variability of 3D joint rotations during treadmill locomotion. We therefore measured the variability of basic gait parameters (stride length and stride time) and 3D hip, knee, and ankle kinematics during locomotion on a motorized treadmill over consecutive strides in men and women.

In support of our hypothesis, the main finding of this study was that women exhibited lower variability of successive 3D joint rotations than did men at the fastest running speed (12 km/hr). In addition, analysis of gender differ-

ences in individual rotations at each speed indicated that women were less variable than were men for transverse plane rotations of the ankle at all running speeds and for transverse plane rotations of the hip, transverse rotations of the knee, and sagittal rotations of the ankle at the fastest running speed. Therefore, five of the six gender differences in variability that we identified at the level of individual joint rotations were related to the transverse plane. We found no gender differences in variability at the level of individual joint rotations during walking. The differences emerged only when participants ran at higher speeds.

Whereas we detected gender differences in variability at the level of the individual joint rotations, we found no such differences for stride interval. That finding supports

the general view that differences in the variable nature of movement output may not be observed at all levels of the motor system. Our findings at the joint level highlight the view that gender differences are more often reflected by subtle differences at the more micro, local level of interjoint coordination than at a more macro level of whole-body locomotion. Consistent with the work of van Emmerik et al. (1999), our findings indicate that variability of stride characteristics offers a less sensitive measure of differences between groups than does variability of joint characteristics.

The population group that we assessed in this study is a further factor to be considered in light of the absence of gender differences in basic gait parameters. Researchers have typically detected differences in stride-to-stride fluctuations of basic gait parameters between clinical patients and neurologically normal individuals (Hausdorff et al., 1998; Hausdorff et al., 1997). Because the participants in our study were young, healthy men and women who did not exhibit gait abnormalities or instabilities that may be expected in a clinical population, the absence of difference in the variability of basic gait parameters may not be surprising. However, as we outlined previously, the emergence of specific gender-related differences in variability may be of clinical importance, especially with regard to possible increased risk of injury.

Of interest in the present study was our determination of whether the biological stress associated with gait speeds that were higher than normal would influence the variability

of 3D joint rotations. Our finding that gender difference in variability occurred at the highest gait speed suggests that women experience a greater degree of biological stress at those speeds than do men and that the increased stress may reflect a reduction in dynamical degrees of freedom that they use for adaptive control of locomotion (Jordan et al., 2006). Although we did not directly assess that problem in the present study, such a reduction in adaptive control may cause women to be less able to adjust to perturbations when running at high speeds. As Pollard et al. (2005) suggested, women's inability to adjust may partially explain the higher incidence of noncontact anterior cruciate ligament injuries (i.e., injuries that typically occur when an athlete changes speed or direction while running or jumping) in women than in men.

Researchers have also suggested that reduced variability in cyclic activities such as running places individuals at greater risk of overuse injuries because mechanical stress acting on anatomical structures such as ligaments, tendons, and cartilage becomes more localized (Hamill et al., 1999). When running at higher speeds, women may therefore experience a greater concentration of stress. The higher levels of stress may be a risk factor for overuse injuries such as iliotibial-band friction syndrome, patellofemoral pain, and anterior-tibial stress syndrome, all of which researchers have reported as occurring more commonly in women (Taunton et al., 2002).

We conducted the present study with a motorized treadmill, so we were able to continuously measure gait parameters and 3D joint rotations during locomotion over multiple strides with an ETS. However, kinematic variability is lower in treadmill locomotion than in over-ground locomotion (Dingwell, Cusumano, Cavanagh, & Sternad, 2001). We therefore do not know how the results of the present study generalize to overground locomotion, although we would expect similar results. Furthermore, we do not know whether the gender differences in variability that we identified in the present study at the same absolute locomotion velocities would be found if researchers matched locomotion velocity according to other criteria likely to differ between genders, such as preferred locomotion velocity, velocity at minimum energy consumption, and velocity normalized to body dimensions. Despite those limitations, the results of the present study provide new evidence for gender differences in variability of 3D rotations during treadmill locomotion. In particular, the findings extend the results of Pollard et al. (2005), who reported reduced variability in women's joint coupling as compared with men's. Our results indicate that women display reduced variability in joint rotations during regular straight-line running at high speed. Researchers must conduct further studies to determine whether there are gender differences in the variability of kinetic variables such as joint reaction forces and moments and, if so, their possible relationship with injury.

Biographical Notes

Rod Barrett teaches biomechanics. Gait analysis and musculoskeletal modeling are some of his research interests.

Maarten Vonk Noordegraaf teaches physical education; his research interest is the biomechanics of running.

Steven Morrison teaches neuroscience and conducts research on bimanual coordination, physiological tremor, and postural sway.

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