SEX DIFFERENCES IN LOWER LIMB MOVEMENT VARIABILITY DURING A FATIGUING REPETITIVE LOADING TASK

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This study evaluated differences in lower limb joint coupling variability between recreationally-active male (n = 21) and female participants (n = 20) during single-leg hopping to exhaustion. Spatio-temporal characteristics and variability of the knee-ankle and hip-knee joint couplings were determined over the duration of hopping. As fatigue progressed joint coupling variability increased by a greater magnitude in females compared to males. Females had significantly lower variability compared to males in the knee-ankle couplings during the propulsion phase at the beginning of the trial but this effect progressively disappeared during the trial. These findings suggest that as fatigue progresses, there is a regression to a similar magnitude of joint coupling variability which may represent a common level of synchronous joint interaction between sexes.

KEY WORDS: fatigue, joint coupling variability, motor control, hopping, stretch-shorten cycle.

INTRODUCTION: Variability within human movement is considered a normal and functional feature of the neuromuscular system (Preatoni et al., 2013). It is suggested that there is an optimal range of variability that permits flexibility to changes in intrinsic or extrinsic factors. Conversely, extreme levels of variability, i.e. too much or too little, may be associated with pathology (Hamill, van Emmerik, Heiderscheit, & Li, 1999; Preatoni et al., 2013).

Interestingly, woman have demonstrated lower levels of movement variability than men during a side cut manoeuvrer (Pollard, Heiderscheit, Van Emmerik, & Hamill, 2005) and treadmill running task (Barrett, Noordegraaf, & Morrison, 2008). It was suggested that the lower variability in woman may limit their ability to adapt to changes in task demands. Further, low levels of variability may expose the musculoskeletal system to repetitive loads. This may be problematic during fatiguing repetitive rapid loading tasks (Hamill et al., 1999).

Previous research has shown that fatigue increases movement variability during repetitive loading tasks (Dal Pupo, Dias, Gheller, Detanico, & Santos, 2013; Ferber & Pohl, 2011; Mudie, Gupta, & Clothier, 2015). However, these studies only investigated males (Dal Pupo et al., 2013) or pooled males and females together (Ferber & Pohl, 2011; Mudie et al., 2015). Thus, it is not clear if the effect of fatigue on movement variability during a repetitive loading task differs between males and females. Therefore, the purpose of this study was to test the effect of sex on lower limb movement variability during a fatiguing repetitive loading task.

METHODS: Forty-one healthy recreationally active male (n = 21; 23 ± 3 years of age; 1.8 ± 0.1 m height; 76.4 ± 7.6 kg mass) and female (n = 20; 22 ± 3 years of age; 1.7 ± 0.1 m height; 61.3 ± 7.7 kg mass) participants completed a single-leg hopping trial to volitional exhaustion. Warm-up and familiarisation trials were completed barefoot and on the participant's dominant leg. Twenty-nine active and fifteen calibration markers were used to model the trunk, pelvis, thigh, shank, hindfoot, forefoot and hallux of the hopping leg (Mudie et al., 2015). To control task performance (hopping frequency and height), an audible metronome was set at 2.2 Hz and tactile feedback set to each individuals target hop height. Target hop height was determined from a 15 s single-leg hopping trial at 2.2 Hz and calculated by a segmental analysis method. Participants then completed one single-leg hopping trial to volitional exhaustion, at 2.2 Hz to the pre-determined target hop height. Volitional exhaustion was defined as the point when the participant could no longer maintain the required performance outcomes of hopping frequency and target hopping height. Kinetic (AMTI, Gen 5, USA) and kinematic data (NDI, Optotrak, Canada) were recorded synchronously at 1500 Hz and 150 Hz (First Principles software, Version 1.2.4) respectively, and processed using Visual 3D (C-Motion, Version 4, USA).

Missing marker data were interpolated using spline interpolation for up to a maximum gap of 10 frames. Kinetic and kinematic data were filtered with a fourth order dual-pass Butterworth filter with a 50 Hz cut-off and a fourth order dual-pass Butterworth filter with an 8 Hz cut-off, respectively. A single hop cycle was defined as a complete flight phase and subsequent contact phase. The contact phase included a loading (initial contact to peak vertical ground reaction force) and propulsive (peak vertical ground reaction force to toe off) phase. Dependant variables for each hop cycle included hopping frequency, vertical displacement of the centre of mass (COM) during flight (z_f), vertical stiffness (K) and joint coupling variability. Vertical stiffness was calculated as the quotient of normalised force and COM displacement during the loading phase. Joint coupling variability was calculated for the knee flexion/extension-ankle flexion/extension (KxAx), hip flexion/extension-knee flexion/extension (HxKx) and knee flexion/extension-ankle eversion/inversion (KxAy) couplings during the loading and propulsive phases. Joint angle data were normalised to 101 data points over the loading and propulsive phases and coupling angles calculated as the orientation of the resultant vector to the right horizontal between two adjacent data points (Pollard et al., 2005) (Equation 1).

$$\Theta_i = abs\ [\tan^{-1} (y_{i+1} - y_i / x_{i+1} - x_i)] \qquad (1)$$

where i = data point 1, 2 and n of the time series. Calculated values were converted from radians to degrees and the standard deviation (SD) of the coupling angle across 10 consecutive hop cycles was calculated on a point-by-point basis for the loading and propulsive phases, providing a measure of between-cycle, within-participant variability (Pollard et al., 2005). Each dependant variable was calculated as the mean of 10 consecutive hop cycles at time periods of 0, 20, 40, 60, 80 at 100% of the trial. A 6 (time period) x 2 (sex) repeated measure ANOVA was used to determine between sex differences over time for all dependant variables. If there was a significant interaction or main effect, post-hoc one-way ANOVA (time period) and independent samples *t*-tests (sex) were performed. Alpha levels were set *a priori* with significance accepted at $p < 0.05$. *Cohen's d* effect sizes were calculated and thresholds of 0.2 = small, 0.5 = moderate and 0.8 = large were used to qualitatively describe effect sizes.

RESULTS: Total hopping duration was (mean ± SD) 79 ± 30 s for males and 78 ± 22 s for females ($p = 0.949$, $d = 0.056$). There were no significant effects of sex on performance output characteristics, including hopping frequency ($p = 0.843$), z_f ($p = 0.355$) and K ($p = 0.715$). However, there was a significant decrease in K for females only from the 0% time period to the 80% ($p = 0.029$, $d = -0.628$) and 100% ($p = 0.010$, $d = -0.588$) time periods.

During loading, there was a significant increase in KxAx for males from the 0% time period to the 80% ($p = 0.025$, $d = 1.026$) and 100% ($p = 0.007$, $d = 1.531$) time periods and females from the 0% time period to the 100% ($p = 0.002$, $d = 1.420$) time period (Figure 1). There was a significant increase in HxKx for males and females from the 0% time period to the 60% ($p = 0.002$, $d = 1.219$; $p = 0.003$, $d = 1.126$), 80% ($p = 0.001$, $d = 2.176$; $p < 0.001$, $d = 1.571$) and 100% ($p < 0.001$, $d = 2.946$; $p < 0.001$, $d = 2.962$) time periods and KxAy from the 0% time period to the 100% ($p = 0.013$, $d = 1.424$; $p = 0.001$, $d = 1.906$) time period (Figure 1). In contrast, there was no significant difference between males and females for KxAx ($p = 0.063$), HxKx ($p = 0.545$) and KxAy ($p = 0.133$) (Figure 1). However, females tended to have lower variability than males with a moderate effect size in KxAx at the 80% ($d = 0.605$) time period and in KxAy at the 0% ($d = 0.621$) time period (Figure 1).

During propulsion, there was a significant increase in KxAx for females only from the 0% time period to the 100% ($p = 0.017$, $d = 0.971$) time period (Figure 2). There was a significant increase in HxKx for females from the 0% time period to the 80% ($p = 0.007$, $d = 1.059$) and 100% ($p < 0.001$, $d = 1.838$) time periods and males from the 0% time period to the 100% ($p = 0.028$, $d = 1.292$) time period (Figure 2). Females were significantly lower than males in KxAx at the 40% (*p* = 0.033, *d* = 0.591) and 60% (*p* = 0.043, *d* = 0.668) time periods and in KxAy at the 20% (*p* = 0.038, *d* = 0.703) time period (Figure 2). Females tended to have lower variability than males with a moderate effect size in KxAx at the 0% (*p* = 0.068, *d* = 0.640) and 20% (*p* = 0.064, *d* = 0.626) time periods and in KxAy at the 0% (*p* = 0.071, *d* = 0.628) time period (Figure 2).

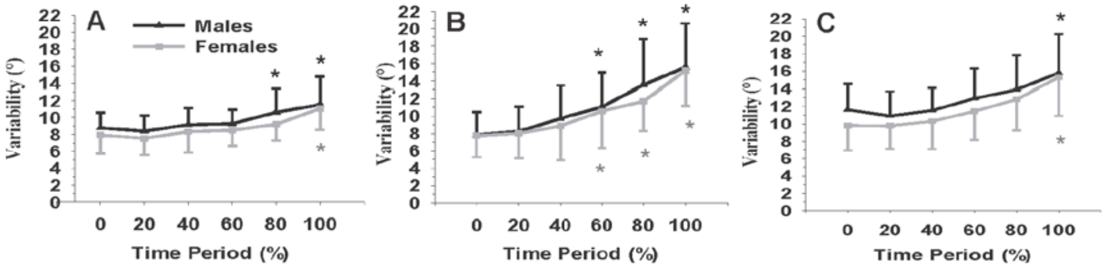

Figure 1: Mean (SD) joint coupling variability (°) during loading for males (black) and females (grey) at each time period. A) Knee flexion/extension–ankle flexion/extension (KxAx); B) hip flexion/extension–knee flexion/extension (HxKx); and C) knee flexion/extension–ankle abduction/adduction (KxAy). * = $p < 0.05$ compared to 0% time period for males (black) and females (grey).

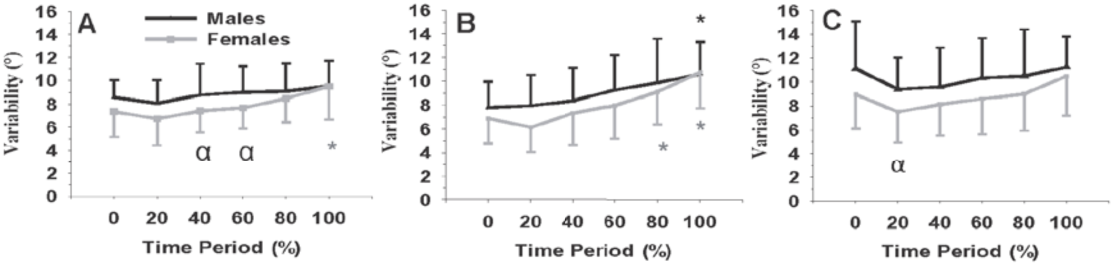

Figure 2: Mean (SD) joint coupling variability (°) during propulsion for males (black) and females (grey) at each time period. A) Knee flexion/extension–ankle flexion/extension (KxAx); B) hip flexion/extension–knee flexion/extension (HxKx); and C) knee flexion/extension–ankle abduction/adduction (KxAy). * = $p < 0.05$ compared to 0% time period for males (black) and females (grey). α = $p < 0.05$ between males and females at the specific time period.

DISCUSSION: This study demonstrated males and females increased joint coupling variability as fatigue progressed during a repetitive loading task. Further, females had lower coupling variability compared to males during the first half of the task. As participants approached exhaustion the difference between the sexes gradually decreased as females increased joint coupling variability by a greater magnitude than males. This suggests that during the continued performance of a repetitive loading task, males and females regress to similar patterns of joint coupling variability.

These results are in agreement with previous studies (Barrett et al., 2008; Pollard et al., 2005) demonstrating females to have lower variability than males during a non-fatigued side cut and running task. A key extension of previous research was that the current task was performed to exhaustion. Further, there were no differences in performance output characteristics between the sexes over the duration of the trial. Although performance output was similar between sexes during the trial, as fatigue progressed females increased their joint coupling variability by a greater magnitude than the males. Resulting in the sexes regressing to similar levels of joint coupling variability as fatigue progressed. Previous research has suggested that lower joint coupling variability may lead to a more localised loading of lower limb musculature (Hamill et al., 1999; Heiderscheit, Hamill, & van Emmerik, 2002). The finding that females had lower joint coupling variability during the first half of the trial may potentially risk females to a greater exposure of a number of cycles with similar loading to tissues within the kinetic chain compared to males. If low coupling variability is considered detrimental to the musculoskeletal system, it is possible females may aim to adapt variability levels to a more 'optimal' range as the task progresses. Therefore, although females may inherently possess lower coupling variability than males, they have the capacity to achieve similar values under particular conditions.

Significant differences between the sexes in joint coupling variability were only shown during the propulsive phase and were smaller in magnitude compared to previous research which had evaluated a side-cut task (Pollard et al., 2005). It is possible both the lower magnitude of difference between sexes and lower absolute values of joint coupling variability in this study compared to Pollard et al., (2005), may be due to being task specific. A single-leg hopping task to a consistent target height and frequency is a highly controlled task compared to other tasks that have been used. On-the-spot single-leg hopping has less available degrees of freedom than other more complex tasks such as running or a side-cut, potentially limiting the amount of variability available at a joint level. The current results demonstrate only subtle differences in joint coupling variability between the sexes during a simple, controlled repetitive task performed to exhaustion. Therefore, differences in variability between men and woman may be relative to the type of task and it is plausible that during a more complex task or within an unpredictable environment, there may be greater differences in variability between the sexes.

CONCLUSION: Although females have lower joint coupling variability than males at the start of a repetitive loading task, as fatigue progresses females increase joint coupling variability by a greater magnitude than males. This results in the sexes regressing to similar levels of joint coupling variability during a fatiguing repetitive loading task. Therefore, although females may inherently possess lower joint coupling variability than males, the capacity to achieve similar values to males under particular conditions has been demonstrated.

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