

# THE EFFECT OF FATIGUE ON LOWER LIMB MOTOR VARIABILITY DURING A CONTROLLED REPETITIVE STRETCH-SHORTEN CYCLE TASK

Kurt L. Mudie, Amitabh Gupta and Peter J. Clothier

School of Science and Health, University of Western Sydney,  
Sydney, NSW, Australia

This study evaluated changes in lower limb joint coupling variability during single-leg hopping to exhaustion. Twenty recreationally active male and female participants performed single-leg hopping at 2.2 Hz to a target height. At 0, 20, 40, 60, 80 and 100% of the total duration of hopping, spatio-temporal characteristics and variability of the knee-ankle (KA) and hip-knee (HK) joint couplings were determined. There was a significant increase in variability of the KA and HK joint couplings in the flexion-extension axes during the loading and propulsion phases as hopping progressed. However, there was maintenance of performance output characteristics throughout the task. These findings suggest that changes in joint coupling variability may be a compensatory strategy to allow continuous single-leg hopping as the effects of muscular fatigue increase.

**KEY WORDS:** fatigue, joint coupling variability, motor control.

**INTRODUCTION:** Motor variability is inherent within human movement and may serve to optimise performance output and allow adaptation to changes in intrinsic and extrinsic factors such as fatigue or the environment (Hamill, Palmer, & van Emmerik, 2012; Preatoni et al., 2013). Whether there is an “optimal” range of motor variability during repetitive tasks remains unknown. However, it has been suggested that large decreases in motor variability may lead to a rigid system while an increase in variability could yield an unstable system (Hamill et al., 2012; Preatoni et al., 2013). This may suggest that small increases in motor variability are an example of the normal modulation of movement strategies based on alterations to intrinsic and extrinsic factors, rather than a marker of maladaptation that may increase the risk of injury (Hamill et al., 2012).

Fatigue is often induced during repetitive tasks, specifically during sporting and athletic activities. It has been demonstrated that fatigue during repetitive lower limb tasks leads to compensatory changes in ankle and knee function (Komi, 2000). These compensatory strategies may lead to subsequent alterations in multi-segment coordination and motor variability. However, the results from a number of studies investigating motor variability during fatiguing repetitive tasks have been conflicting. During a continuous run to exhaustion coordinative variability was shown to remain unchanged (Miller, Meardon, Derrick, & Gillette, 2008), whilst during treadmill walking fatigue of the tibialis posterior muscle (Ferber & Pohl, 2011) and the performance of a repetitive maximal vertical jump test (Pupo, Dias, Gheller, Detanico, & Santos, 2013) led to an increase in coordinative variability. The effect of fatigue on variability may be confounded by changes in the performance output of the task. Further, due to coordinative variability only being measured before and after the fatiguing protocol (Ferber & Pohl, 2011; Pupo et al., 2013) and at the start, middle and end of the continuous task (Miller et al., 2008), task learning and subsequent change in motor patterning throughout the trial could confound the effect of fatigue. Thus, it is not clear whether lower limb coordinative variability is sensitive to increases in fatigue during a repetitive task when performance output is controlled. Therefore, the purpose of this study was to examine the effect of fatigue on lower limb joint coupling variability (JCV) during repetitive lower limb loading when performance output remained unchanged.

**METHODS:** Twenty healthy recreationally active male and female participants completed a single-leg hopping trial to volitional exhaustion. Kinetic (AMTI, Gen 5, USA) and kinematic data (NDI, Optotrak, Canada) were collected synchronously at 1500 Hz and 150 Hz (First Principles software, Version 1.2.4), respectively. All trials were performed barefoot and on

the participant's self-selected dominant leg. Consistent with previous research, a seven-segment model was used to model the trunk (G. Wu et al., 2005), pelvis, thigh, shank (Ball, 2011), hindfoot, forefoot (W. L. Wu et al., 2000) and hallux of the hopping leg. Following a warm-up and familiarisation trials, participants then completed a 15 s single-leg hopping trial from which each individual's target hop height was calculated from the sacral marker cluster. To control each individual's hop height, tactile feedback was provided via a custom built apparatus and set to the participants target hop height. Participants then completed one experimental trial to volitional exhaustion of on-the-spot, single-leg hopping at 2.2 Hz using an audible digital metronome and aiming to hop 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 cadence and target hopping height. Kinetic data were dual-pass filtered with a low pass Butterworth filter and 50 Hz cut-off. Kinematic data were interpolated using spline interpolation for up to a maximum gap of 10 frames and dual-pass filtered using a fourth order Butterworth filter with an 8 Hz cut-off (Visual 3D, Version 4). Derived variables included hopping frequency, vertical displacement of the centre of mass (COM) during flight ( $z_f$ ) and loading phases ( $z_l$ ) and JCV. 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 loading and propulsive phases. Joint angle data were normalised to 101 data points over 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, Heiderscheit, Van Emmerik, & Hamill, 2005). Calculated values were converted from radians to degrees and the standard deviation (SD) of the coupling angles across 10 hop cycles 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). All derived variables were calculated as the mean of 10 consecutive hop cycles at time periods of 0, 20, 40, 60, 80 and 100% of the duration of each trial. A repeated measure ANOVA was used to determine differences and trends over time for all dependant variables. Post-hoc pairwise comparisons were made to further explore differences between each of the six hopping periods. Alpha levels were set *a priori* with significance accepted at  $p < 0.05$ .

**RESULTS:** Total hopping duration was (mean  $\pm$  SD)  $75 \pm 34$  s. There was no significant main effect detected between hopping frequency,  $z_f$  or  $z_l$  across the duration of the trial. There was a significant increase in KxAx, HxKx and KxAy during loading over time ( $p < 0.001$ ) with a significant increasing linear trend ( $p < 0.001$ ). Post hoc pairwise comparisons determined that KxAx and HxKx during loading were greater at 40 ( $p = 0.015$ ;  $p = 0.002$ ), 60 ( $p = 0.014$ ;  $p = 0.001$ ), 80 ( $p = 0.005$ ;  $p = 0.001$ ) and 100% ( $p = 0.001$ ;  $p = 0.001$ ) compared to the start of the trial (Figure 1). Post hoc pairwise comparisons for KxAy during loading revealed the 80 and 100% time periods were significantly greater than 0% ( $p = 0.015$ ;  $p = 0.001$ ) whilst 60% was only borderline significantly greater ( $p = 0.042$ ) (Figure 1). There was a significant increase in KxAx and HxKx during propulsion over time ( $p < 0.001$ ) with a significant increasing linear trend ( $p < 0.001$ ). Post hoc comparisons only revealed KxAx to significantly increase from 0 to 100% ( $p = 0.004$ ) and HxKx to significantly increase from 0 to 60 ( $p = 0.036$ ), 80 ( $p = 0.037$ ) and 100% ( $p = 0.002$ ) during propulsion (Figure 2).

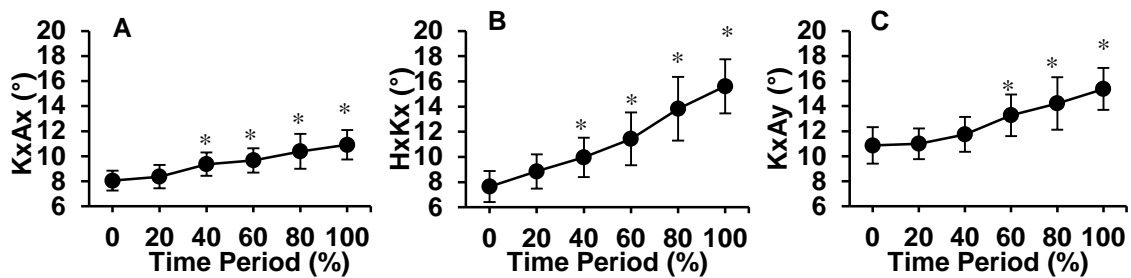


Figure 1: Mean (2SE) joint coupling variability (degrees) during loading at each time point for A) knee flexion/extension – ankle flexion/extension (KxAx); B) hip flexion/extension – knee flexion/extension (HxKx); and C) knee flexion/extension – ankle abduction/adduction (KxAy). \* indicates  $p < 0.05$  compared to 0% time period.

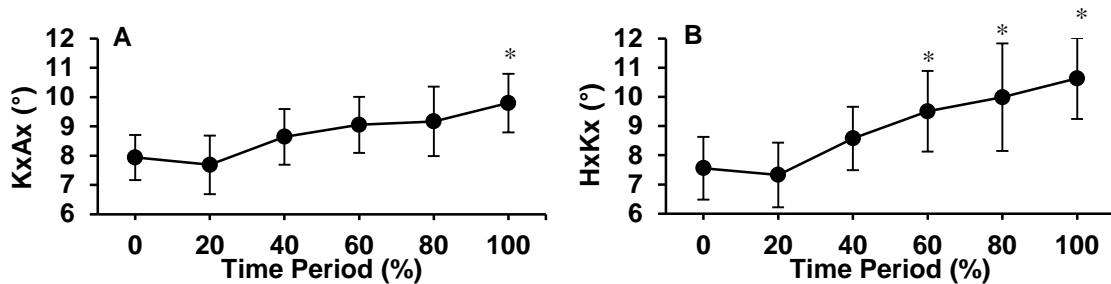


Figure 2: Mean (2SE) joint coupling variability (degrees) during propulsion at each time point for A) knee flexion/extension – ankle flexion/extension (KxAx); and B) hip flexion/extension – knee flexion/extension (HxKx). \* indicates  $p < 0.05$  compared to 0% time period.

**DISCUSSION:** This study demonstrated that there was greater JCV during both loading and propulsion phases as participants approached fatigue while motor performance remained unchanged. This finding supports previous research (Hamill et al., 2012; Preatoni et al., 2013) and suggests that motor variability is not detrimental to motor performance and in fact may allow the continuation of a repetitive submaximal task until volitional exhaustion. Increased JCV did not impact the performance with maintenance of spatiotemporal characteristics of the COM and may be appropriate and expected as a strategy to counter the effects of muscular or physiological fatigue (Pupo et al., 2013; Singh, Varadhan, Zatsiorsky, & Latash, 2010). The preservation of performance output as fatigue increased may be due to co-variance between KxAx and HxKx during the loading and propulsion phases, demonstrated by a similar linear increase in the variability of both couplings. Co-variance between fatigued and less fatigued segments has been demonstrated in other repetitive tasks when the performance output was maintained such as with finger tapping (Singh et al., 2010), postural sway (Singh & Latash, 2011) and walking (Ferber & Pohl, 2011). However, these adaptive patterns had previously not been shown during a fatiguing and rapid loading task when performance outcomes were maintained. Co-variance has been suggested to be a mechanism to preserve the performance output of the fatiguing task by controlling the variability into a region of “good variance” (Singh et al., 2010). For example, if the variability of only the distal coupling was to increase without a subsequent increase in the variability of the proximal coupling the performance output of the task may be affected. Therefore, to maintain the performance output of the task the less fatigued coupling co-varied with the fatigued coupling resulting in minimal impact on performance output. Increased JCV may act as a preventative mechanism to minimise the risk of injury due to repetitive loading. Previous research has revealed greater lower limb variability in healthy compared to injured individuals (Hamill, van Emmerik, Heiderscheit, & Li, 1999; Heiderscheit, Hamill, & van Emmerik, 2002). They proposed that greater coordinative variability permitted healthy individuals numerous intra-segment motor patterns that may be used to successfully complete the continuous task. Therefore, increases in lower limb JCV during a fatiguing and repetitive task which does not affect the performance may allow the magnitude of forces to be attenuated between the coordinated limb segments.

**CONCLUSION:** Motor variability and co-variation at a kinematic level may be an essential strategy utilised by healthy individuals to prolong the detrimental effects of fatigue that can affect performance during a repetitive task (Singh et al., 2010). Further, increasing JCV may be a strategy used by healthy individuals to allow external forces to be distributed over numerous tissues, rather than repeatedly loading the same tissues. Therefore, increases in lower limb motor variability during a repetitive and rapid loading task which utilises the stretch-shorten cycle may serve to potentially lower the risk of lower limb overuse injuries as fatigue levels increase (Hamill et al., 2012; Singh & Latash, 2011).

## REFERENCES:

- Ball, K. A. (2011). Kinematic comparison of the preferred and non-preferred foot punt kick. *Journal of Sports Sciences, 29*(14), 1545-1552.
- Ferber, R., & Pohl, M. B. (2011). Changes in joint coupling and variability during walking following tibialis posterior muscle fatigue. *Journal of Foot and Ankle Research, 4*(6), 1-8.
- Hamill, J., Palmer, C., & van Emmerik, R. E. A. (2012). Coordinative variability and overuse injury. *BMC Sports Science, Medicine and Rehabilitation, 4*(1), 45.
- Hamill, J., van Emmerik, R. E. A., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*(5), 297-308.
- Heiderscheit, B. C., Hamill, J., & van Emmerik, R. E. A. (2002). Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of Applied Biomechanics, 18*(2), 110-121.
- Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. *Journal of Biomechanics, 33*, 1197-1206.
- Miller, R. H., Meardon, S. A., Derrick, T. R., & Gillette, J. C. (2008). Continuous relative phase variability during an exhaustive run in runners with a history of iliotibial band syndrome. *Journal of Applied Biomechanics, 24*(3), 262-270.
- Pollard, C. D., Heiderscheit, B. C., Van Emmerik, R. E. A., & Hamill, J. (2005). Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. *Journal of Applied Biomechanics, 21*(2), 143-152.
- Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E. A., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics, 12*(2), 69-92.
- Pupo, J. D., Dias, J. A., Gheller, R. G., Detanico, D., & Santos, S. G. D. (2013). Stiffness, intralimb coordination, and joint modulation during a continuous vertical jump test. *Sports Biomechanics, 12*(3), 259-271.
- Singh, T., & Latash, M. L. (2011). Effects of muscle fatigue on multi-muscle synergies. *Experimental Brain Research, 214*(3), 335-350.
- Singh, T., Varadhan, S. K. M., Zatsiorsky, V. M., & Latash, M. L. (2010). Fatigue and motor redundancy: Adaptive increase in finger force variance in multi-finger tasks. *Journal of Neurophysiology, 103*(6), 2990-3000.
- Wu, G., van der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., . . . Wang, X. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38*(5), 981-992.
- Wu, W. L., Su, F. C., Cheng, Y. M., Huang, P. J., Chou, Y. L., & Chou, C. K. (2000). Gait analysis after ankle arthrodesis. *Gait and Posture, 11*(1), 54-61.