Effects of Fatigue and Recovery on Knee Mechanics during Side-Step Cutting

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ABSTRACT

TSAI, L., S. M. SIGWARD, C. D. POLLARD, M. J. FLETCHER, and C. M. POWERS. Effects of Fatigue and Recovery on Knee Mechanics during Side-Step Cutting. Med. Sci. Sports Exerc., Vol. 41, No. 10, pp. 1952–1957, 2009. Introduction: Changes in knee mechanics immediately after a fatiguing bout of exercise are thought to place an individual at a greater risk for anterior cruciate ligament (ACL) injury. However, the recovery time required to restore normal knee kinetics and kinematics after fatigue has not been established. Purpose: The purpose of this study was to examine knee mechanics during side-step cutting immediately after a fatigue protocol and after 20 and 40 min of rest. Methods: Knee kinematics (eight-camera system Vicon 612; Oxford Metrics, Oxford, United Kingdom) and kinetics (AMTI force platform; AMTI, Newton, MA) of 15 female recreational athletes were recorded during a side-step cutting task. Data were obtained at four different time points: 1) before a fatigue protocol, 2) immediately after the fatigue protocol, 3) 20 min after the fatigue protocol, and 4) 40 min after the fatigue protocol. Peak knee joint angles and knee joint moments in the sagittal, frontal, and transverse planes were identified during the deceleration phase of the cutting task. One-way ANOVA with repeated measures were used to compare variables among the four time points. Results: Peak internal knee adductor moments (external knee valgus moments) and peak knee internal rotation angles were significantly greater after fatigue and remained elevated at 20 and 40 min after fatigue. Peak knee abduction (valgus) angles immediately after the fatigue protocol were significantly greater but returned to prefatigue levels after 20 min of rest. The fatigue protocol had no influence on any other of the variables examined. Conclusions: Fatigue resulted in changes in knee mechanics that are thought to be associated with ACL injury. Forty minutes of recovery was not sufficient in restoring knee mechanics to prefatigue levels. Key Words: ANTERIOR CRUCIATE LIGAMENT, INJURY, KINETICS, KINEMATICS

Muscular fatigue can be defined as a failure to maintain the required force or power production after prolonged exercise (13,30). Previous studies have shown that muscular fatigue results in decreased joint proprioception and postural stability as well as increased joint laxity (8,19,27,28). Muscular fatigue has also been shown to alter the control of lower extremity mechanics during cutting (21), landing (3,14,18,20), running (6,22,31), and single-leg hopping (2).

After a fatiguing bout of exercise, it has been hypothesized that injury risk may increase (11,21). More specifically, alterations in knee mechanics immediately after fatigue are thought to place an individual at a greater risk for anterior cruciate ligament (ACL) injury (3,18). Chappell et al. (3) investigated the effects of fatigue during the landing phase of three stop-jump tasks. These authors reported significantly greater peak proximal tibial anterior shear forces and external knee valgus moments (internal knee adductor moments) as well as decreased knee flexion angles after fatigue for both male and female recreational athletes. McLean et al. (18) investigated the effects of a generalized lower extremity fatigue protocol on the mechanics of the lower extremity during the landing phase of a drop-jump task. In this study, subjects demonstrated increases in knee abduction (valgus) and internal rotation moments (internal rotation of the tibia relative to femur) as well as increases in external knee valgus and internal rotation moments after fatigue. Greater external knee valgus and internal rotation moments have been shown to increase loading on the ACL in vitro (15) and are thought to be associated with the increased risk of noncontact ACL injury (10).

Although the studies of Chappell et al. (3) and McLean et al. (18) have provided evidence that fatigue may be associated with the increased risk of noncontact ACL injury, the time required to restore normal knee kinematics and kinetics to prefatigue levels has not been investigated. Most studies that have investigated the effects of recovery time after fatigue have focused on the recovery of muscle strength (13,17,25,29) as opposed to the recovery of lower extremity mechanics. Knowledge of the time required for “biomechanical recovery” would be useful for the design of proper

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activity–rest cycles to minimize the potential for fatigue-related injury. Therefore, the purpose of the current investigation was to examine knee kinematics and kinetics during side-step cutting immediately after a generalized fatigue protocol and after 20- and 40-min recovery periods. On the basis of the results reported by Chappell et al. (3) and McLean et al. (18), we hypothesized that female athletes would exhibit decreases in knee flexion, increases in knee abduction and internal rotation angles, and increases in frontal and transverse plane knee joint moments immediately after a fatiguing bout of exercise. We also hypothesized that these changes in knee mechanics would return to the prefatigue levels after 40 min of rest.

METHODS

Subjects. Fifteen female recreational athletes between the ages of 22 and 36 yr were recruited for this study (Table 1). On the basis of the external knee valgus moment data reported by McLean et al. (18), it was estimated that a sample size of 15 would achieve 99% power to detect differences between the prefatigue and postfatigue conditions (7). All participants in the current investigation exercised regularly at least three times per week for 30 min. Subjects reported no lower extremity injury within the 6 months before data collection and were free of pain at the time of study. Subjects were excluded from the study if they had previous knee surgery, ligamentous instability, or any medical or neurologic condition that would impair their ability to perform a side-step cutting task. Before participation, all procedures were explained to each subject, and informed consent was obtained as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Instrumentation. Reflective markers were placed at specific anatomic landmarks (see next paragraph for details) and were recorded at a rate of 250 Hz using an eight-camera motion analysis system (Vicon 612; Oxford Metrics, Oxford, United Kingdom). Ground reaction forces were collected at a rate of 1500 Hz using an AMTI force plate (AMTI, Newton, MA).

Procedures. Before data collection, 21 reflective markers (14-mm spheres) were attached to the following bony landmarks: distal first toe, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral epicondyles of femur, greater trochanters, anterior superior iliac spines, iliac crests, and the L5–S1 junction. In addition, noncollinear tracking cluster markers were placed on the heels, lateral shanks, and lateral thighs.

For the cutting task, subjects ran 8 m at a set speed (4–5 m s⁻¹), planted their dominant foot (the foot used to kick a ball) on the force plate, and changed direction toward the nondominant side at an angle of 45°. Approach speed was monitored with the use of photoelectric switches. Each subject performed the side-step cutting task before, immediately after, 20 min after, and 40 min after a fatigue protocol. Four successful trials were collected for each subject at each of the four time points. Trials were repeated if the approach speed did not fall within the predetermined range. The average approach speeds for the four time points were nearly identical (4.3, 4.3, 4.4, and 4.3 m s⁻¹).

The fatigue protocol used in the current study was similar to that used by Chappell et al. (3). Briefly, it consisted of a sequence of five consecutive vertical squat jumps (50% of the subject’s maximal vertical jump height) followed by a 30-m sprint. Subjects repeated this sequence until they reached a fatigued state that was defined as the inability to reach 50% of the maximal vertical jump height for all five consecutive squat jumps or the inability to continue the protocol because of volitional exhaustion. To estimate the physiological response to the fatigue protocol and recovery, the HR of each subject was measured before each of the four data collection sessions using a strapless HR monitor watch (Reebok, 1-W-L0101A, Canton, MA).

Three-dimensional marker coordinates were reconstructed using Vicon Workstation software (Workstation; Oxford Metrics). Visual3D (C-motion, Rockville, MD) was used to process the raw coordinate data to compute the segmental kinematics and kinetics for the dominant lower extremity. Trajectory data were filtered using a fourth-order zero-lag Butterworth 12-Hz low-pass filter. The pelvis was modeled as a cylinder, and the lower extremity segments were modeled as a frustra of cones. The local coordinate systems of the pelvis, thigh, shank, and foot were derived from a standing calibration trial. Joint kinematics was calculated using Euler angles with the following order of rotations: flexion/extension, abduction/adduction, and internal/external rotation. The knee joint angles were defined as the orientation of the shank segment with respect to the thigh segment. Three-dimensional net joint moments were calculated using standard inverse dynamics equations (4,33). Segment mass, center of mass location, and moment of inertia were approximated on the basis of data by Dempster (5). Moments were normalized to body mass and are presented as internal (muscle) moments.

Data analysis. Peak knee joint angles and normalized internal knee joint moments in the sagittal, frontal, and transverse planes were identified during the deceleration phase of the cutting task. The deceleration phase was defined as the period from initial foot contact to the maximal knee flexion. For each dependent variable, a one-way ANOVA with repeated measures (SPSS Version 15.0; SPSS Inc., Chicago, IL) was used to compare the differences among the four time points. If significance was found ($P \leq 0.05$), post hoc paired $t$-tests were used to compare each of the three postfatigue

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conditions to the prefatigue condition. A modified Bonferroni adjustment as proposed by Rom (26) was used to control for the family-wise error rate for the three post hoc multiple comparisons. This method has been shown to control for the type I error rate with a higher level of power when compared with other modified Bonferroni adjustments (23,32). Given that three post hoc paired t-tests were conducted for each dependent variable that demonstrated significance on the ANOVA test, the three observed P values were first arranged in a descending order and were sequentially compared with the adjusted critical significant level at $P = 0.05$, $P = 0.025$, and $P = 0.0169$, respectively (32). If the highest observed $P$ value of the three post hoc paired $t$-tests was less than or equal to 0.05, all post hoc comparisons were considered significant; otherwise, the second-ranked observed $P$ value was compared with 0.025. If the second-ranked observed $P$ value was less than or equal to 0.025, the post hoc comparisons with a $P$ value less than or equal to 0.025 were considered significant; otherwise, the third-ranked observed $P$ value was compared with 0.0169 (23,26,32). Effect sizes for each significant post hoc comparison were calculated using Cohen’s $d$.

RESULTS

HR. The ANOVA assessing HR among the four time points reached statistical significance ($F_{3,42} = 264.8$, $P \leq 0.05$). Post hoc testing indicated that the HR of all of the three postfatigue conditions were significantly higher than those of the prefatigue condition (Fig. 1).

Knee joint kinematics. ANOVA tests reached significance for the peak knee abduction angle ($F_{3,42} = 5.0$, $P \leq 0.05$) and peak knee internal rotation angle ($F_{3,42} = 17.1$, $P \leq 0.05$). There was no statistical significance for the peak knee flexion angle among the four time points ($F_{3,42} = 1.1$, $P > 0.05$). Post hoc testing indicated that the peak knee abduction angles immediately after the fatigue protocol were significantly greater than those of the prefatigue protocol (Fig. 2). On average, the peak knee abduction angle increased by $2.4 \pm 3.0^\circ$ (range $= -4.4^\circ$ to $7.7^\circ$; effect size $= 0.80$) immediately after fatigue. No significant differences were found between the peak prefatigue knee abduction
angles and the peak knee abduction angles 20 and 40 min after fatigue. The peak knee internal rotation angles of all of the three postfatigue conditions were found to be significantly greater than those of the prefatigue condition (Fig. 3). The peak knee internal rotation angle increased by 4.9 ± 2.7° (range = -0.3° to 9.4°; effect size = 1.81) immediately after the fatigue protocol. When compared with the prefatigue value, the peak knee internal rotation angle 20 min after fatigue was 2.4 ± 3.4° higher (range = -2.6° to 8.1°; effect size = 0.71) and remained elevated by 2.0 ± 3.4° (range = -3.5° to 7.3°; effect size = 0.59) 40 min after fatigue.

**Knee joint kinetics.** ANOVA tests reached significance for the peak internal knee adductor moments (external knee valgus moments: \( F_{3,42} = 3.6, P \leq 0.05 \)). There were no statistical significances for the peak knee extensor moment (\( F_{3,42} = 1.4, P > 0.05 \)) and external rotator moment (\( F_{3,42} = 0.4, P > 0.05 \)). Post hoc testing indicated that the peak knee adductor moments of all of the three postfatigue conditions were significantly greater than those of the prefatigue conditions (Fig. 4). On average, the peak knee adductor moment increased by 0.30 ± 0.30 N·m·kg\(^{-1}\) (range = -0.10 to 0.82 N·m·kg\(^{-1}\); effect size = 1.00) immediately after the fatigue protocol. When compared with the prefatigue value, the peak knee adductor moment 20 min after fatigue was 0.26 ± 0.41 N·m·kg\(^{-1}\) higher (range = -0.27 to 0.91 N·m·kg\(^{-1}\); effect size = 0.63) and remained elevated by 0.25 ± 0.44 N·m·kg\(^{-1}\) (range = -0.31 to 1.47 N·m·kg\(^{-1}\); effect size = 0.57) 40 min after fatigue.

**DISCUSSION**

The purpose of this study was to investigate the effects of a fatiguing bout of exercise and recovery on knee kinematics and kinetics during side-step cutting. Immediately after the fatigue protocol, subjects in the current study demonstrated increased peak knee abduction and internal rotation angles and increased peak internal knee adductor moments. The observed change in knee internal rotation angles and knee adductor moments after fatigue did not fully return to prefatigue levels after 40 min of rest.

Our findings of increased knee adductor moments as well as knee abduction and internal rotation angles immediately after fatigue are consistent with those of the previous investigations by Chappell et al. (3) and McLean et al. (18). On average, subjects in the current study demonstrated a 25% increase in the peak knee adductor moment, a 102% increase in the peak knee internal rotation angle, and a 52% increase in the peak knee abduction angle immediately after the fatigue protocol. The peak knee adductor moments and internal rotation angles remained significantly elevated after 20 min (22% and 51%, respectively) and 40 min (21% and 42%, respectively) of rest. In contrast, the peak knee abduction angles returned to the prefatigue levels after 20 min of rest.

Consistent with the results reported by other investigators (3,18), the changes in knee mechanics after the fatigue protocol used in the current study support the premise that fatigue-related changes in knee mechanics may place an individual at a greater risk for noncontact ACL injury. Increased knee internal rotation may increase the loading on the ACL as it is a primary restraint for this motion (15). Applying an internal rotation and valgus torque at the knee has been shown to generate high stress within the ACL in vitro (15,16). In addition, a prospective study conducted by Hewett et al. (10) identified increased peak knee abduction angles and adductor moments as predictors of ACL injury with high specificity and sensitivity.

In the current study, we used a generalized lower extremity fatigue protocol as opposed to a localized muscle fatigue protocol (19,21,28). We opted for a generalized fatigue protocol because of its ability to better simulate the fatigue mechanism that may be experienced during basketball, soccer, and volleyball games (3). Therefore, the results of this study may be more generalizable for athletes under actual sports competitions. For example, a typical soccer or basketball game halftime ranges from 15 to 20 min. If a female athlete experienced fatigue similar to that induced by the protocol of the current study, our results suggest that the halftime period may not be sufficient in restoring knee mechanics to the prefatigue levels. This finding may be relevant to injury risk, as Hawkins and Fuller (9) have reported that more injuries occurred in the second half of a soccer match when compared with the first half.

Previous studies investigating the effects of fatigue on knee extensor muscle performances have reported that 1 to 96 h is needed to recover full muscle strength (13,17,25,29). Given that normal knee joint mechanics is dependent on the proper timing and torque production capability of the knee joint muscles (21), it is not entirely surprising that
altered knee mechanics were still evident after 40 min of rest. Immediately after the fatigue protocol, HR were 126% higher compared with prefatigue levels (72 vs 163 bpm) and gradually returned to prefatigue levels. However, 40 min after the fatiguing bout of exercise, HR were still 30% higher than prefatigue levels (72 vs 94 bpm), indicating that full cardiovascular recovery had not been achieved. Whether the restoration of knee mechanics would coincide with full restoration of cardiovascular recovery remains to be seen.

In contrast to the studies of Chappell et al. (3) and McLean et al. (18), only female subjects were evaluated in the present study. Given that females have a higher risk of noncontact ACL injury compared with males (1), we sought to investigate how fatigue and recovery affects females during side-step cutting, an activity in which ACL injury is reported to occur (12,24). Although Chappell et al. (3) and McLean et al. (18) reported similar changes in knee mechanics after fatigue for male and female subjects, whether males and females recover altered knee mechanics at the same rate remains unknown.

The results of the present study should be interpreted with caution because of two limitations. First, the laboratory fatigue protocol may not represent the level of fatigue experienced by athletes in actual sporting activities. Second, the participants in the current study were female recreational athletes. Whether female recreational athletes respond differently to fatigue when compared with elite or professional athletes should be the focus of future investigations. Furthermore, the increases in knee internal rotation and valgus angles after fatigue were relatively small (i.e., 2°–5°). Although these changes were statistically significant, whether the small changes in knee kinematics after fatigue were meaningful with respect to injury risk requires further investigation.

**CONCLUSIONS**

The current study investigated the effects of fatigue and recovery on knee kinematics and kinetics in female recreational athletes during a side-step cutting maneuver. A generalized fatigue protocol resulted in changes in knee mechanics that have been associated with ACL injury. Forty minutes of rest was not sufficient in fully restoring knee mechanics to prefatigue levels. Future studies are needed to investigate the required rest period for the restoration of normal knee kinematics and kinetics after a fatiguing bout of exercise. In addition, research is needed to determine whether various training or injury prevention programs can facilitate the recovery of knee mechanics after fatigue.

The results of the present study do not constitute endorsement by American College of Sports Medicine.

**REFERENCES**


