



The effects of fatigue and anticipation on the mechanics of the knee during cutting in female athletes[☆]

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ABSTRACT

Background: Unanticipated cutting tasks which do not allow for pre-planning of a movement have been reported to promote knee mechanics which may increase the risk of anterior cruciate ligament injury. Fatigue has also been reported to have similar effects. Athletes must often perform unanticipated tasks when they are fatigued. Previous studies have reported that the effects of anticipation become more prominent as an athlete progresses through a fatigue protocol. However, the protocols previously utilized may not mimic the demands of sports participation.

Methods: Three-dimensional knee joint kinematics and kinetics were collected from 13 female athletes while they performed a run-and-cut task, before and after completion of an intermittent shuttle run. Trials were further divided (pre-planned, unanticipated) to assess the effects of anticipation.

Findings: There were no significant interactions between the effects of fatigue and anticipation for the peak knee angles or moments of the knee joint in any plane. Subjects did demonstrate a 68% increase in their peak knee abduction angles following completion of the intermittent shuttle run. Anticipation also had a significant effect on the mechanics of the knee in all planes. Most notably, there was a 23% increase in peak knee abduction angles and a 33% increase in the peak internal knee adduction moments.

Interpretation: Both fatigue and anticipation promoted knee mechanics which are associated with an increased risk of knee injury. However, it does not appear that their effects combine when athletes are at a level of fatigue which is thought to reflect sports participation.

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1. Introduction

The annual incidence of anterior cruciate ligament (ACL) injury is as high as 200,000 in the United States alone (Griffin et al., 2006) and the cost of surgery is estimated to be 1–1.5 billion dollars per year (Griffin et al., 2000). Unfortunately, even athletes who undergo a successful ACL reconstruction demonstrate evidence of early knee osteoarthritis (Harris et al., 2015). In an attempt to prevent ACL injuries, programs have been developed which target modifiable neuromuscular risk factors (Gilchrist et al., 2008; Mandelbaum et al., 2005; Myer et al., 2004; Myklebust et al., 2003) with mixed results in targeted populations. Regardless, there has been no reduction in the overall rate of ACL injuries in female athletes (Agel et al., 2005), which suggests that key factors related to injury risk are not being incorporated into these programs. Also, authors have reported that significant variability exists in the frequency and duration of training, specific program components, and subject groups included in these programs (Noyes and Barber-Westin, 2014). Both the limited effectiveness and significant variability may be due to

an incomplete understanding of the precise neuromuscular contributors to ACL injury (Bahr and Krosshaug, 2005; Hewett et al., 2005; Kernozek et al., 2008; Yu and Garrett, 2007).

The majority of ACL injuries are non-contact in nature (Boden et al., 2000), often occurring in sports such as soccer (Boden et al., 2000; Olsen et al., 2004), which require cutting in response to an external stimulus (Besier et al., 2001a, 2001b; Kipp et al., 2013). Previous studies investigating the mechanics of the knee during cutting tasks have often allowed a subject to pre-plan their movement prior to initiating a trial (Besier et al., 2001a, 2001b; Sanna and O'Connor, 2008). However, many have questioned the ecological validity of this approach as athletes are afforded limited time to identify relevant stimuli and develop an appropriate motor plan within the sports environment (Besier et al., 2001a, 2001b; Brown et al., 2009; Kim et al., 2014). As a result, studies have investigated the effect that the anticipation status of a task (pre-planned vs. unanticipated) has on the mechanics of the lower extremity. Multiple studies have reported that unanticipated tasks, which do not allow an athlete to develop a motor plan prior to initiating a movement, promote mechanics of the knee which are thought to increase the risk of ACL injury (Besier et al., 2001a, 2001b; Kim et al., 2014; Lee et al., 2013; Mornieux et al., 2014). The deleterious effects associated with unanticipated tasks are thought to be due to the temporal

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constraints imposed on the components of the central nervous system which control movement (Besier et al., 2001a, 2001b; Mornieux et al., 2014). It appears that an athlete's risk of ACL injury is dependent on their ability to process information within the central nervous system and execute an effective motor response.

Fatigue is also thought to play a significant role, as athletes in sports such as soccer are at greater risk of sustaining an ACL injury at the end of competition (Hawkins and Fuller, 1999; Hawkins et al., 2001; Rahnama et al., 2002). Fatigue is typically characterized as having an effect proximal (central fatigue) or distal (peripheral fatigue) to the neuromuscular junction (Gandevia, 2001; Taylor et al., 2006). In addition, central fatigue can be separated into supraspinal and spinal components, with supraspinal fatigue being thought to be the result of suboptimal output from the motor cortex (Gandevia, 2001; Taylor et al., 2006). A variety of fatigue protocols have been utilized with some designed to induce peripheral fatigue (Augustsson et al., 2006; Fagenbaum and Darling, 2003; Kernozek et al., 2008) and others designed to induce more generalized fatigue (Benjaminse et al., 2008; Chappell et al., 2005; Lucci et al., 2011; Sanna and O'Connor, 2008), which has both central and peripheral effects. Multiple studies have demonstrated that fatigue promotes knee mechanics which are associated with an increased risk of ACL injury (Chappell et al., 2005; Lucci et al., 2011; McLean and Samorezov, 2009; McLean et al., 2007). This may be the result of changes in the kinematic profile of the contact limb and/or changes in whole body center of mass control, which would alter the ground reaction force profile (Donnelly et al., 2012).

It appears that both anticipation and fatigue are risk factors for ACL injury due to their effects on the mechanics of the knee. However, it is possible that these factors are not independent of one another as previous studies have reported that a significant interaction exists between the effects of fatigue and anticipation (Borotikar et al., 2008; McLean and Samorezov, 2009). For example, one study (Borotikar et al., 2008), which assessed a single-leg land-and-cut task in a group of female athletes, found that the effects of anticipation become more prominent as an athlete progresses through a general fatigue protocol. They concluded that the “worst case scenario” for ACL injury may exist when an athlete is required to perform an unanticipated task, while in a fatigued state. Understanding the relationship between the effects of anticipation and fatigue has important clinical implications. If these two risk factors have a combined effect, ACL injury prevention programs may optimally require athletes to perform unanticipated tasks while they are fatigued (Borotikar et al., 2008).

Previous studies which have reported an interaction between the effects of anticipation and fatigue have utilized fatigue protocols which may not mimic the physiological demands of sports such as soccer (Borotikar et al., 2008; McLean and Samorezov, 2009). For example, Borotikar et al. (2008) had subjects alternate between bodyweight squats and lateral cutting trials until the point in which they could no longer perform three squats without assistance. Before adapting injury prevention programs, it is important to analyze the combined effects of anticipation and fatigue using fatigue protocols which are designed to replicate sports participation, as there is recent evidence that the effects of fatigue and anticipation may not interact when a less demanding fatigue protocol is utilized (Khalid et al., 2015). Previous studies have also not determined where in the central nervous system the effects of fatigue occur (spinal vs. supraspinal). Developing this understanding may have important implications when designing ACL injury prevention programs.

As a result, the purpose of this study was to analyze the combined effects of fatigue and anticipation on the angles and moments of the knee during a side-step cutting task in a group of female Division I college athletes. The exercise protocol was an intermittent shuttle run (ISR), which has been previously utilized to analyze the effects of fatigue on the mechanics of the knee during a cutting task (Sanna and O'Connor, 2008) and is thought to mimic the physiological effects of a soccer match (Edwards et al., 2003; Gleeson et al., 1998). Subjects' reaction

time in response to a visual stimulus was assessed using the Eriksen–Flanker task (Eriksen and Eriksen, 1974), in order to determine where the effects of the fatigue associated with the ISR occur within the central nervous system. The main hypothesis was that the effects of anticipation would become more prominent after the athletes were exposed to the ISR. This would indicate that the level fatigue experienced during a soccer match may significantly impact the components of the central nervous system which control movement. It was also hypothesized that subjects' reaction time would be negatively affected by exposure to the ISR, which will indicate the effects of fatigue were supraspinal in nature.

2. Methods

Our study included thirteen US NCAA Division I collegiate female soccer players who had a mean (SD) age, mass, and height of 21.6 (2.2) years, 62.4 (6.8) kg, and 1.7 (0.1) m respectively. All had over 10 years of competitive soccer experience. Subjects were excluded if they 1) had any previous lower extremity surgery, 2) had an injury in the previous 6 months which limited participation, or 3) were currently pregnant. The study protocol was approved by a university institutional review board.

Three-dimensional marker trajectories were collected at 200 Hz using a ten-camera Motion Analysis Eagle System (Santa Rosa, CA, USA) while three-dimensional ground reaction force (GRF) data were synchronously collected at 1000 Hz using an AMTI OR6–5 force plate (Watertown, MA, USA). Participants all wore identical Saucony Jazz footwear (Lexington, MA, USA).

Testing was performed over 2 days for a total of 3 h. During the initial session, subjects were familiarized with the data collection procedures. Then, subject's maximal oxygen uptake ($\dot{V}O_2$ max) was estimated using the Progressive Aerobic Cardiovascular Endurance Run (PACER) test (Fitnessgram, Human Kinetics, Champaign, IL, USA). This required the subjects to run back and forth between two cones placed 20 m apart as running speed was increased by 0.14 m/s each minute until exhaustion. The results of the PACER test were used to determine the running speed at the estimated $\dot{V}O_2$ max ($\dot{V}O_2$ max speed). This was used to determine the speeds used in the ISR protocol (Sanna and O'Connor, 2008).

During a second session (at least 48 h later), subjects performed three trials of a maximal one-legged countermovement jump (CMJ) in which they began and ended each trial with one foot on the force plate. Twenty-five reflective markers were then placed on the pelvis and lower extremity. Calibration markers were placed on the first and fifth metatarsal heads, lateral and medial malleoli, and lateral and medial epicondyles of the right leg as well as the bilateral greater trochanters and iliac crests. Tracking markers, which stayed on during the cutting trials, were placed on the bilateral anterior superior and posterior superior iliac spines. Also, four tracking markers mounted on rigid plates were attached to the thigh and shank and a rigid plate with three tracking markers was mounted onto the back of the shoe. Following the application of these markers, a 3 second standing calibration trial was collected.

Once the static calibration trial was collected, the cutting trials began. This required subjects to run down a 15-m runway at a speed of 4.5–5.0 m/s with running speed monitored by two photoelectric timing gates. Five trials of three different conditions were performed: 1) a straight run, 2) a 45° cut to the left off of the right foot, and 3) a stop as quickly as possible. For the cutting trials, subjects were instructed to cut along a 1 m wide path, which ensured that the angle would be between 40° and 50° (Weinhandl et al., 2013). For the unanticipated trials, subjects were unaware of which task they were to perform until they passed the first set of timing gates which were 3 m away from the force plate. When this plane was crossed, an image was displayed on a projector straight ahead which dictated the movement to be executed. Participants had approximately 600 ms to react

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