THE EFFECT OF FATIGUE ON ACL INJURY RISK IN THE ATHLETIC POPULATION

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THE EFFECT OF FATIGUE ON ACL INJURY RISK IN THE ATHLETIC POPULATION

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CHAPTER I

FATIGUE AND INJURY TO THE ANTERIOR CRUCIATE LIGAMENT IN ATHLETES

ACL Injuries in the Athletic Population

Injury to the anterior cruciate ligament (ACL) can be very costly and often results in substantial loss of athletic playing time. It is estimated that over 2 billion dollars is spent annually on treatment and rehabilitation of ACL injuries in the United States (Silvers & Mandelbaum, 2011), with at least half of these injuries occurring in athletes 15-25 years of age (Griffin et al., 2006). In addition, an athlete who ruptures the ACL is expected to miss 6-9 months of athletic competition (Silvers & Mandelbaum, 2011) and often suffers chronic deficits in muscle strength, proprioceptive ability (Kvist, 2004), as well as significant long-term meniscal and articular cartilage loss (Murrell, Maddali, Horovitz, Oakley, & Warren, 2001).

Epidemiological evidence suggests that approximately 70% of ACL injuries are non-contact in nature and are not the result of a direct blow to the knee (Agel, Arendt, & Bershadsky, 2005; Hewett, Myer, & Ford, 2006a; Pollard, Davis & Hamill, 2004; Smith et al. 2009). As a result, the majority of research on ACL injuries is aimed at non-contact injuries, due to the possibility of preventing this type of injury (Hewett, Myer, & Ford, 2006b). Evaluation of non-contact injury scenarios has led to the conclusion that the majority of non-contact ACL injuries occur during rapid deceleration maneuvers such as landing or changing running direction with the knee at or near full extension, the hip internally rotated and adducted, knee abducted, and the tibia internally rotated (Hewett et al., 2006a; Koga et al., 2010). An athlete who adopts this movement pattern while competing in sports that routinely require these types of tasks (i.e. basketball, volleyball, soccer, etc.) will demonstrate an increased reliance on the ACL for stability and, consequently, will be vulnerable to excessive strain and possibly rupture (Shimokochi & Schultz, 2008).

Several review papers have been published (Alentorn-Geli et al., 2009; Boden, Griffin, & Garrett, 2000; Griffin et al., 2006; Hewett et al., 2006a; Hughes & Watkins, 2006; Shultz et al., 2010) identifying the mechanisms and risk factors that increase the likelihood an athlete suffering this type of injury. These factors include: environmental factors such as playing surface (Boden et al., 2000; Griffin et al., 2006), the anatomical composition of the athlete (Alentorn-Geli et al., 2009; Griffin et al., 2006; Hewett et al., 2006a; Hughes & Watkins, 2006; McLean, 2008; McLean & Beaulieu, 2010; Shultz 2010), hormone levels (Boden et al., 2000; Hewett et al., 2006; Wojtys et al., 2002), and the neuromechanical profile of the athlete (Alentorn-Geli et al., 2009; Boden et al., 2000; Griffin et al., 2006; Hewett et al., 2006a; Hughes & Watkins, 2006; McLean & Beaulieu, 2010; Shultz 2010).). Although, it is a combination of several of these factors that typically leads to ACL rupture (McLean & Beaulieu, 2010), the majority of research has focused on the neuromuscular factors due to the potential to modify these factors. Several ACL injury prevention programs aimed at neuromuscular training have demonstrated success in reducing the incidence of these injuries (Hewett, Linenfeld, Riccobene, & Noyes, 1999; Gilchrist et al., 2008; Mandelbaum et al., 2005; Myklebust et al., 2003). Nevertheless, ACL injuries continue to plague the athletic population (Agel et al., 2005), and further investigation as to how these factors manifest during competition to cause injury is warranted.

Fatigue is a phenomenon frequently cited as a risk factor for ACL injury in the athletic population (Alentorn-Geli et al., 2009; Griffin et al., 2006; Hewett et al., 2006a; Hughes & Watkins, 2006; McLean, 2008; Shultz, 2010). Fatigue, often defined as a reduction in the muscles ability to produce force, is a naturally occurring phenomenon that is common in any high intensity sporting event (Barry & Enoka, 2007). Fatigue is reported to alter neuromuscular control (Green, 1997; Johnston, Howard, Cawley, & Losse, 1998), and consequently, exacerbate neuromuscular risk factors that compromise the functional integrity of the knee joint. Fatigue of the lower extremity has been demonstrated to increase knee joint laxity (Rozzi et al., 1999; Wojtys, et al., 1996), and decrease knee proprioception (Allen, Leung, & Proske, 2010; Ribeiro, Santos, Goncalves, & Oliveira, 2008) both of which have been associated with increased ACL injury risk (Uhorchak et al., 2003). In addition, several authors have reported an increased distribution of injuries in a variety of sports towards the end of the half or match (Gabbett, 2000; Hawkins, Hulse, Wilkinson, & Gibson, 2001; Rahnama, Reilly, & Lees, 2002), which is likely to be the result of elevated levels of fatigue.

These observations are consistent with the hypothesis that fatigue is a likely contributor to ACL injury in the dynamic sporting environment. However, by nature fatigue is a complex phenomenon that results from a variety of mechanisms at central and peripheral levels (Barry & Enoka 2007; Behm & St-Pierre, 1997; Binder-Macleod & Ross, 1999). Due to this multi-faceted nature of fatigue's onset, it is difficult to determine the effect of fatigue on ACL injury risk during competition.

Recent studies have sought to advance knowledge on fatigue's effect on ACL injury risk by observing lower extremity movement patterns during the completion of a functional task before and after the exposure to a protocol designed to induce fatigue. This type of experimental design recreates an ACL injury situation as it occurs during sport competition; however, the literature has reported mixed results and the effect of fatigue on injury risk remains unclear (Augustsson et al., 2006; Benjaminse et al., 2007; Borotikar et al., 2008; Chappell et al., 2005; Coventry, O'Connor, Hart, Earl, & Ebersole, 2006; James et al., 2010; Kernozek et al., 2008; Madigan & Pidcoe, 2003; Mclean et al., 2007; Mclean & Samorezov, 2009; Moran & Marshall, 2006; Nyland, Caborn, Shapiro, & Johnson, 1999; Orishimo & Kremenic, 2006; Ortiz et al., 2010; Pappas, Sheikhzadeh, Hagins, & Nordin, 2007; Sanna & O'Connor, 2007; Smith et al., 2009 Thomas, McLean & Palmieri-Smith, 2010; Tsai et al., 2010). This inconsistency is likely the result of several differences in the experimental design of these studies. Therefore, this chapter will provide a review of the current literature evaluating the effect fatigue on movement patterns during a functional task and focus on patterns that are indicative of increased ACL injury risk.

The Effect of Fatigue on Lower Extremity Movement Patterns

Studies on the effect of fatigue and ACL injury risk have used a variety of methods to both define and induce fatigue. The fatigue protocols utilized in the research include: resistance exercise (Augustsson et al., 2006; James et al., 2010; Kernozek et al., 2008; Nylandet al., 1999; Smith et al., 2009 Thomas et al., 2010), cycling (James et al., 2010; Ortiz et al., 2010), graded treadmill jogging (Benjaminse et al., 2007; Moran & Marshall, 2006), stepping exercise (Orishimo & Kremenic, 2006), alternated landings and squats (Borotikar et al., 2008; Coventry et al., 2006; Madigan & Pidcoe, 2003; Mclean & Samorezov, 2009) continuous jumping, (Pappas et al., 2007), prolonged running (Sanna & O'Connor, 2007), a combination of jumping and running (Chappell et al., 2005; Tsai et al., 2010) and plyometric bounds alternated with step ups (Mclean et al., 2007). These fatigue methods have been used to induce fatigue and study its effect on several functional tasks including: bilateral drop landings (James et al., 2010; McLean et al., 2007; Moran & Marshall, 2006; Pappas et al., 2007; Smith et al., 2009), unilateral drop landings (Coventry et al., 2006; Kernozek et al., 2008; Madigan & Pidcoe, 2003; Ortiz et al., 2010), cutting maneuvers (Nyland et al., 2009; Sanna & O'Connor, 2008; Tsai et al., 2010), unilateral stop jumps (Benjaminse et al., 2007), bilateral stop jumps (Chappell et al., 2005), unilateral hops (Augustsson et al., 2006; Orishimo & Kremenic 2006; Thomas et al., 2010), and land and cut maneuvers (Borotikar et al., 2008; McLean and Samorezov, 2009).

This type of experimental design offers insight into the direct effect of fatigue on lower extremity kinematics during a simulated ACL injury mechanism. However, the differences in the experimental design of these studies, specifically in the protocols used to induce fatigue make it difficult to make comparisons across studies and reach conclusions regarding fatigue's possible role in ACL injury risk during competition. Behm & St. Pierre (1997) report that the type of fatigue experienced by a particular muscle or muscle group depends on the properties of the muscles themselves as well as the frequency, force, duration, and type of contractions that caused the muscle fatigue. This concept is known as task dependency, which explains the notion that fatigue, and the mechanisms underlying fatigue, are dependent upon the task performed to induce fatigue (Binder-Macleod & Ross, 1999). Therefore, the alterations observed in these studies will depend on the type of fatigue experienced by the subjects in each study and are vulnerable to high levels of variation.

The protocols used to induce fatigue in the current literature on ACL injury risk can be organized onto a continuum with isolated muscle fatigue falling on one end and simulated sports competition on the other. For this review we will arrange these experiments into two categories based on the methods used to induce fatigue. On one end will be the general fatigue protocols which are those that induce fatigue by performing movements that are not similar to the (functional) task being analyzed or characteristic of the sport or sports in which this type of movement occur. Functional fatigue protocols will fall at the other end of the continuum. The fatigue protocols in this category fatigue the subject with movements similar or identical to the task being analyzed or the sport environment the experimenters are interested in. Results from all types of fatigue protocols can carry significance to the advancement of knowledge of fatigue on ACL injury risk. General protocols can provide insight into the effect of fatigue of specific muscles or muscle groups on functional tasks. The next section will discuss the effect of these types of fatigue protocols and identify possible implications for ACL injury risk.

General Fatigue Protocols

Fatigue induced by general fatigue protocols are shown to consistently alter lower extremity kinematics. Many of these studies induced fatigue with continuous contractions on an isokinetic dynamometer until force fell below a predetermined percentage of maximum force. For example, Nyland et al. (1999) recruited 20 healthy active females to participate in 3 weeks of crossover cutting training followed by a hamstring fatigue session to determine the effect of hamstring fatigue on transverse plane knee control deficits during cutting. The fatigue protocol required the subjects to perform maximal eccentric hamstring contractions at 30 deg/sec through a range of motion from 30° to 90° of knee flexion until a peak torque reduction of 20% was achieved. The results demonstrate that this type of fatiguing exercise significantly (p=.014) increased mean internal rotation velocity at heel strike in the fatigued state. This alteration indicates that that eccentric hamstrings fatigue induced by exercise on an isokinetic dynamometer led to reduced control of the knee in the transverse plane, and possibly increased the risk for ACL injury.

A similar study conducted by Augustsson et al. (2006) also utilized a general fatigue protocol to induce isolated fatigue of one muscle group. The researchers recruited 8 healthy, physically active males to perform maximal hops onto a force plate before and after the completion of a quadriceps fatigue protocol. Specifically, the fatigue protocol required the subjects to perform unilateral knee extensions at 80% of their 1RM until failure during the first testing session followed by unilateral knee extensions at 50% of their 1RM on the contralateral limb until failure during the following test session. A subject was allowed to freely perform the knee extensions at his own pace; fatigue was determined to be the point at which the subject could no longer lift the designated weight under his own control. Flexion angles of the hip, knee and ankle were analyzed at landing. Hip flexion angles at peak vertical ground reaction force (vGRF) upon landing significantly ($p<.01$) decreased in the 80% 1RM fatigue condition; however, this value significantly recovered 3 minutes after the termination of the fatigue protocol. Quadriceps fatigue did not appear to alter sagittal plane knee angles while landing from a hop. It must be noted that hop length was variable depending on the subject's ability and decreased from pre to post testing conditions for the group, which could have interfered with the results. Augustsson et al. (2006) found that quadriceps fatigue at 50% and 80% of 1RM resulted in a decreased hop distance of 20% and 11%, respectively. It is quite possible that isolated quadriceps fatigue may have led to a dysfunctional landing pattern. However, this hypothesis cannot be supported based on the findings of this study.

In a more recent research study, Thomas and colleagues (2010) found that combined fatigue of the quadriceps and hamstrings induced isokinetically caused subjects to land from a unilateral hop with greater hip internal rotation (p=.03), knee extension (p <.001), and knee external rotation at initial contact (p<.05). The subjects also demonstrated greater knee extension (p=.002) and external rotation (p=.02) at peak vertical ground reaction force. Twenty-five healthy subjects (13 males, 12 females) participated in this study. The hopping task analyzed consisted of each subject completing a single leg takeoff and landing onto a force platform, which was positioned a distance equal to the length of the subject's leg from the takeoff position. After 3 successful pre-fatigued landing trials were completed the subjects performed the fatigue protocol which consisted of the subject alternating quadriceps and hamstrings maximum voluntary concentric contractions (MVC) at 180°/sec through a range of motion of 0°-100° until the peak torque feel below 50% of the peak torque measured at baseline. The subject was then given 2 minutes rest and asked to repeat this cycle. This cycle continued until the subject's first 5 repetitions of a set was below 50% MVC at which time the subject was determined to be fatigued. The subject then immediately completed 3 additional hops in the same manner as the pre fatigue condition. The fatigue protocol in this study fatigued both the hamstrings and quadriceps as opposed to the isolation of one muscle group in the previous two studies (Augustsson et al., 2006; Nyland et al., 1999). Based on the results, it seems evident that a combined quadriceps/hamstrings fatigue led to a greater dysfunction in movement patterns compared to isolated quadriceps or hamstrings fatigue. Another important observation is that this study utilized multiple sets of fatiguing activity until failure with rest in between to ensure maximum fatigue of the thigh musculature. This type of protocol may be more representative of the nature of competition in which the muscles are vigorously exerted to their limit multiple times a match. However, isokinetic machines facilitate an open kinetic chain exercise and do not allow the freedom of movement typical of athletic competition and, therefore, can only provide insight on the effect of fatigue of isolated muscle groups on movement patterns.

In addition to isolated muscle fatigue, general fatigue protocols aimed at fatiguing the entire lower extremity have also been employed incorporating leg press (Ghering, Melnyk, & Golhofer, 2009), controlled squats (Kernozek et al., 2008) and isometric squats (James et al., 2010; Smith et al., 2009) to study landing patterns in a fatigued state. The kinematic alterations produced by these fatigue protocols display conflicting results with regard to ACL injury risk. The fatigue protocols which utilized isotonic contractions caused the subjects to land with a greater degree of knee flexion than before fatigue (Ghering et al., 2009; Kernozek et al., 2008). As mentioned before a greater degree of flexion at the knee joint results in a decrease in the anterior load placed on the ACL and is not characteristic of the kinematic profile of an ACL injury situation. As for the experiments that incorporate an isometric fatigue protocol to induce fatigue Smith et al. (2009) found perturbations in the kinematic profile in several individual subjects that would appear to indicate a dysfunctional landing form, while James et al. (2010) did not report alterations in their group. There are several differences in the experimental design of these studies to consider that may account for these conflicting results that will be addressed further.

Ghering, Melnyk, and Gollhofer (2009) recruited 13 physically active males and females to have their lower extremity mechanics analyzed during bilateral drop landings from 52cm before and after fatigue. Fatigue was induced with 1 set of a leg press exercise performed at 50% 1RM until the subject could no longer lift the weight. Post-test measurements indicate that fatigue increased maximal knee flexion angle (p=.004) during the drop landings. These results correspond with those of Kernozek et al. (2008) who also observed a significant (p=.025) increase in knee flexion angles during drop landings after the completion of a fatigue protocol. These authors recruited 16 males and 14 females to perform 50 cm unilateral drop landings before and after a fatigue protocol. In order to induce fatigue the subjects performed controlled, cadenced squats that required the subjects to squat to a position with thighs parallel to the ground and extend fully back up on a cadence of 3.2 seconds (1.7 second descent, 1.5 second ascent). Each set consisted of continuous squats performed until failure with ninety seconds of rest in between. Fatigue was determined to be when the subject could no longer lift the weight after the completion of at least four sets. In addition to the increase in knee flexion, the subjects also exhibited significant increases in maximal hip flexion (p=.012), maximal dorsiflexion (p=.007). Also, a fatigue by gender interaction (p=.026) for knee flexion was also reported for the post-fatigue landings. Men landed with a greater level of knee flexion post-fatigue as opposed to the women who demonstrated no change after the fatiguing exercise. Although there were several differences in the study designs of these two experiments (bilateral vs. unilateral landings, 1 set of exercise vs. 4 sets, etc.) neither fatigue protocol seemed to cause dysfunctional movement patterns that might indicate an increased ACL injury risk.

In two similar research studies using squats to induce fatigue Smith et al. (2009) and James et al. (2010) used identical fatigue protocols comprised of isometric squats to induce fatigue and examine its effect on bilateral drop landings. The protocol consisted of a 15 s isometric squat at 60° of flexion followed by 5 s of rest. This process was repeated until the subject’s total force output for a set fell under 50% of their baseline MVC. At this point the subjects were considered to be fatigued and post testing measurements were initiated. Smith et al. (2009) reported fatigue to have caused significant alterations in maximum frontal plane knee motion ($p=.012$) during 50 cm bilateral landings for the group. Several subjects exhibited alterations in frontal plane knee motion at 30° of knee flexion and at max knee flexion. However, there was not a consistent trend for the group as some subjects exhibited greater valgus angles and some greater varus angles. These alterations suggest that fatigue induced by isometric squats has the potential to increase the strain placed on the ACL (Shimokochi & Schultz, 2008) due to an increase in frontal plane knee motion. On the other hand, James et al. (2010) report no differences in landing mechanics during a 61 cm bilateral landing after this isometric fatigue protocol. Unfortunately, the two authors chose to analyze different variables and the results of one study cannot confirm or refute the other. Smith et al. (2009) analyzed frontal plane knee motion while, James et al. (2010) analyzed sagittal plane motion. Based on the findings of Smith et al. (2009), it is possible that this isometric fatigue protocol has the potential to elicit movement patterns that more closely resemble ACL injury mechanism. Frontal plane knee motion has been shown to significantly load the ACL especially under weight-bearing conditions with the knee at low levels of flexion (<30°) (Shimokochi & Schultz, 2008). Nevertheless, when analyzing results from the same fatigue protocol James et al. (2010) observed no difference in knee flexion angle after the isometric fatigue protocol. Therefore, this protocol does not appear to cause both frontal and sagittal plane alterations that are characteristic of ACL injury (Koga et al., 2010). However, in the presence of an existing dysfunction in landing pattern, an increase in frontal plane knee motion could lead to rupture of the ACL.

To add to these findings, James et al. (2010) also incorporated a cycling fatigue protocol into the experimental design of their study. On a separate testing day fatigue was induced using a cycle ergometer by having the subjects pedal at 60% of their peak work rate at a frequency of 60-80 rpm until the subject could no longer maintain a cycling cadence of 40 rpm. Knee flexion decreased significantly due to fatigue ($p=.043$) experienced from the cycle ergometer. Knee flexion angle at contact was reported to be 5.2° smaller ($p<.017$) during the cycling fatigue condition compared to the isometric squat condition. This finding indicates that the cycling fatigue protocol may have led to a landing profile that is hypothetically more indicative of ACL injury risk. Kinematic measurements of movement in the frontal, and transverse planes would have offered greater insight into how these fatigue responses differed as a result of each fatigue protocol. However, the results of this experiment demonstrate the task dependent nature of fatigue and show that two different fatigue protocols produced different lower extremity alterations when all other aspects of the experimental design were controlled for. These results could provide justification for the use of functional fatigue protocols in the study design in order to reduce the margin for error in generalizing the effect of fatigue in the testing environment to fatigue experienced during athletic competition.

The decrease in knee flexion angle after fatigue on a cycle ergometer observed by James et al. (2010) is consistent with the findings Ortiz et al. (2010) who also reported decreased knee flexion angles after a fatiguing cycling exercise. Ortiz and colleagues (2010) chose to administer the Wingate 30- second anaerobic cycling protocol to induce fatigue in 15 recreationally active females and measure the effect on both bilateral drop landings from a 40 cm platform and unilateral hops onto a 20 cm platform. These authors observed a significant decrease in knee flexion angle ($p=.029$) after the fatiguing exercise during the hop task; however, only a slight decrease in knee flexion angle (1.05°) during the drop landing was evident. Ortiz et al. (2010) also noted a trend for increased valgus angles pre to post-fatigue in both the hop (5.80° vs. 8.19°) and drop landing (9.88° vs. 10.38°). Although the fatigue protocol utilized produce similar alterations (i.e. decreased knee flexion) as the protocol utilized by James et al. (2010) there are several differences in the study design that should be noted. First, James et al. (2010) evaluated the effect of fatigue on bilateral drop landings while Ortiz et al. (2010) chose unilateral landings.

It is possible that the effect of fatigue on landing may differ between bilateral and unilateral tasks, which are more difficult by nature. It has been reported that ACL injuries commonly occur with one limb bearing all or the majority of the weight (Koga et al., 2010) which may imply that the analysis of a unilateral task may be more appropriate and relevant to the sporting environment. In addition, the fatigue protocol used in the previous study consisted of a prolonged cycling activity which was intended to produce fatigue at both the central and peripheral levels (Smith et al., 2010). In contrast, the protocol administered by Ortiz et al. (2010) lasted only 30 seconds and was likely to produce a metabolic fatigue that occurs mainly at the peripheral level. It has been reported that recovery from metabolic fatigue that is the result of high frequency contractions occurs rapidly (Binder-Macleod & Russ, 1999) and this may have decreased the statistical power of any mechanical alterations that may have been present immediately post-fatigue. Nevertheless, it is evident that fatigue of the lower extremity induced by cycling has the potential to alter lower extremity kinematics in a manner that may be indicative of increased ACL injury risk.

Graded treadmill running has also been used to induce fatigue and study its effect on stop-jumps (Benjaminse et al., 2007), and drop landings (Moran & Marshall, 2006) with varying results. Benjaminse and colleagues (2007) recruited 30 physically active adults (15 male, 15 female) to perform a stop-jump task at a distance equal to 40% of the subject’s recorded height both before and after treadmill fatigue. The fatigue protocol that consisted of jogging at 5-8 mph (self-selected; male=6.3 ± .62 mph; female=5.8 ± .43 mph) for 3 minutes at 0% grade, with increasing grade by 2.5% every minute thereafter until exhaustion (men= 14:00 ±2:34 min; women=11:43± 1:50 min). Results indicate that subjects demonstrated significantly less maximal knee valgus angles (p=.038), and knee flexion angles (p=.009) after the exhaustive running protocol. Several previous fatigue models have also led to a decrease in knee flexion angle which is thought to be indicative of increased ACL injury risk. However, this is the only study that reported a decrease in knee valgus alignment as well. A decreased knee valgus angle while landing would suggest a decreased strain placed on the ACL, (Shimokochi & Schultz, 2008) and consequently, would reduce the risk for injury. Therefore, based on these results, it can be asserted that treadmill running caused alterations in lower extremity kinematics but it cannot be concluded whether this type of fatigue protocol created the decrease in sagittal plane movement in conjunction with increased frontal plane movement that is typical of ACL injury mechanisms.

Moran and Marshall (2006) used a similar treadmill protocol to induce fatigue in 15 physically active men. Unlike the study conducted by Benjaminse et al. (2007), the results of this study indicate that fatigue induced by a graded treadmill running protocol did not significantly affect landing kinematics. There are several differences in the study design of these two experiments that may account for these differences. First, the fatigue protocol in the current study consisted of treadmill running at 6 mph at 0% grade with a 1.5% increase in grade every minute and fatigue was determined to be the point at which the participant reported an RPE of 17 or greater. This placed a greater starting workload on the subjects than that in the study conducted by Benjaminse et al. (2007) which led to a faster time to fatigue in the current study compared to the previous one

(Benjaminse 14 min; Moran 8.3 min). Furthermore, the study by Moran and Marshall (2006) chose to evaluate fatigue's effect on bilateral drop landings from both 30 and 50 cm as opposed to unilateral hops. As mentioned previously, the unilateral task may be more relevant to the nature of an ACL injury and may be more sensitive in detecting of alterations compared to a bilateral task**.** Therefore, the results of Moran and Marshall (2006) should not be viewed to contradictory those of Benjaminse et al. (2007). The differences reported are likely the result of differences in the designs of the two experiments.

Using a protocol composed of step ups, Orishimo and Kremenic (2006) reported an increased peak knee flexion angle (p=.045) as a result of fatigue during a unilateral hop at 80% of maximum hop length. The authors recruited 13 healthy males to induce fatigue and study its effect on landing. The protocol consisted of sets of 50 step ups which were repeated until at least two full sets had been completed and the subject could no longer surpass 80% of their maximum unilateral hop length. The authors analyzed several other variables that may have implications for ACL injury risk and it appears that fatigue of the lower extremity induced by step ups did not alter the kinematic profile during hopping to more closely resemble that of an ACL injury situation. As mentioned previously, Thomas et al. (2010) reported significant decreases in knee flexion angle during a hopping task as a result of fatigue induced by isokinetic dynamometer. Once again there appears to be a difference in the fatigue response based on variations in the activities used to induce fatigue. As noted earlier, this lack of consistency may also be attributed to other variations found in the experimental design of these two studies. However, differences in the protocol used to induce fatigue appear to be a likely contributor.

It is clear that fatigue of the lower extremity induced by general fatigue protocols results in alterations in movement patterns when performing a functional task. However, these alterations tended to vary dramatically based on several details of each particular study design. Overall, several studies reported increases in knee sagittal (Benjaminse et al., 2007; James et al., 2010; Ortiz et al., 2010; Thomas et al., 2010), frontal (Smith et al., 2009), and transverse plane (Nyland et al., 1999; Thomas et al., 2010) kinematic risk factors for ACL injury risk, while two studies (Augustsson et al., 2006; Moran & Marshall, 2006) did not report any significant changes in lower extremity kinematics as a result of a general fatigue protocol.

When analyzing these results it is important to understand that these fatigue protocols do not attempt to recreate fatigue as typically occurs during competition. These experiments do, however, provide basic knowledge on the effect of fatigue induced by standardized exercise models on lower extremity kinematics. The findings of these studies support the hypothesis that fatigue may contribute to increased ACL injury risk in the sport context. Nevertheless, since it is evident that the effect of fatigue varies between protocols used to induce fatigue (James et al., 2010). Therefore to allow for generalizability of these results to sports competition, it may be necessary to incorporate more functional fatigue protocols into the experimental design composed of the actions characteristic of the sport(s) in which non-contact ACL injuries typically occur (e. g. basketball, volleyball, handball). The next section of this paper will review the literature evaluating lower extremity movement patterns before and after the completion of a fatigue protocol that incorporates functional tasks to induce fatigue.

Functional Fatigue Protocols

Functional fatigue protocols that incorporate movements that are naturally occurring in the sport(s) of interest are helping to provide further insight into ACL injury mechanisms. Several researchers have incorporated movements such as intermittent running (Sanna & O'Connor, 2008), repeated landing activities (Borotikar et al., 2007; Coventry et al., 2006; Madigan & Pidcoe, 2003; McLean & Samorezov, 2009), repeated jumping movements (Pappas et al., 2007) or a combination of these (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009) into fatigue protocols to recreate movements that are characteristic of those performed during high risk sports. These experiments have consistently reported alterations in movement patterns (Borotikar et al., 2008; Chappell et al., 2005; McLean et al., 2007; Sanna & O'Connor, 2008; Tsai et al., 2009), however, like general fatigue protocols, the results show a large degree of variation across studies. Furthermore, like general fatigue protocols the designs of functional fatigue protocols share very few similarities and the fatigue responses resulting from these protocols should be generalized with extreme caution.

For example, Madigan and Pidcoe (2003) induced fatigue through repeated cycles of unilateral squats and landings from a 25 cm platform. The 12 male subjects were required to perform an alternating cycle of 2 unilateral landings on the dominant leg followed by three unilateral squats on that same leg. This sequence was to be completed in approximately 20s and continued until the subjects “felt their right knee would collapse upon the next landing” (average=19.2±7.4 cycles). Lower extremity kinematics were measured throughout the fatigue protocol. The authors reported significant increases in peak knee flexion ($p<.05$) and ankle dorsiflexion ($p<.01$) after the completion of the fatiguing exercise. These alterations do not represent a dysfunctional landing pattern that would indicate increase strain placed on the ACL. It should be noted that only sagittal plane kinematics were analyzed and analysis of motion along the frontal and transverse planes may offer more insight into the effect of this fatigue protocol on ACL injury risk.

These results are similar to the findings of Coventry et al. (2006) who administered a fatigue protocol to 8 male subjects which consisted of alternating 5 unilateral squats with unilateral landings at 80% of maximal CMJ until they “felt they could not stick the next landing”. In this study analysis of sagittal plane kinematics reveal that fatigue increased initial contact hip ($p=.013$) and knee ($p=.002$) flexion, increased hip flexion at peak ($p=.033$), and decreased ankle range of motion ($p=.02$). As with the previous study, increase in sagittal plane motion does not suggest an increased ACL injury risk. Frontal and transverse plane motion analysis would be beneficial in helping gain a better understanding of the effect of this type of fatigue protocol on lower extremity kinematics.

Using the same type of fatigue design Borotikar et al. (2008) and McLean and Samorezov (2009) analyzed motion along all three planes and report alterations that would suggest an increased ACL injury risk post-fatigue. The results of these experiments seem to be inconsistent with those of the previous two studies. For example, in the study conducted by Borotikar et al. (2008) a decrease in initial contact hip flexion ($p<.001$), and internal rotation ($p<.001$) were reported. Furthermore, subjects also demonstrated increases in peak knee abduction ($p<.001$), knee internal rotation ($p<.001$), and ankle supination ($p<.01$) after the completion of the fatigue protocol. In this study fatigue was induced by alternating each landing with 5 bilateral squats at a frequency of 1 Hz until the subject could no longer complete 3 squats unassisted. The landings consisted of a random order of a left footed landing followed by an aggressive jump to the right, a right footed landing followed by an aggressive jump to the left, and a two footed landing followed by a maximum vertical jump.

The results may be different due to differences in the tasks analyzed by Borotikar et al. (2008) compared to the previous two studies (Coventry et al., 2006; Madigan & Pidcoe, 2003). Borotikar et al. (2008) analyzed a forward jump landing, while the previous two (Coventry et al., 2006; Madigan & Pidcoe, 2003) analyzed drop landings. In addition, the endpoints used to define fatigue as well as the subjects used could have also attributed to the differences in reported results. Both Coventry et al. (2006) and Madigan and Pidcoe (2003) recruiuted physically active males and defined fatigue as the point in which the subject felt he could not stick the next landing. Contrarily, Borotikar et al. (2008) recruited female division 1 athletes to participate in the study and fatigue was defined as the point in which the subject could no longer complete the squatting task. Any of these differences in the experimental design of these studies may have attributed to the inconsistencies in the fatigue response. However, it is impossible to determine how each of these factors may have contributed to these disparities.

Using a nearly identical experimental design as Borotikar et al. (2008), McLean and Samorezov (2009) reported significant increases in peak stance hip internal rotation (p<.01), and knee abduction (p<01) as well as a decrease in initial contact knee flexion (p<.01) after the completion of a fatigue protocol. The protocol consisted of the same sequence of landings as Borotikar et al. (2008) except this this experiment alternated these landings with unilateral squats performed on a base that moved 10 cm continuously in a medial to lateral direction at a frequency of 2 Hz. This protocol produced alterations that are similar to those reported by Borotikar et al. (2008). Both studies report an increase in transverse and frontal plane motion during peak stance, however, Mclean and Samorezov (2009) also reported a decrease in initial contact knee flexion that was not observed by Borotikar et al. (2008).

Nevertheless, these increases in frontal and transverse plane movement patterns are likely to reflect an increase in tension placed on the ACL during landing and suggest an increased risk of injury. It appears that unilateral squats on a moving base created a more dysfunctional landing pattern than bilateral squats due to the greater level of alterations observed by Mclean and Samorezov (2009). In this study a decrease in knee flexion angle was observed and a low knee flexion angle is reported to be one of the most important determining factors in strain placed on the ACL (Shimokochi & Schultz, 2008). These findings are further implicated in the presence of increased frontal and transverse plane movements which have been shown lead to greater loading of the ACL (Shimokochi & Schultz, 2008). Based on the results of these two studies it can be asserted that an alternating sequence of landing with a squatting exercise until the squats can no longer be maintained can elicit a fatigue response that increase the risk of suffering an ACL injury in experienced collegiate athletes.

Another interesting finding of these studies (Borotikar et al., 2008; McLean & Samorezov, 2009) is that all variables that experienced significant alterations displayed these alterations at the 50% fatigue level compared to baseline and did not significantly increase from the 50% fatigue level to maximum fatigue. Madigan and Pidcoe (2003) also observed a similar progression of fatigue with the two variables in that study (knee flexion and ankle dorsiflexion) reaching a level of significant change 15% of the way through the fatigue protocol.

Furthermore, Borotikar et al. (2008) and Mclean and Samorezov (2009) also incorporated a decision making condition in which the subjects were instructed on what foot to land with by an automated light switch approximately 350 ms prior to landing. This condition demonstrated an interaction with fatigue for peak knee abduction ($p<.001$), and initial contact hip flexion and internal rotation ($p<.05$) in the study by Borotikar et al. (2008) and peak stance hip internal rotation and knee abduction ($p<.05$) in the study conducted by McLean and Samorezov (2009). It is possible that fatigue's effect on ACL injury risk may be more pronounced when decision making is involved. This scenario is very common in the dynamic nature of competition.

To further support this theory, McLean and Samorezov (2009) also noted that there were no differences observed for any kinematic variables between the fatigued limb and the non-fatigued limb during the unanticipated landings. This crossover effect suggests the fatigue protocol caused deficits in central control which led to dysfunctional landing patterns in the non-fatigued limb due to inadequate time to make adjustments in the pre-programmed landing strategy (McLean & Samorezov. 2009). This indicated that the altered movement as a result of fatigue was mediated by a central mechanism. These results further explain how fatigue may contribute to injury risk during competition. Since most movements during competition are unanticipated, it may be necessary to incorporate decision making into the analysis of movement in the experimental context to gain a better understanding of how fatigue may increase the risk of ACL injury in the athletic population.

McLean et al. (2007) also used division 1 collegiate athletes to evaluate the effect of a functional fatigue protocol on movement patterns during landing. The subjects in this study were required to complete a continuous 4 minute cycle of 20 step ups onto a 20 cm step followed by 6 meters of bounds a direction turn and 6 additional meters of bounds as many times as possible. Significant increases in peak knee abduction ($p<.001$), and peak knee internal rotation ($p<.001$) were found during the 50 cm bilateral drop landings after the completion of the fatigue protocol. As observed in previously reviewed functional protocols (McLean & Samorezov, 2009) this fatigue protocol caused significant increase in frontal and sagittal plane knee motion which may suggest increased ACL injury risk. The findings in this study are unique in that this is the only fatigue protocol to increase frontal and transverse plane movement during bilateral landings. Smith et al. (2009) also observed similar frontal plane alterations after isometric squat fatigue; however, the changes were only significant in individual subjects and there was not a significant change across the group. These results suggest that the functional fatigue protocol used in the current study (McLean et al., 2007) was effective in interrupting movement patterns and possibly increasing ACL injury risk during a bilateral landing task.

In another attempt to mimic fatigue experienced in the sporting environment, Pappas et al. (2007) developed a fatigue protocol that consisted of 100 jumps over short (5-7 cm) obstacles and 50 maximal vertical jumps. The results of the MANOVA revealed a significant effect of fatigue ($p<.019$) on lower extremity mechanics for the 40 cm bilateral landings, however, no individual kinematic variables were significantly altered as a result of this fatigue protocol. Previous research has also found no effect of fatigue induced by graded treadmill jogging on bilateral landings (Moran & Marshall, 2006) at two different drop heights. Like the previous study (McLean et al., 2007), the same amount of work was completed by every subject, which included 16 men and 14 women. Unlike the previous study, however, this study did not recruit a uniform group of subjects with common characteristics (D1 athletes). This may have caused varying fatigue levels among subjects which would make it difficult to observe consistent lower extremity changes throughout the group.

Two other recent studies also incorporated a series of jumps into their fatigue protocol to induce fatigue (Chappell et al., 2005; Tsai et al., 2009). Chappell et al. (2005) used a fatigue protocol comprised of continuous cycles of 5 vertical jumps at 115% of reach height followed by a 30 m sprint until the subjects achieved a state of volitional exhaustion. The researchers found that this type of fatigue protocol significantly decreased peak knee flexion (p=.03) across all three bilateral forward stop jump tasks evaluated. Similarly, Tsai et al. (2009) established that the same protocol with a different jump criteria and end point significantly increased (p<.05) peak internal rotation in a 45° plant and cut task. This fatigue protocol lead to increasingly risky kinematic postures in both tasks analyzed. The forward stop jump is a task that is performed commonly during a basketball and volleyball. This task generates a great degree of anteriorly drawn forces at the knee joint. Therefore, a decrease in knee flexion angle during this task reported after fatigue (Chappell et al., 2005) indicates an increased percentage of the anteriorly drawn force placed on the ACL joint to maintain stability (Shimokochi & Schultz, 2008). This can be a dangerous landing pattern to adopt when experiencing fatigue during competition. In addition, this protocol also increased knee internal rotation during a run and cut maneuver. This type of move is performed often in soccer and basketball and can is a frequent cause of ACL injury. The increase in knee internal rotation evident throughout the movement would increase the strain placed on the ACL and increase the risk of injury. The fatigue protocol utilized in these two studies seems likely to induce movement patterns that more are more closely representative of an ACL injury situation. Since the movements used to induce fatigue and analyze lower extremity mechanics in these studies are similar to movements commonly performed during high risk sports (i.e. running and jumping), the results of these studies may suggest that fatigue causes movement patterns that are indicative of increased ACL injury risk during competition.

In another experiment analyzing the effect of fatigue on cutting, Sanna and O'Connor (2008) aimed to recreate the fatigue experienced in a soccer game to study the effect of fatigue on lower extremity mechanics during a side-step cut. The fatigue protocol utilized was a 1 hour shuttle run that was divided into 4 blocks with each of the first 3 blocks containing a series of 3 walks, 3 jogs, 3 cruises and 1 sprint between two cones located 20 m apart. The 4th block consisted of alternating jogging and cruising. The alternating walking, jogging, and cruising were meant to replicate the movement that a soccer player would engage in during competition. This fatigue protocol did not cause a significant change in CMJ power output compared to baseline measures; however, the protocol lead to a significant increase in knee internal rotation movement (p=.017) during the cutting task. This is consistent with previous findings that fatigue causes transverse plane knee deficits during a cutting task (Nyland et al., 1999; Tsai et al., 2009). This was the only study we found that aimed to replicate the type and duration of activity observed in a specific sport to induce fatigue and evaluate its effect on a functional task. Although other studies have also implemented sport-specific protocols into their fatigue design (Greig & Walker-Johnson, 2007; Ribiero, Santos, Gonclaves, & Oliveira, 2008), the authors of these research endeavors did not evaluate fatigue's effect on performance measures during a functional task. Therefore, the current study (Sanna & O'Connor, 2008) is unique in its experimental design and may offer deeper insight into the effect of fatigue on ACL injury risk during competition. Based on the current issues regarding the lack of consistency in experimental design in current research models it may be appropriate to assume that future research would benefit from the standardization of fatigue protocols to specific sporting contexts. This would allow for comparisons to be made across studies and would, consequently, allow for conclusions to be reached regarding fatigues effect on ACL injury risk during athletic competition.

Conclusion

ACL injuries continue to jeopardize the athletic careers and long term functional ability of many young athletes (McLean, 2008). Due to the nature of athletic competition it is clear that the manifestation of fatigue can lead to dysfunctional movement patterns that increase ACL injury risk. Based on current research, it is apparent that fatigue of the lower extremity can increase neuromuscular risk factors for ACL injury in the athletic population. Several types of fatigue models have produced dysfunctional movement patterns in the frontal, sagittal, and transverse planes (Benjaminse et al., 2007; Borotikar et al., 2008; Chappell et al., 2005; James et al., 2010; McLean et al., 2007; Nyland et al., 1999; Ortiz et al., 2010; Sanna & O'Connor, 2008; Smith et al., 2009; Thomas et al., 2010; Tsai et al., 2009). However, other models did not lead to the same detrimental alterations (Gehrig et al., 2003; Kernozek et al., 2008; Madigan & Pidcoe, 2003; Moran & Marshall, 2006; Orishimo & Kremenic, 2006; Pappas et al., 2006). It appears that this variability may be the result of several inconsistencies in the experimental design of these studies, particularly in the methods used to define and induce fatigue, which make it difficult to compare results and reach conclusions.

To our knowledge, only one study (Sanna & O'Connor, 2008) sought to recreate the fatigue experienced during a specific sport and analyze its effect on performance of a functional task. Due to the task dependent nature of fatigue, inducing fatigue in a manner similar to athletic competition may be necessary in order to more confidently generalize the results of these studies to the competitive environment. If this is the case these issues must be addressed in order to maximize the efficiency of future research in this area. It is important to determine whether current functional fatigue models can be representative of and generalized to fatigue experienced during competition. If not, it may be necessary to validate and standardize fatigue models that are representative of participation in athletic competition. Incorporating these methods into future research models may eliminate current obstacles in determining the effect of fatigue on ACL injury risk and permit the advancement of knowledge into fatigue's effect on ACL injury during athletic competition.

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CHAPTER II

VALIDATION OF TWO FATIGUE PROTOCOLS TO A SIMULATION BASKETBALL GAME FOR THE STUDY OF LANDING TECHNIQUE

Introduction

Injury to the anterior cruciate ligament (ACL) is considered to be one of the most debilitating and unpredictable injuries in sports. An ACL reconstruction carries an average price tag of $17,000 (Bach, Barker, & Strauss, 2010), and is typically followed by approximately 6 to 9 months of rehabilitation before an athlete is able return to competition (Silvers & Mandelbaum, 2011). Approximately 250,000 ACL injuries occur each year in the United States alone (Silvers & Mandelbaum, 2011), with at least half of these injuries occurring in athletes 15-25 years of age (Griffin et al., 2006). These young athletes who fall victim to an ACL injury are often plagued with chronic deficits in muscle strength and proprioceptive ability (Kvist, 2004) as well as significant long-term meniscal and articular cartilage loss that persists well after the termination of sport participation (Murrell, Maddali, Horovitz, Oakley, & Warren, 2001).

Epidemiological evidence suggests that approximately 70% of these injuries occurring in sport are non-contact in nature (Agel, Arendt, & Bershadsky, 2005; Hewett, Myer, & Ford, 2006a; Pollard, Davis & Hamill, 2004; Smith et al. 2009) and, thus, some may be prevented by reducing the risk factors that increase an athlete's vulnerability to this type of injury (Hewett, Myer, & Ford, 2006b). Several factors have been identified to increase the rate of non-contact ACL injury. Previous research has classified these factors as either environmental, anatomical, hormonal, or neuromuscular (Alentorn-Geli et al., 2009; Boden et al., 2000; Griffin et al., 2006; Hewett et al., 2006a; Hughes & Watkins, 2006; Shultz et al., 2010).

Research efforts have paid particular attention to neuromuscular factors due to the potential to modify these factors through neuromuscular training. ACL injury prevention programs have been successful at decreasing the neuromuscular risk factors for non-contact ACL injuries in athletic populations (Hewett, Linenfeld, Riccobene, & Noyes, 1999; Gilchrist et al., 2008; Mandelbaum et al., 2005; Myklebust et al., 2003). However, based on the continuing high incidence of ACL injury rates in sport (Agel et al., 2005), further investigation into how these risk factors manifest within an athlete and interact with one another to cause injury during competition is warranted (McLean & Beaulieu, 2010).

Fatigue, defined as a reduction in the muscles ability to produce force (Barry & Enoka, 2007), is a neuromuscular risk factor that has recently received attention in sports medicine research for its possible contribution to ACL injury risk during competition (Boden et al., 2000; Griffin et al., 2006; Hewett et al., 2006a; Hughes & Watkins, 2006; Shultz et al., 2010). Fatigue is a complex phenomenon that originates from a variety of mechanisms at the central and peripheral levels and is common to high intensity, prolonged exercise (Barry & Enoka 2007; Behm & St-Pierre, 1997; Binder-Macleod & Ross, 1999). Fatigue is reported to alter neuromuscular control (Green, 1997; Johnston, Howard, Cawley, & Losse, 1998) by reducing force production (Barry & Enoka, 2007), increasing knee joint laxity (Rozzi et al., 1999; Wojtys, et al., 1996), and decreasing knee proprioceptive ability (Allen, Leung, & Proske, 2010; Ribeiro, Santos, Goncalves, & Oliveira, 2008). Theoretically, these alterations to the neuromechanical profile as a result of fatigue will lead to an increased reliance on the ligaments to maintain the integrity of the knee joint (Solomonow et al., 1987), and, consequently, an increased probability of rupture to the ACL. Epidemiological evidence from multiple sports supports the hypothesis of fatigue as a risk factor for ACL injury by demonstrating a greater distribution of injuries towards the latter part of a match (Gabbett, 2000; Hawkins, Hulse, Wilkinson, & Gibson, 2001; Rahnama, Reilly, & Lees, 2002), which is usually concomitant with high levels of fatigue. Despite these findings, the effect of fatigue on ACL injury risk during competition remains unclear.

Several researchers have advanced knowledge in this area by measuring lower extremity mechanics during landing and cutting maneuvers similar to ACL injury mechanisms before and after the completion of a fatiguing protocol (Augustsson et al., 2006; Benjaminse et al., 2007; Borotikar et al., 2008; Chappell et al., 2005; Coventry et al., 2006; James et al., 2010; Kernozek et al., 2008; Madigan & Pidcoe, 2003; Mclean et al., 2007; McLean & Samorezov, 2009; Moran & Marshall, 2006; Nyland, Caborn, Shapiro, & Johnson, 1999; Orishimo & Kremenic, 2006; Ortiz et al., 2010; Pappas, Sheikhzadeh, Hagins, & Nordin, 2007; Sanna & O'Connor, 2007; Smith et al., 2009; Thomas, McLean & Palmieri-Smith, 2010; Tsai et al., 2010). Unfortunately, due to a lack of uniformity in the experimental design of these studies, particularly in the protocols used to induce fatigue, conclusions as to how fatigue may contribute to ACL injury risk have yet to be reached. It is reported that the type of fatigue experienced by a particular muscle or muscle group depends on the properties of the muscles themselves as well as the frequency, force, duration, and type of contractions that caused the muscle fatigue (Behm & St-Pierre, 1997). Due to this unique characteristic of fatigue, it would be unreasonable to assume that the fatigue experienced as a result of the completion of these diverse fatigue protocols can be compared to one another or generalized to the fatigue which occurs during sport participation with confidence. Therefore, the purpose of this technical note is to compare the effect of fatigue induced by two fatigue protocols similar to those used in previous research efforts to one another and to a simulated basketball game on lower extremity kinematics during a functional task. This is an exploratory study of the ecological validity of common fatigue protocols will offer insight into the similarities or differences in movement pattern alterations that may occur during a jump landing as a result of variations in the methodology used to induce fatigue.

Methods

Subjects

One male recreationally active basketball player (age=24, height=183 cm, mass= 86.3 kg) was recruited for this study. For the purpose of this study recreationally active was operationally defined as participating in pick-up basketball at least three days of the week. In addition, the subject was required to have high school varsity basketball experience in order to be considered for inclusion in this study. The subject was also required to be free from any chronic injury to the lower extremity and free from any recent (<6 months) lower extremity injury that might alter lower extremity mechanics and interfere with the results of this study. The subject was advised of the risks of the study and signed a consent form approved by the university IRB prior to participation in the study.

Instrumentation

Maximum vertical jump height (Vmax) was measured before the first testing session using the Vertec vertical jump testing device (Sports Imports,Inc., Columbus, OH, USA). Heart rate was monitored during the simulated basketball game using a Polar heart rate monitor (Model F-6, Polar Electro Inc., Woodbury, NY, USA) in order to document playing intensity relative to published research evaluating basketball competition. Pelvis and lower extremity 3-D joint kinematics for the dominant leg were measured using Ascension's Flock of Birds (Ascension Technologies Inc, Burlington, VT, USA) electromagnetic sensors and Motion Monitor for Research software (Innovative Sports Training, Inc., Chicago, IL, USA). Electromagnetic sensors were placed on the sacrum distal lateral thigh, and proximal medial shank using double sided tape and elastic wrap. Global and segment axes were established with the Y-axis designated as positive forward/anteriorly, the X-axis designated as positive leftward/ medially, and the Z-axis positive upward/ superiorly (Blackburn & Padua, 2008). The hip, knee, and ankle joint centers were modeled by estimating these points using a digitizing stylus. The hip joint center was estimated using the bell method, the knee joint center was estimated as the midpoint between the digitized medial and lateral femoral condyles, and the ankle joint center was estimated by the midpoint between the digitized medial and lateral femoral condyles (Blackburn & Padua, 2008). All kinematic data were sampled at a frequency of 240 Hz, and low pass filtered at 8 Hz according to standard Motion Monitor protocols. Reliability of the data across testing sessions was documented by control trials of standing, neutral posture. Positive rotations for each respective variable were defined as knee flexion and internal rotation, lower leg varus angulation, and hip internal rotation and abduction.

An isokinetic dynamometer (Biodex System 4 Pro, Biodex, Inc, Shirley, NY) was used to determine the subject's peak torque and induce fatigue in the dominant limb for the isokinetic fatigue protocol. The subject performed maximum effort concentric flexion/extension exercises at a velocity of 180°/ sec (Thomas, Mclean, &Palmieri-Smith, 2010) through the subject's active range of motion.

Experimental Design

The subject reported to the lab on 3 separate occasions for testing separated by at least a week in between sessions. During the first session vertical jump height was measured to establish a baseline Vmax after the completion of a dynamic warm up. After Vmax was assessed the subject then began the pre-fatigue landing trials. All landing trials required the subject to jump and reach a point marked at 50% of the subject's Vmax from a horizontal distance of 70 cm from the force plate followed by a one-legged landing onto the force plate and an immediate jump out of the landing. This type of task has been used previously (Shaw, Gribble, & Frye, 2008; Wikstrom, Powers, & Willman, 2004), and is similar to a basketball rebound which is hypothesized as a common ACL injury mechanism (Koga et al., 2010).

Before the initiation of testing the subject was instructed on how to perform and complete the jump landing according to protocol and was allowed practice attempts for familiarization with the task. The subject was then required to complete five successful trials of the landing. This number of trials has been found as a reliable number in similar research designs (Benjaminse et al., 2007; Moran & Marshall, 2006; Ortiz et al., 2010; Smith et al., 2009). Trials in which the subject lost balance, did not immediately complete the maximum vertical jump, did not land solely in the landing area, or did not touch the point marked 50% of Vmax was considered invalid and were repeated. Immediately after the completion of pretesting the subject completed one of three fatiguing protocols.

After the completion of the fatigue protocol the subject completed the post fatigue landing trials in the same manner as before the fatigue protocol. The delay between the termination of the fatigue protocol and the initiation of testing was standardized to 8 minutes and 27 seconds across the three fatigue protocols based on the time required to initiate the testing procedures after the completion of the simulated basketball game. For this reason the subject participated in the simulated basketball game during the initial testing session, the functional landing protocol during the second week, and the general fatigue protocol on the isokinetic dynamometer during the final testing session.

Fatigue Protocols

Simulated Basketball Game. The subject was tested before and after competing in two pickup basketball games. Each game was played to 30 points on a regulation sized basketball court with a 5 minute break in between games. The subject participated in a total of 45 minutes and 6 seconds of gameplay and had a mean HR of 156 beats per minute (BPM). This HR is similar to that reported by McInnes et al. (1995) who reported a HR of 165 ±9 BPM during a competitive basketball game using 8 elite Australian NBL players. Upon completion of the game the subject was immediately be taken to the lab for data collection. The time delay to get the subject to the lab, the perspiration toweled off and prepared for testing was recorded for standardization across the other testing procedures.

Drop Landings. The drop landing fatigue protocol consisted of an alternating series of 2 unilateral landings from a height of 60 cm followed by 3 unilateral squats from the drop landing platform until the subject could no longer complete 3 consecutive squats unassisted. The squat task was a body weight squat that was performed to a position in which the thighs were parallel to the ground. Consistent with previous research the entire landing sequence was be completed in a 20 second time frame in order to prevent any recovery that may occur (Madigan & Pidcoe, 2003). The subject was able to complete 36 cycles of this landing activity before fatigue was determined and he could no longer complete the squats unassisted.

Isokinetic Dynamometer. Fatigue on the isokinetic dynamometer was accomplished by continuous sets of quadriceps and hamstring concentric (180°/sec) contractions. Peak knee extension torque was determined by a series of 5 alternating quadriceps and hamstrings (QH) maximum voluntary concentric contractions (MVCC). After 2 minutes of rest the subject began the fatigue protocol which will consisted of sets of 10 QH MVCC until the subject's peak knee extension torque dropped below 50% of the baseline value for 5 consecutive knee extension repetitions. The desired level of fatigue was achieved during the sixteenth set of this exercise protocol.

Statistical Analysis

Kinematic data were sampled over a 0.4 second interval centered around the instant of peak knee flexion (PF). Respective values for hip adduction/abduction, and internal/external rotation, knee flexion/extension, valgus/varus and internal/external rotation were calculated for each landing trial at the moment of peak knee flexion. The knee valgus/varus variable refers to the motion of the lower leg in the frontal plane. Previous research has shown that knee flexion angles as well as frontal and transverse plane movement of the hip and knee joints are indicators of ACL strain and may represent underlying injury risk (Shimokochi & Schultz, 2008).

The kinematic data were averaged and change scores between the pre-fatigued and fatigued landings were calculated for all dependent variables (hip abduction/adduction, internal/external rotation and knee flexion/extension, valgus/varus, and internal/external rotation) across all three conditions. A 95% confidence interval was calculated for the change scores during the simulation basketball game and used for comparison across the other two conditions. P-value will be set at .05 for all statistical tests. Cohen's effect size (d) was also calculated to determine the magnitude of differences between the fatigue protocols. A value less than 0.2 was considered a small effect size, any value greater than 0.8 was considered large, and any value in between was considered a medium effect (Cohen, 1988).

Results

The neutral stance posture was consistent across testing session with mean (sd) values of 0.8 (4.4) degrees of knee flexion, -0.2 (1.0) degrees of knee external rotation, 0.2 (7.3) degrees of lower leg valgus (lower leg abduction), 7.2 (5.6) degrees of hip adduction, and -0.4(.34) degrees of hip external rotation. Descriptive data for the pre-fatigue landing kinematics at the point of maximum knee flexion for the basketball protocol are reported in Table 1. Subsequent analysis of change scores relative to fatigue controlled for small day-to-day variations in pre-fatigue landing technique.

Every outcome measure was significantly different ($p<.05$) from the basketball fatigue condition and at least one of the other fatigue protocols (Table 2). There was significantly (d = 1.6) less maximum knee flexion (16.1 degrees) in the landing protocol than the basketball protocol. Opposing adaptations in knee internal/rotation were observed across the isokinetic and landing fatigue protocols, with the isokinetic fatigue protocol producing significantly more (d=1.0) external rotation (10.3 degrees) and the landing protocol producing significantly greater(d=1.1) internal rotation (10.4 degrees) angles when compared to the basketball fatigue condition. The isokinetic fatigue protocol also resulted in significantly less (d=3.7) lower leg valgus (11.4 degrees) than the control condition. As for the hip variables the drop landing fatigue protocol produced significantly larger (d=5.5) hip abduction (50.3 degrees) angles, while both fatigue protocols caused the subject to land with a significantly smaller degree of hip internal rotation (d=2.2, isokinetic; d=2.4, landing) than the basketball protocol, (23.9 and 24.2 degrees respectively).

Discussion

The purpose of this study was to determine whether the hip and knee kinematic alterations in landing experienced as a result of basketball competition differed from the changes that resulted from participation in two fatigue protocols similar to those used in previous research evaluating the effect of fatigue on ACL injury risk. As hypothesized there were significant differences in the joint angles at the point of maximum knee flexion across the three fatigue protocols for the test subject. For the isokinetic fatigue protocol three of the five variables showed a large effect size and four of the five had a large effect size for the landing fatigue protocol. These results support the hypotheses of fatigue researchers that fatigue is task dependent and performance changes as a result of exhausting activity may vary with the activity used to induce this condition.

To our knowledge only one other study (James et al., 2010) has used multiple protocols to induce fatigue and compare their effects on landing performance. James and colleagues fatigued ten physically active male subjects using a cycling and an isometric squat protocol and measured sagittal plane hip and knee kinematics during bilateral drop landings from 61 cm. The authors reported a peak knee flexion angle during landing that was significantly larger (5.2°) for the squat fatigue protocol than the cycling fatigue protocol. These results indicate a different performance response for each of the two protocols and support the findings of the current study that changes iun knee flexion angle as a result of fatigue are dependent upon the protocol used to induce fatigue.

In the current study we used basketball competition as the control condition to examine the ecological validity of landing and isokinetic fatigue protocols on lower extremity kinematics during a forward jump landing. The results showed that all of the five hip and knee kinematic variables were subject to alterations that were different from simulated basketball competition in at least one of the other two conditions. For example, peak knee flexion increased after the basketball condition as well as the isokinetic fatigue condition, while the opposite was observed for the drop landing fatigue protocol which led to a decrease in peak knee flexion after the induction of fatigue. Previous research on the effect of fatigue on angular landing kinematics has also demonstrated both significant increases (Gherig et al., 2009; Kernozek et al., 2008; Madigan & Pidcoe, 2009; Orishimo & Kremenic, 2006) and decreases (Benjaminse et al., 2007; Borotikar et al., 2008; Chappell et al., 2005; James et al, 2010; McLean & Samorezov, 2009; Thomas et al., 2010) in knee flexion during landing after fatigue. These differences in performance changes are likely due to the variations in the protocols used to induce fatigue, e.g. (resistance exercise, repeated landing). Due to numerous differences in the fatigue protocols and experimental designs employed in these studies, it is difficult to predict sagittal plane knee kinematics that may result from a specific type of fatiguing activity.

The simulated basketball competition also led to an increase in knee internal rotation and lower leg valgus alignment (knee abduction) at the moment of peak knee flexion. This increase in knee internal rotation and knee abduction was also present in the landing fatigue protocol, but was not present in the isokinetic fatigue protocol. These performance changes indicate a compromised control of the knee in the transverse and frontal planes that were present after basketball competition and the landing fatigue protocol; however, did not result from isolated joint motion on the isokinetic protocol. This could be expected due to the nature of the isokinetic exercise which consisted of movement only in the sagittal plane and would not fatigue the muscles that are responsible for frontal and transverse plane movement. Previous research (Borotikar et al., 2008; McLean et al., 2007) has reported similar increases in knee internal rotation and lower leg valgus after fatigue resulting from performance of unilateral forward jump landings and bilateral drop landings, respectively. These researchers chose to fatigue the subjects using a fatiguing landing protocol (Borotikar et al., 2008) similar to the one utilized in the current study and a 4 minute series of bounds and step ups (McLean et al., 2007). It is evident that fatigue through the performance of dynamic activities can potentially compromise control of the knee joint in the transverse and frontal planes, and thereby, led to increased risk of ACL injury (Mclean & Beaulieu, 2010). This type of performance deficiency was not observed after the completion of resistance exercise that fatigued the muscles only in the sagittal plane.

Although the drop landing and basketball activities both produced increases in knee internal rotation, the drop landing fatigue protocol led to significantly larger increases in knee internal rotation (10.2°) when measured at peak knee flexion than basketball competition. These results demonstrate the possibility of exaggerating the performance changes that occur as a result of fatigue during competition through the use of a functional fatigue protocol to represent fatigue in the sporting environment. This information along with the differences observed with isokinetic exercise provide justification for fatiguing the muscles using more dynamic, ecologically valid exercises in order to more accurately determine the contribution fatigue may have on ACL injury risk during competition. Validation of fatigue protocols that represent fatigue as it is typically experienced in the sporting context could alleviate this issue and lead to a more thorough understanding of how fatigue in sport can contribute injury risk.

Basketball competition led to an increase in adduction and an increase in external rotation of the hip, while isokinetic fatigue led to an increase in hip adduction with no change in hip internal/external rotation, and the fatiguing landing protocol led to a large increase in hip abduction with no change in hip internal/external rotation. The most notable difference observed for the hip variables was the 50.3° larger hip abduction angle observed for the landing fatigue protocol compared to the basketball condition. This is a very large difference which may be explained by trunk positioning during the unilateral landing which the subject tended to vary greatly in order to maintain balance. The subject was qualitatively observed to engage in lateral trunk flexion directed toward the landing limb after the landing fatigue protocol. This type of alteration was not reported in any previous research; however, the nature of the landing in the current study was meant to replicate the actions of a basketball rebound and was different than landings that were used previously. In this study the subject was required to reach and touch a point marked 50% of his Vmax which diverted his full attention from landing and may have caused a more variable landing technique. This type of task has been shown to result in significantly different alterations as a result of fatigue compared to a drop landing (Edwards, Steele, & McGhee, 2010) which was chosen as the analyzed task in many of the previous research efforts. Therefore, the variations observed in this study may be representative of the dynamic landing tasks performed in basketball, and could also be representative of the perturbed landings that have been identified as contributing to ACL injury (Koga et al., 2010).

While the results of the current study provide support for the use of a sport-specific fatigue protocol to induce and study the effects on human performance, there are several limitations that must be noted. First, the single subject design of the study does not allow for any fatigue induced alterations reported as a result of fatigue to be generalized to any specific or general population. This limitation to our study does not allow conclusions on fatigue's effect on performance to be made confidently, as the experiment may have produced changes that were unlike those that may be observed with a larger, more heterogeneous population. However, the aim of the current study was simply to determine whether changes would occur across fatigue protocols and future research attempting to identify those changes should use a larger number of subjects in order to reliably determine the effect of sport-specific fatigue that can be generalized to a specific population of interest.

Another limitation is the large degree of variability within conditions that was observed for many of the landing variables analyzed. Again due to the single subject design chosen for this study a large degree of variability would be expected. Fortunately, despite this variability significant changes were observed pre to post fatigue indicating that the fatigue protocols produced consistent changes in the subjects' angular landing kinematics at the moment of peak knee flexion.

Also, due to the extreme values obtained for some of the hip abduction values, these values should be interpreted with caution. The possibility of movement of the sensor placed on the sacrum cannot be ruled out. The placement of this sensor made it difficult to ensure that it was securely mounted throughout the landing trials while the subject was perspiring which compromised the adhesive capabilities of the double-sided tape and cover all that was used to mount the sensor. A customized hip strap that would secure the sensor’s position on the subject would likely alleviate this problem and will be considered for future experiments when working with the Motion Monitor system.

Another limitation to the study is that basketball was used as a control condition to the other two fatigue protocols which makes the findings of this study specific to basketball competition. Although participation in other high risk sports such as soccer or volleyball may have also produced performance alterations that were different than those observed after completion of the fatigue protocols, this information is beyond the scope of this study and no conclusions can be made regarding the ability of these fatigue protocols in replicating the fatigue of other sports. In addition, simulated basketball fatigued the entire lower extremity, while the other two conditions focused on the dominant limb. This may have led to some of the differences in the performance changes observed as a result of the fatiguing activities. Due to the fact that testing was only done on the dominant limb, this was not considered a problem. Furthermore, previous research has reported a crossover effect of unilateral fatigue to the contralateral limb (McLean & Samorezov, 2009) and therefore, may result in the same alterations as a bilateral fatiguing activity.

Although several limitations existed in this study, it can be concluded that for the subject and tasks analyzed the fatigue experienced as a result of basketball play resulted in alterations to lower extremity angular kinematics at the moment of peak knee flexion that were not like those observed after an isokinetic or landing fatigue protocol. These findings have implications for future research on the effect of fatigue on ACL injury risk. Since ACL injuries are frequent among the young, athletic population (Griffin et al., 2006), it seems logical that in order to advance our understanding of the effect of neuromuscular fatigue on ACL injury risk researchers should induce fatigue using sport-specific movements or actual sports competition. Future research should incorporate fatigue protocols that are both more specific and validated as representative of participation in the sport of interest in order to offer greater insight regarding the effect of fatigue on ACL injury risk.

Table 1. Means and Standard Deviations (degrees) for Angular Landing Kinematics at the Moment of Peak Flexion Prior to the Basketball Fatigue Condition

Variable	Mean	SD
Knee flexion/extension	42.7	10.2
Knee internal/external rotation	-0.5	4.4
Lower leg valgus/varus	-16.9	2.9
Hip abduction/adduction	17.2	9.2
Hip internal/external rotation	15.6	9.9

Table 2. Means, Standard Deviations, and Cohen's d of Change Scores for Variables at Peak Knee Flexion After the Completion of Fatigue Protocols (degrees)

	Basketball Fatigue			Isokinetic Fatigue			Landing Fatigue		
	M	SD	CI	M	SD	d	M	SD	D
KFE	11.3	7.8	4.4, 18.1	8	10.5	0.3	-4.8*	10	1.6
KIE	4.2	2.3	2.1, 6.2	-5*	3.1	1.0	14.6*	2.1	1.1
KVV	-9.7	3.3	-12.6, -6.8	0.9*	6.2	3.7	-9.2	2.1	0.2
HAA	-17	1.4	-27.6, -7.6	-10.4	7.2	0.7	33.3*	5.5	5.5
HIE	-26.2	12.7	-37.3, -15	-4.1*	5.4	2.2	-2*	3.4	2.4

Knee Flexion/Extension (KFE), Knee Internal/External Rotation (KIE) , Knee Varus/Valgus (KVV), Hip Abduction/Adduction (HAA), Hip Internal/ External Rotation (HIE)
* Significant (p<.05) difference from the basketball fatigue condition

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