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Knee Kinematics is Altered Post-Fatigue While Performing a Crossover Task

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Abstract

Purpose—To examine the effect of a sequential fatigue protocol on lower extremity biomechanics during a crossover cutting task in female soccer players.

Methods—Eighteen female collegiate soccer players alternated between a fatigue protocol and two consecutive unanticipated crossover trials until fatigue was reached. Lower extremity biomechanics were evaluated during the crossover using a 3D motion capture system and two force plates. Repeated measures ANOVAs analyzed differences between three sequential stages of fatigue (pre, 50%, 100%) for each dependent variable ($\alpha=0.05$).

Results—Knee flexion angles at initial contact (IC) for pre- ($-32\pm9^\circ$) and 50% ($-29\pm11^\circ$) were significantly higher than at 100% fatigue ($-22\pm9^\circ$) ($p<0.001$ and $p=0.015$, respectively). Knee adduction angles at IC for pre- ($9\pm5^\circ$) and 50% ($8\pm4^\circ$) were significantly higher ($p=0.006$ and $p=0.049$, respectively) than at 100% fatigue ($6\pm4^\circ$).

Conclusions—Fatigue altered sagittal and frontal knee kinematics after 50% fatigue whereupon participants had diminished knee control at initial contact. Interventions should attempt to reduce the negative effects of fatigue on lower extremity biomechanics by promotion appropriate frontal plane alignment, and increased knee flexion during fatigue status.

Keywords

Kinematics; ACL injury; knee; female; soccer; decision-making

Introduction

The incidence of noncontact anterior cruciate ligament (ACL) injuries among female athletes remains stable despite resolute efforts to reduce the incidence of injuries to the lower extremity.[1, 2] In collegiate soccer, females experience an almost three-fold greater

ACL tear rate than their male counterparts (0.32 vs. 0.12, respectively).[2, 31] The immediate and long-term implications of an ACL injury include functional restrictions, related pain 10–20 years subsequent to diagnosis, and high prevalence of radiographic osteoarthritis (OA), with little evidence to suggest a reduction of OA incidence following surgical ACL reconstruction.[14, 20, 21, 24, 29] Although the specific mechanisms of ACL injuries remain unclear, several risk factors pertaining to neuromuscular, biomechanical, hormonal and structural domains have been explored.[34] One potential risk factor, neuromuscular fatigue, has been recently evaluated to determine the nature and the extent of its role in ACL injury risk.[23, 27, 28]

Fatigue negatively affects lower extremity biomechanics during the execution of athletic maneuvers.[6, 23, 27, 28] It potentially contributes to increased ACL strain by decreasing hip and knee flexion angles and increasing knee valgus and peak knee anterior shear forces during various movements, including single-leg landings and stop-jump tasks.[6, 19] Fatigue also affects dynamic muscle control during a variety of athletic tasks.[6, 30] Peripheral and central fatigue mechanisms together impact lower limb movement patterns leading to potentially high ACL injury-risk situations.[6, 16, 28] Due to the fact that soccer players encounter long bouts of high-intensity activity, the effect of fatigue on lower extremity injury risk is vastly important.

Neuromuscular fatigue alone diminishes dynamic control of the lower extremities; the addition of decision-making when the athlete is concurrently fatigued presents an additional challenge.[10, 18] Fatigue combined with decision-making often leads to high-risk neuromuscular strategies potentially increasing an athlete's susceptibility to ACL injury.[5] Fatigue-induced biomechanical changes have been shown to be greater during unanticipated landings than anticipated landings.[5, 28] Unanticipated landings have been reported to result in significant increases in hip internal rotation at initial contact and knee abduction angles at peak stance.[5, 28] The combination of central fatigue and decision-making cause significant biomechanical modifications, which remain unclear relative to ACL injury risk, and warrant further exploration.[5, 28]

Overall, fatigue may negatively impact lower extremity biomechanics and dynamic control. Thus, when prescribing rehabilitation programs for athletes who have had surgery post knee injury, it may be essential for clinicians to not only increase their athletes' time to fatigue but also teach their athletes to focus on maintaining lower extremity movement mechanics during fatigue. Previous studies have evaluated the effects of fatigue on various athletic tasks and observed potentially detrimental movement patterns that could result in injury.[5, 6, 19, 23, 27, 28] However, few studies have assessed the point at which fatigue impacts biomechanical movement patterns.[5, 28] An even smaller number of studies have utilized a soccer-specific sequential fatiguing protocol to evaluate the effect of fatigue combined with decision-making on a maneuver that is specific to soccer, the sidestep cutting task.[23] Other soccer-specific movements such as the crossover task have not been studied using this methodology. While it has been suggested that fatigue alters lower extremity biomechanics potentially placing athletes at higher risk, most studies have been conducted within a highly control environment. There is a need to further understanding how fatigue exacerbates lower

extremity biomechanics during an unanticipated situation that replicates a soccer situation that is similar to the participants' activity.

Therefore, the aim of this study was to examine the effect of a sequential fatigue protocol combined with an unanticipated task on the lower extremity biomechanics of a crossover task (CO) in collegiate female soccer players. Our hypothesis was that fatigue would have a progressively detrimental effect on lower extremity biomechanics suggesting an increased risk e.g., ACL injury. Specifically, it was hypothesized that fatigue would lead to decreases in knee flexion angles and increases in knee abduction at initial ground contact during the late stages of fatigue (50–100%).

Materials and Methods

A convenience sample of eighteen NCAA Division 1 female soccer players (age = 19 0.9 years; height = 166 5 cm; mass = 62 5 kg) volunteered to participate in this study. All of the athletes who were enrolled in the study were free of lower extremity injuries. Prior to data collection, all participants understood the procedures and provided written informed consent and the Institutional Review Board of Old Dominion University (#07-074) approved the experimental protocol.

Experimental Procedures

The participants were instructed to wear team running shoes (Adidas Supernova, AG, Herzogenaurach, Germany), as well as a sports bra and spandex shorts. Anthropometric data (i.e. height, mass, skinfolds) were obtained prior to biomechanical testing. The dominant leg was determined as the leg that the participant would use to kick a soccer ball for maximal distance.[23] Participants were allotted a warm-up time (10 minutes) consisting of cycling and self-guided stretching. Subsequently, the VERTEC (Sports Import, Hilliard, OH) device was utilized to determine each participant's maximum vertical jump.[6]

The experimental protocol required the participants to repeatedly perform four unanticipated tasks (two running-stop and two crossover) immediately followed by a fatiguing protocol until complete fatigue was reached. Lower extremity three-dimensional joint kinematic and ground reaction force data was recorded during the execution of the unanticipated tasks. For the purpose of this study, only the crossover task was kept for analysis with the running-stop being discarded prior to analysis, since the running-stop was only included to create the unanticipation/decision-making factor.

The crossover task consisted of a running approach, step with the dominant foot on the force plate, and a crossover step with the non-dominant foot to the ipsilateral side at a 45° angle. Prior to data collection, the participants were given three practice trials, or until they felt comfortable with the task. On average, participants performed four trials to become acquainted with the task. During testing, if the participant failed to fully contact the force plate or did not execute the task at a minimum speed of 3.5 m/s, the trial was discarded and repeated. As well, trials were discarded and repeated if the participant surpassed the maximum speed of 5.0 m/s. The maximum speed was set to ensure that the participant was reacting to the visual cue received and not performing a pre-planned movement, as a speed

greater than 5.0 m/s would not allow time for the participant to perform such a reaction.[33] The speed of the participant was determined by two telemetered Brower timing systems (Brower, Draper UT, USA), set one meter prior to, and directly at, the front edge of the force plates.

The unanticipated factor was controlled by a photoelectric gate that was placed two meters before the force plates. When the participant crossed the light beam, a software program was activated to randomly project a soccer scenario onto a screen in front of the participant.[8] The participant was told to react to the soccer scenario with the appropriate athletic task (running stop or crossover).

Functional Agility Short-Term Fatigue Protocol (FAST-FP)

Immediately after completing four successful unanticipated tasks, the participant performed the functional agility short-term fatigue protocol consisting of three counter-movement jumps at 90% of their maximum vertical jump, three parallel squats to 90° of knee flexion, a 5-10-5 agility drill, and step-ups on a 30-cm box for 20 seconds, at a rate of 200 beats per minute as determined by a metronome.[23, 27] (Figure 1) After completing the fatigue protocol, the participant returned to attempting four successful unanticipated tasks (Figure 2). The participant continued to alternate between the four unanticipated tasks and the fatiguing protocol until maximum fatigue was reached. Fatigue was determined by: a) failure to attain all three vertical jumps at 90% of their maximum vertical jump for two consecutive fatigue sets, and/or b) a heart rate plateau that was within 90% of the participant's estimated heart rate maximum (the plateau had to occur over three consecutive fatigue sets).[13] The participant's heart rate was continuously monitored using a Polar system (Model FS2C, Polar Electro, Lake Success NY, USA). Prior to statistical analyses, the crossover tasks were normalized to a percentage of fatigue. The first set of crossover tasks was considered pre-fatigue (e.g., 0%); the last set when maximum fatigue was achieved was considered 100% fatigue. The data point of 50% fatigue was calculated as the median trial as previously reported.[6]

Biomechanical Analysis

Forty reflective markers were placed on specific body landmarks; ten of the forty were calibration markers and were removed prior to the fatigue protocol.[23] Pelvic tracking markers were secured with surgical glue, and thigh and shank cluster markers were secured with pre-wrap and powerflex tape. Cluster plates with five markers were attached to the participants' shoes with athletic tape.[23] The same researcher placed the markers on all subjects. Based on data from our laboratory, we have shown good to excellent reliability in marker placement (ICC=0.620 to 0.889).[7] Eight high-speed motion analysis cameras (Vicon, Oxford, England) sampling at 300 Hz were used to acquire trajectory data, while two force plates (Bertec, Columbus OH, USA) sampling at 1200 Hz obtained GRF's. From the standing trial, a kinematic model (pelvis, thigh, shank, and foot) was created for each participant using Visual 3D software (C-Motion, Germantown MD, USA) with a least-squares optimization.[22] The kinematic model was used to quantify the motion at the hip, knee, and ankle joints with rotations being expressed relative to the standing trial. A standing trial with circular motion about the pelvis was used to calculate functional hip joint

centers.[3, 32] A fourth-order Butterworth zero lag filter with 7 and 25 Hz cutoff frequency was used to filter trajectory data and GRF data, respectively.[36] An inverse dynamic method, using segment inertial characteristics estimated for each participant was employed to the kinematic and GRF data to calculate three-dimensional forces and moments.[12, 35] Joint moments were defined as internal moments and were expressed to the respective joint-coordinate system (e.g., a knee internal extension moment will resist an external flexion load applied to the knee). All data were normalized to 100% of stance, with initial contact being the point when vertical ground reaction force exceeded 10N and ended with toe-off.

Statistical Analyses

Our sample size was estimated in accordance with previous research examining the effects of fatigue on lower extremity biomechanics and to achieve 80% statistical power with an alpha level of 0.05. [5, 6, 23, 28] The independent variable was fatigue at three levels (pre-fatigue, 50% and 100% fatigue). Separate repeated-measures analysis of variance (ANOVA) determined whether there was a difference between levels of fatigue for each dependent variable. When significance was noted, paired *t*-tests, with a Bonferroni adjustment, were utilized to determine where the significance occurred between levels of fatigue. The dependent variables included hip and knee flexion and abduction angles and moments, measured at initial contact and peak stance.[27] Peak stance represents the maxima or minima, dependent upon the rotational direction of the angle or moment, occurring between 0–50% of the stance phase.[27] All data were reduced using Visual 3D and a custom-made MATLAB program (MathWorks, Natick MA, USA). Statistical procedures were conducted in SPSS 16.0 (IBM, Chicago, IL). Alpha level was set *a priori* at 0.05.

Results

Significant differences in knee flexion and knee abduction angles were observed throughout the fatiguing protocol (Table 1). The sequential fatigue protocol significantly decreased the knee flexion and adduction angles at initial contact during the crossover task from 50% to 100% of fatigue. Specifically, knee flexion angle at initial contact for pre-fatigue and 50% of fatigue were significantly higher than at 100% of fatigue ($p<0.001$ and $p=0.015$, respectively). Similarly, knee adduction angle at initial contact for pre-fatigue and 50% of fatigue were significantly higher than at 100% ($p=0.006$ and $p=0.049$, respectively). The fatiguing protocol altered lower extremity kinematics primarily in the sagittal and frontal knee angles.

No significant differences between fatigue levels were observed for the other kinematic and kinetic variables: hip flexion angle at initial contact, hip abduction angle at initial contact, hip flexion angle at peak stance, knee flexion angle at peak stance, hip adduction moment at initial contact, and knee adduction moment at initial contact (*n.s.*). Further, there was no statistically significant difference between pre-fatigue and 50% of fatigue for frontal and sagittal plane knee angles, with most of the kinematic change observed after 50% of fatigue (Figures 3a and 3b).

Discussion

The most important finding of the present study was that fatigue, paired with an unanticipated factor, significantly altered lower extremity kinematics of an athletic task, potentially placing the participant at a higher risk of injury. The results are in agreement with previous studies that have shown a significant effect of fatigue and decision-making on lower extremity kinematics during athletic tasks.[5, 6, 28] The results partially supported the hypothesis that fatigue combined with decision-making would alter lower extremity biomechanics during the crossover task. There were significant kinematic changes over time for two variables, sagittal plane knee angle at initial contact and frontal plane knee angle at initial contact, however there was no change in the other dependent variables. While no significant changes occurred between 0–50% of fatigue, a disparity was noticeable from 50%–100% of fatigue, a pattern that is consistent with previous work.[28]

The effects of neuromuscular fatigue on kinematics have been evaluated for a variety of movements including single-leg jump landings, sidestep cutting and stop-jump tasks.[5, 6, 23, 28] However, we believe the present study is the first to specifically examine collegiate soccer players during the performance of the crossover maneuver, a task that is frequently executed in soccer. It is possible that the specific biomechanical demands of the crossover task, as well as the characteristics of the fatigue protocol we used in this study, the pre- and post-fatigue kinematic changes we observed are considerably different from previous findings.[5, 6, 28] A fatigue protocol consisting of repetitive double leg squats and single-leg jump landing tasks resulted in increases in initial contact hip extension, hip internal rotation, peak stance knee abduction, peak stance knee internal rotation and ankle supination angles during the single-leg jump landing task.[5] Likewise, Chappell et al. (2005) observed increased valgus moments during a biomechanical evaluation of three different stop-jump landing tasks. It is unclear whether the discrepancy between the abovementioned studies and our study is primarily associated with the tasks evaluated, the fatigue protocol, or a combination of the two factors. However, it should be noted that in our previous research we found that biomechanical demands are task-specific.[9]

The results of the present study demonstrated that a combination of fatigue and decision-making while conducting a running crossover task had a significant and detrimental effect on the knee flexion angle at initial contact. Landing in an extended knee position has been reported to increase the proximal anterior tibial shear forces thus placing considerable strain on the ACL.[25, 26, 37] Fatigue combined with decision-making resulted in a 10° decrease in knee flexion at initial contact from pre-fatigue to 100% fatigue. The post-fatigue value is within the potentially hazardous range of 10–30° of knee flexion at initial contact, which is the range at which the quadriceps muscle has been shown to exert its maximum anterior shear force.[4, 15] Even though the knee angle at 100% fatigue ($-22 \pm 9^\circ$) may seem less favorable than the pre-fatigue value ($-32 \pm 9^\circ$), both values are considered at-risk. This at-risk position may be directly related with typical female landing patterns where it is suggested that females have decreased knee flexion angles than males during landing.[11]

While high-risk strategies may occur before an athlete is fatigued, we concluded that fatigue was only detrimental to knee kinematics in the later stages (post 50% fatigue). It was

hypothesized that the aberrant kinematics between 50–100% of fatigue may have been a result of the athlete's inability to control knee angles while coping with neuromuscular fatigue and decision-making. This effect was greater and more unfavorable for the sagittal plane knee angle than the frontal plane knee angle. The frontal plane knee angle decreased from pre-fatigue to 100% of fatigue indicating movement towards increased valgus knee motion, which has been shown to predict subsequent increased ACL injury risk.[17] Although a statistically significant difference, the knee angle during the crossover task remained positive, indicating a varus position at maximum fatigue. Because of the varus knee angle, the risk of injury is theorized to be minor. Overall, the pattern of fatigue in the present study supported previous findings, which evaluated the effect of a fatiguing protocol on single-leg landings.[28] Fatigue had a unique effect on lower extremity biomechanics that appears to be task-dependent, however the changes occurred during the same fatigue phase suggesting that significant biomechanical decline may not be noticeable until the athlete is sufficiently fatigued. Therefore, it may be beneficial to evaluate athletes for injury risk factors while they are adequately fatigued in order to expose additional biomechanical deficiencies that may be harmful to the ACL.

Limitations to the study should be carefully considered. The athletes were presented with a simulated soccer scenario yet they did not have to interact with or avoid actual players. Further, the laboratory setting prevented the presence of variable terrain (grass, turf, holes, slippery surfaces), which could increase injury risk in a real-life scenario. The pattern of fatigue may also have been different in this study compared to a soccer match. In our lab-controlled environment, the participants' fatigue level increased until maximum fatigue was determined without rest periods. However, a soccer match contains brief moments of rest and recovery followed by sudden surges of maximal effort. We also only assessed three time points throughout the fatigue process (pre, 50%, and 100%), and further division into smaller periods (e.g., 0, 25, 50, 75, 100%) may yield additional information. Lastly, our population was highly trained and our results may not be transferable to general sporting population.

The findings of this study support the notion that fatigue combined with decision-making presents a unique neuromuscular challenge to the athlete. In addition, the biomechanical changes that occur during the later phases (50–100%) of a fatiguing protocol appear to be task-specific. The information provided by this study suggests that pre-season movement screenings should occur before, during and after fatiguing events with the aim of identifying additional risk factors that may not be visible pre-fatigue and become visible post-fatigue. This information could be valuable to identify those athletes that are able to cope with fatigue and those who may require additional intervention training. Coaches and sports medicine professionals should understand that the effect of fatigue on lower extremity biomechanics may be task-specific. Therefore, future studies should evaluate the unique effects of fatigue on injury-risk during various soccer maneuvers. Intervention programs should also be employed while the athlete is fatigued using unanticipated factors such as perturbation or reactive exercises to potentially improve lower extremity kinematics.

CONCLUSION

This study was conducted to determine the effects of fatigue on an unanticipated crossover task at three instants (pre, 50%, and 100% fatigue). A detrimental effect on lower extremity biomechanics was noted for knee sagittal and frontal kinematics from 50 to 100% fatigue. Any other biomechanical variable was not significantly affected by fatigue.

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References

1. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med.* 2005; 33(4):524–530. [PubMed: 15722283]
2. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train.* 1999; 34(2):86–92. [PubMed: 16558564]
3. Begon M, Monnet T, Lacouture P. Effects of movement for estimating the hip joint centre. *Gait and Posture.* 2007; 25(3):353–359. [PubMed: 16733087]
4. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med.* 1995; 23(1):24–34. [PubMed: 7726347]
5. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon).* 2008; 23(1):81–92.
6. Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *Am J Sports Med.* 2005; 33(7):1022–1029. [PubMed: 15983125]
7. Cortes N, Blount E, Ringleb S, Onate J. Soccer-specific video simulation for improving movement assessment. *Sports biomechanics / International Society of Biomechanics in Sports.* 2011; 10(1):12–24. [PubMed: 21560748]
8. Cortes N, Blount E, Ringleb S, Onate JA. Soccer-specific video simulation for improving movement assessment. *Sports Biomech.* 2011; 10(01):22–34. [PubMed: 21560749]
9. Cortes N, Onate J, Van Lunen B. Pivot task increases knee frontal plane loading compared with sidestep and drop-jump. *Journal of sports sciences.* 2011; 29(1):83–92. [PubMed: 21086213]
10. Covassin T, Weiss L, Powell J, Womack C. Effects of a maximal exercise test on neurocognitive function. *Br J Sports Med.* 2007; 41(6):370–374. discussion 374. [PubMed: 17224438]
11. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon).* 2003; 18(7):662–669.
12. Dempster WT. Space requirements of the seated operator. Wright Air Development Center Technical Report. 1955; 55159:55–159.
13. Gellish RL, Goslin BR, Olson RE, McDonald A, Russi GD, Moudgil VK. Longitudinal modeling of the relationship between age and maximal heart rate. *Med Sci Sports Exerc.* 2007; 39(5):822–829. [PubMed: 17468581]
14. Golightly YM, Marshall SW, Callahan LF, Guskiewicz K. Early-onset arthritis in retired National Football League players. *J Phys Act Health.* 2009; 6(5):638–643. [PubMed: 19953841]
15. Griffin LY, Agel J, Albohm MJ, Arendt EA, Dick RW, Garrett WE, Garrick JG, Hewett TE, Huston L, Ireland ML, Johnson RJ, Kibler WB, Lephart S, Lewis JL, Lindenfeld TN, Mandelbaum BR, Marchak P, Teitz CC, Wojtys EM. Noncontact anterior cruciate ligament

- injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000; 8(3):141–150. [PubMed: 10874221]
16. Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynon BD, Demaio M, Dick RW, Engebretsen L, Garrett WE Jr, Hannafin JA, Hewett TE, Huston LJ, Ireland ML, Johnson RJ, Lephart S, Mandelbaum BR, Mann BJ, Marks PH, Marshall SW, Myklebust G, Noyes FR, Powers C, Shields C Jr, Shultz SJ, Silvers H, Slaughterbeck J, Taylor DC, Teitz CC, Wojtyk EM, Yu B. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* 2006; 34(9):1512–1532. [PubMed: 16905673]
 17. Hewett TE, Myer GD, Ford KR, Heidt RS Jr, Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005; 33(4):492–501. [PubMed: 15722287]
 18. Isaacs L, Pohlman E. Effects of exercise intensity on an accompanying timing task. *Journal of Human Movement Studies.* 1991; 20:123–131.
 19. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med.* 2008; 36(3):554–565. [PubMed: 18006677]
 20. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med.* 2007; 35(10):1756–1769. [PubMed: 17761605]
 21. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum.* 2004; 50(10):3145–3152. [PubMed: 15476248]
 22. Lu TW, O'Connor JJ. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *J Biomech.* 1999; 32(2):129–134. [PubMed: 10052917]
 23. Lucci S, Cortes N, Van Lunen B, Ringleb S, Onate J. Knee and hip sagittal and transverse plane changes after two fatigue protocols. *J Sci Med Sport.* 2011; 14:453–459. [PubMed: 21636322]
 24. Maffulli N, Longo UG, Gougoulas N, Loppini M, Denaro V. Long-term health outcomes of youth sports injuries. *Br J Sports Med.* 2010; 44(1):21–25. [PubMed: 19952376]
 25. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slaughterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995; 13(6):930–935. [PubMed: 8544031]
 26. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament: An in vitro study performed with a new experimental technique. *J Bone Joint Surg Am.* 1990; 72(4):557–567. [PubMed: 2324143]
 27. McLean SG, Fellin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc.* 2007; 39(3):502–514. [PubMed: 17473777]
 28. McLean SG, Samozov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. *Med Sci Sports Exerc.* 2009; 41(8):1661–1672. [PubMed: 19568192]
 29. Oiestad BE, Engebretsen L, Storheim K, Risberg MA. Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. *Am J Sports Med.* 2009; 37(7):1434–1443. [PubMed: 19567666]
 30. Orishimo KF, Kremenik JJ. Effect of fatigue on single-leg hop landing biomechanics. *J Appl Biomech.* 2006; 22(4):245–254. [PubMed: 17293621]
 31. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy.* 2007; 23(12):1320–1325. e1326. [PubMed: 18063176]
 32. Schwartz MH, Rozumalski A. A new method for estimating joint parameters from motion data. *J Biomech.* 2005; 38(1):107–116. [PubMed: 15519345]
 33. Shelton J, Kumar GP. Comparison between auditory and visual simple reaction times. *Neuroscience & Medicine.* 2010; 1(1):30–32.
 34. Shultz SJ, Schmitz RJ, Nguyen AD. Research retreat IV: ACL injuries—the gender bias: April 3–5, 2008 Greensboro, NC. *J Athl Train.* 2008; 43(5):530–531. [PubMed: 18833316]
 35. Winter, DA. Biomechanics and motor control of human movement. John Wiley & Sons Inc; 2009.

36. Yu B, Gabriel D, Noble L, An K. Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *J Appl Biomech*. 1999; 15(3):318–329.
37. Yu B, Lin CF, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech (Bristol, Avon)*. 2006; 21(3):297–305.

Figure 1.
Sequence of fatigue protocol from left to right: step-ups, squats, vertical jumps, and 5-10-5 agility drill.

Figure 2.
Data collection sequence of events

a)

b)

Figure 3.

a & b. Knee flexion and abduction angles at initial contact presenting a significant change from pre and 50% to 100% fatigue.

Means $\pm$ SDs of the Dependent Variables at Different Fatigue Levels (Prefatigue, 50% Fatigue, and 100% Fatigue) at Initial Contact and Peak Stance During a Crossover Task

Table 1

Dependent Variable	Pre-fatigue		50% fatigue		100% fatigue		p
	Mean	SD	Mean	SD	Mean	SD	
Knee Flexion IC	-32	9	-29	11	-22	9	<0.001**
Knee Adduction IC	9	5	8	4	6	4	0.011*
Hip Flexion IC	50	13	50	16	47	15	n.s.
Hip Abduction IC	1	9	0.1	7	1	8	n.s.
Knee Flexion PS	-49	8	-47	9	-46	6	n.s.
Hip Flexion PS	40	13	42	16	40	15	n.s.
Knee Adduction Moment IC	0.1	0.1	0.0	0.1	0.0	0.1	n.s.
Hip Adduction Moment IC	-0.1	0.2	-0.1	0.1	-0.1	0.1	n.s.

IC (Initial Contact); PS (Peak Stance)

* $p < 0.05$

** $p < 0.001$

n.s. – not significant