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The Effects of Isolated Hip Abductor Fatigue on Frontal Plane Knee Mechanics

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Abstract

Purpose: Anterior cruciate ligament injuries (ACL) and patellofemoral pain syndrome (PFPS) are both common and significant injuries to the knee that have been associated with hip weakness. Prospective studies have linked the risk of experiencing either injury to alterations in the frontal plane knee angle and moment during activity. These components of knee mechanics are theorized to be affected by hip abductor weakness. The purpose of this study

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was to identify the effects of isolated hip abductor fatigue-induced weakness on lower extremity kinematics and kinetics in recreationally active women.
Methods: Twenty participants performed cut, jump, and run tasks off of a raised platform while three-dimensional motion analysis data were collected. Participants then performed an isolated hip abductor fatigue protocol in side-lying against isokinetic resistance, followed immediately by repeated biomechanical data collection. Separate repeated measures ANOVA's ($p<0.05$) were used for each dependant variable.
Results: Following the hip fatigue protocol, regardless of task, the knee angle at initial ground contact was more adducted (pre: 0.7 ± 3.4°, post: 1.2 ± 3.9°, $F_{(1,19)}=5.3$, $p=0.032$), the knee underwent greater ROM into abduction (pre: 0.7 ± 1.5°, post: 2.1 ± 1.6°, $F_{(1,19)}=73.2$, $p<0.001$), and there was a greater internal knee adductor moment (pre: -2.6 ± 13.3 Nm, post: 4.7 ± 14.1 Nm, $F_{(1,19)}=41.0$, $p<0.001$) during the weight acceptance phase of stance.
Conclusions: This study demonstrates that simulated hip abductor weakness causes small alterations of frontal plane knee mechanics. Although some of these alterations occurred in directions associated with increased risk of knee injury, changes were small in magnitude, and the effect of these small changes on knee injury risk is unknown.

KEYWORDS: Anterior Cruciate Ligament, Lower Extremity, Athletic Injury, PFPS

Introduction

Anterior Cruciate Ligament (ACL) injuries and Patellofemoral Pain Syndrome (PFPS) both occur at significant rates in athletics, more often in college and high school age groups, and more frequently in women than men. (21, 32) These injuries cost society financially both in immediate costs associated with acute medical treatment (7, 21, 25) and in future costs for treatment of associated co-morbidities such as meniscal tears and knee osteoarthritis. (11, 28) Thus, substantial efforts have been made to understand the cause of these injuries and offer methods for their prevention.

Although the cause of each injury is considered multi-factorial, (22, 40) movement patterns in the frontal plane have emerged as a risk factor for both injuries. Acute, rapid increases in frontal plane knee abduction range of motion (ROM) have been demonstrated to increase strain on the ACL, at times enough to induce ligament rupture. (8, 13, 19) This is in agreement with observational studies which report that most ACL injuries involve a mechanism that includes a valgus positioning at the knee. (2, 35) Additionally, a prospective study demonstrated that an increase in knee abduction angle at initial contact with the ground, and the peak knee (external) abduction moment at the knee during the ground contact phase were predictive of increased risk for ACL injuries in a group of female soccer, basketball, and volleyball players. (17) Thus, frontal plane knee movement may be an important factor in ACL injuries.

During repetitive movements, frontal plane loading may not reach the levels necessary to put the ACL at risk. However increased knee abduction has been hypothesized to laterally displace the patella (36), which increases the compressive forces between the lateral facet and the lateral femoral condyle. (8, 26) This is hypothesized to lead to PFPS (Patellofemoral Pain Syndrome). (36) Therefore frontal plane motion and loading appear relevant to both the occurrence of ACL injuries, and the development of PFPS.

It is possible that weakness of the hip abductors is responsible for the increases in knee abduction ROM and knee adductor moments, as the hip abductors primarily stabilize the femur during frontal plane lower extremity motion. (31) Bobbert & van Zandijk reported that in the sagittal plane, the moments at the knee and ankle were largely a function of the forces generated by the hip musculature. (1) A computer model has demonstrated this in the frontal plane. A 50% decrease in hip abductor stiffness led to alterations in knee abduction motion and decreased the axial load that the knee could withstand before surpassing an injury threshold set at an estimated level of knee stiffness in the frontal plane. (6) This was most apparent when the knee was positioned in greater valgus. Additionally, hip abductor weakness has been associated cross-sectionally with a number of lower extremity injuries including iliotibial band friction syndrome (10) anterior knee pain / PFPS, (23) and general overuse injuries. (33) Brindle also identified decreased hip abductor activation in participants with PFPS while negotiating stairs. (4) However, these studies leave in doubt whether hip abductor weakness, insufficiency, and decreased activation existed prior to these injuries or became evident secondary to the injury. The acute effects of decreased hip abductor force output on knee kinematics and kinetics have not been reported. Yet many injury prevention programs now focus on conditioning and learning to control dynamic frontal plane knee movement, (18) even though the initial causes of altered frontal plane knee movement characteristics are not yet fully understood.

Previous studies have utilized a fatigue protocol to simulate insufficiency of a muscle group in order to evaluate the effects on movement characteristics. (5, 14, 34) These studies provide a design framework with which to examine the effects of decreased muscular force production on movement characteristics. However no previous study has precisely focused on the kinematic and kinetic changes in the lower extremity with isolated hip abductor fatigue-induced weakness during unilateral activity. Therefore, the purpose of this study was to identify the effects of isolated hip abductor fatigue-induced weakness on lower extremity kinematics and kinetics in recreationally active women. Specifically, we hypothesized that after an isolated hip abductor fatigue protocol, internal hip abductor moments would decrease, and increases would be noted in hip adduction ROM, knee abduction ROM, and internal knee adductor moments during the critical weight acceptance phase of landing activities.

Methods

Institutional Review Board (IRB) approval was obtained for this study from the University of Wisconsin-Milwaukee IRB, and a deferral was obtained from the Marquette University IRB to the IRB at UW-Milwaukee where the research was performed.

Participants

Data from previous published literature (5, 17) was used to estimate the effect size of hip abductor fatigue or weakness on knee moment. From this data and from pilot testing, an effect size of d=0.75 was estimated for the effect of hip abductor fatigue on knee frontal plane angle and moment. This effect size estimate, a desired power of 80 percent ($1-\beta=0.80$), and desired alpha=0.05 were used to calculate the necessary sample size to be 17 participants. To account for participant attrition, 20 recreationally active female participants were recruited from the local university population. Participants were 20.7 (1.7) years, 1.67 (0.06) meters in height, and 63 (10.3) kg. Participants were free from any lower extremity pain or injury that limited activity in the past 6 months, and from any past injury requiring surgery to the lower extremity. They were involved in recreational or competitive physical activity involving ground impact for at least 30 minutes three times per week. Informed consent was obtained from all subjects upon arrival for the study, and all questions were answered.

Instrumentation

Three-dimensional motion of the pelvis and dominant stance lower extremity was collected via a 7 camera Eagle Digital Camera System (Motion Analysis Corp, Santa Rosa, CA). Data were collected using the EVa Real Time software, version 5.0 (Motion Analysis Corp, Santa Rosa, CA). Kinetic data were collected simultaneously utilizing an AMTI force plate (AMTI Corp., Watertown, MA). Positional data were collected at 200 Hz, with force data collected synchronously at 1000 Hz.

The Biodex System III power head was used for resistance to hip abduction during strength testing and the fatigue protocol (Biodex inc, Shirley, NY). The torque produced before and during the fatigue protocol was captured from the Biodex with custom software written in Labview 8.2 (National Instruments Corporation, Austin, TX).

Procedures

The testing procedure was split into two days, one week apart (Figure 1). The first day was to familiarize the participant with the functional tasks to be collected, and to document the effects of the fatigue protocol on force production of the hip abductors over the immediate post fatigue time period. For this study, the fatigued state was defined as the inability of the participant to produce greater than 80% of the maximum measured hip abduction torque. This definition has been used previously to define the fatigued versus non-fatigued state when evaluating hamstring muscle function. (34) Additionally, a number of studies report a decrease in hip abduction strength on the side of injury when compared to control and uninjured lower extremities. (10, 12, 23, 27) In these studies, the difference between injured and non-injured hip abductors was approximately 20 percent. Thus, defining a decrease of 20 percent in force production as "fatigued" is supported in a previous study and was felt to be functionally significant. It is recognized that this fatigue protocol may have caused local muscle fatigue or may have resulted in central changes associated with fatigue such as decreased neural drive, or a combination of both. However, since a decreased force producing ability of the muscle was the parameter of interest, muscle weakness was defined in this study as the inability of the muscle to produce at least 80% of maximal peak torque during an isometric contraction. It was determined through pilot testing that motion analysis data collection after the fatigue protocol could be accomplished in two minutes or less. Thus, an additional inclusion criterion was that a participant's hip abductor force production had to remain below 80% for two minutes following cessation of the practice day fatigue protocol. If the participant's hip strength returned too quickly on the practice day, they were disqualified from the study.

Fatigue Protocol. The dominant stance leg was used as the test leg throughout the study (19 left, 1 right). This was identified by the participant as the opposite leg from the one they would use to kick a ball for distance. Participants were positioned side-lying in front of the isokinetic dynamometer for the fatigue protocol as shown in Figure 2. The speed of the isokinetic resistance was set at 60 degrees per second during concentric hip abduction, and at 300 degrees per second during the adduction phase. The 300 deg/sec speed during adduction was chosen to provide no resistance to adduction. Participants were instructed to not allow their leg to free fall, and to lower their leg at approximately the same speed as they raised it. Thus, the participant was forced to use the hip abductor muscles to eccentrically lower the leg into adduction. Instructions were standardized to raise the leg into abduction as hard as possible, then lower the leg into adduction taking about one second to descend. As the muscle fatigued in the concentric portion first, when participants could no longer raise the leg unassisted, assistance was given during raising, and the participant was responsible for lowering the leg slowly. When the descent could not be controlled over the one second period, the muscle was also fatigued in the eccentric contraction. Participants performed an average of 105 repetitions (±27, range 67-147 reps) during this fatigue protocol.

On day 1 of the study, participants performed the fatigue protocol as explained above. When final fatigue was reached, they remained attached to the Biodex, and hip abductor isometric force production was re-tested at 30 seconds, 1 minute, 2 minutes, and 3 minutes after the cessation of the fatigue protocol. If participants demonstrated the appropriate fatigue time course on the practice day (remained below 80% peak torque for at least 2 minutes), they were taught the study tasks, and were scheduled for data collection not sooner than one week in the future. They were asked not to alter their normal activity pattern or change their workout routines during the interim period, but to avoid aggressive lower extremity exercise.

Tasks

During data collection on the second testing day, kinematic and kinetic data were collected during three tasks designed and chosen to represent the movements and forces associated with ACL injuries and PFPS. The two most common mechanisms for ACL injury involve a sudden deceleration on the involved lower extremity, or a similar activity followed by a cut laterally. (2) Thus tasks were chosen that presented kinematically and kinetically similar to cutting, jumping, and running movements. The timing of data collection following the fatigue protocol necessitated that tasks be collected expediently, with minimal repeating of faulty trials. A running or cutting task in the lab would have likely required multiple trials to achieve correct foot placement on the force plate without an alteration of normal gait mechanics. Through pilot testing, three tasks were identified that allowed both expedient data collection post-fatigue, and presented movement characteristics similar to planting, cutting, and running activities. These tasks all started on a platform (MF Athletic, Cranston, RI) equal in height to the participant's vertical countermovement jump height. Their jump height was determined on day 1 of the study by having the participant perform a maximum jump on the force plate. Vertical jump height was then calculated utilizing the impulse-momentum relationship. This platform height was chosen for the task starting position as representative of the highest position vertically from which participants would have to land during athletic competition, such as when landing from a rebound in basketball. This has been used previously in published studies. (16) The platform was set away from the center of the force plate a distance equal to each participant's maximal stride length on level ground. Thus, when participants landed on the force plate during data collection, they had a standardized, controlled forward and downward velocity. Participants started all tasks standing on the platform on the non-test leg. They leaped forward, landing on the force plate with the test leg, and as fast as they could performed one of the three tasks. The first task was a side-step cutting maneuver (Figure 3), referred to as the "cut". After landing, the participant quickly cut to the opposite side of the test leg, taking a large step at a 90 degree angle to the direction of approach, as if they were "cutting in basketball." This task was chosen as representative of an ACL injury mechanism involving direction change. During the second task, after landing, the participant quickly performed a maximal vertical jump off of the test leg, referred to as the "jump". This task involved a straight plane deceleration, another noted ACL injury mechanism. For the third task, after landing, the participant continued running forward in the same straight plane that they approached the force plate from, the "run". In pilot testing, this task kinetically appeared similar to running without the uncertainty of the test leg falling on the force plate during an uninterrupted stride. Starting each task above ground height and away from the force plate increased the vertical and horizontal velocity of the participant in a consistent manner, replicating a running start at a constant speed for each task. The chosen tasks were also of sufficient rigor that alterations due to changes in maximal force production would likely be detectable. Participants were allowed to practice each task numerous times until comfortable with the performance of the tasks, and until the investigator was comfortable with the participant's technique.

Data Collection

Participants had 25 reflective markers placed on their body for the collection of kinematic data. Participants wore standardized Saucony Jazz running shoes from the lab which have a neutral midsole to prevent variance due to footwear. After collection of a standing trial, both iliac crest markers, both greater trochanter markers, the medial and lateral knee markers, the medial and lateral malleolus markers, and the first and fifth metatarsal head markers were removed, leaving both ASIS and PSIS markers, and all three clusters (thigh, shank, heel) for segment identification.

The tasks were reviewed and participants allowed to practice 1-2 repetitions of each to feel comfortable with task performance. Three trials of each task were then collected before the fatigue protocol. Sufficient rest was given to prevent fatigue from affecting each subsequent trial. Following the pre-fatigue data collection, the fatigue

protocol was performed. Care was taken to ensure that the markers remained in place during performance of the fatigue protocol.
The resistance arm of the Biodex was carefully aligned with the lateral knee between the thigh and shank clusters so that no contact occurred throughout the fatigue protocol (Figure 2). All markers remained well clear of the resistance arm. Hip abductor torque during the entire fatigue protocol was recorded. When participants could no longer control the descent of their leg in the eccentric phase, the fatigue protocol was terminated. A timer was immediately started and the dynamometer was again locked at zero degrees of abduction to record the torque from one final isometric contraction. These recordings were utilized to compare the test day fatigue data to the practice day fatigue timeline to ensure that the participants were truly fatigued enough to affect hip abductor performance for 2 minutes.

The participants then quickly repeated the three movement tasks, one repetition of each sequentially to a maximum of 3 trials during the 2 minute period following the fatigue protocol. The order in which tasks were performed was consistent from pre- to post-fatigue for each participant, but was counterbalanced (run, cut, jump) between participants throughout the study.

Data Analysis

Three-dimensional coordinate data were processed using Visual 3D software (C-Motion inc., Germantown, MD). The kinematic and kinetic data were filtered using a 4th order low pass Butterworth filter with a cutoff frequency of 18 Hz (30). Hip, knee, and ankle joint angles were calculated using a joint coordinate system approach. (15) Joint centers for the knee and ankle were defined as the midpoint between the medial and lateral joint markers. The hip joint center was estimated at 25% of the horizontal distance between the greater trochanters from the test side trochanter marker. (37) An inverse dynamics approach (3, 24) was used to derive the joint kinetic data of the hip, knee, and ankle from the GRF and kinematic data. All moments reported are internal net joint moments, and are reported in the distal segment. For clarity of presentation, during processing, left leg data was inverted in the frontal plane so that numeric results are all presented from the perspective of a right lower extremity. For all three tasks, the weight acceptance phase (WA) was defined as the period from when the vertical-GRF (v-GRF) exceeds 30N to the first trough in the v-GRF. (1)

Given that the majority of ACL injuries occur within the first 20 percent of stance phase, (3) and that the peak GRF for each task was within this phase for all three tasks, analysis was confined to just the WA phase. Dependent variables extracted for analysis were the frontal plane hip and knee angle at initial ground contact (IC), frontal plane hip and knee range of motion during WA (defined as the excursion of the hip and knee from IC to maximum joint angle - ROM), and the mean frontal plane hip and knee moment during WA.

Statistical Analysis

Statistical analyses were performed using SPSS version 16.0 (SPSS inc., Chicago, IL). Paired t-tests were performed between pre- and post-fatigue maximal hip abductor peak torque for both the practice day and the test day. Additionally, the percentage of strength deficit was calculated by dividing the immediate post-fatigue torque by the pre-fatigue torque multiplied by 100, and a paired t-test was performed to compare the strength deficit between days.

Separate repeated measures ANOVAs were used to identify significant differences in the three dependent variables across the three tasks. The independent variables were fatigue with 2 levels (pre and post-fatigue), and task with 3 levels (cut, jump, and run). The dependent variables were the hip and knee frontal plane angles at IC, hip and knee joint frontal plane ROM during WA, and mean hip and knee frontal plane moments during WA. The significance level for each test was set a priori at $p<0.05$.

Results

Twenty-two participants underwent the orientation day fatigue protocol testing. One participant did not demonstrate the necessary force decrements in hip force production following the fatigue protocol and was disqualified after the practice day. Another participant opted not to continue after the practice day, leaving 20 participants with test day data for analysis.

Hip Fatigue

Hip abductor force production was significantly decreased following the fatigue protocol on both the orientation day (pre: 115±21ft-lbs, post 73±17ft-lbs, $t_{(38)}= 19.49$, $p<0.001$) and test day (pre: 102±20, post: 64±17, $t_{(38)}= 13.58$, $p<0.001$) (Figure 4).

Although peak torque was greater on orientation day than on test day both pre- and post-fatigue, the strength deficit from pre-fatigue to post-fatigue was not significantly different between the orientation day and test day (orientation day: 62±7%, test day: 63±11%, $t_{(38)}$= -0.068, p=0.946), indicating that the level of fatigue reached was the same between days (Figure 4).

Joint Dynamics

The frontal plane knee angle (Figure 5) and moment (Figure 6) time series are presented, and individual task by variable results are found in Table 1. Analysis of the frontal plane hip and knee data revealed no significant *fatigue*task* interactions for any of the dependent variables. Main effects for *fatigue* were noted for all three frontal plane dependent variables at the hip and the knee. Following the hip abductor fatigue protocol, the hip angle at initial ground contact was more abducted (difference of 1.6±6.2 deg., p<0.001), the hip ROM during the WA phase was greater, from abduction to adduction (difference of 0.7±2.2 deg., p=0.006), and mean hip abductor moment over the WA phase decreased (difference of 4.2±21.9 Nm, p=0.016). The knee angle at IC was more adducted (difference of 0.5±3.1 deg., p=0.032), knee ROM over WA moved from a greater adducted position to a greater abducted position (1.4±1.3 deg., p<0.001), and the knee moment shifted toward a greater internal adductor moment during WA (difference of 7.4±13.4 Nm, p<0.001). This indicates that following the hip fatigue protocol, participants landed initially in a more varus knee position, shifted to a greater valgus knee position as the hip collapsed into more adduction, while the knee experienced a greater mean knee adductor moment throughout WA, regardless of task (Table 1).

Main effects for *task* were also noted for each variable. There was a difference between the cut, jump, and run in all hip and knee dependent variables. However, hip abductor fatigue did not affect each task differently (Table 1).

Discussion

The results of this study indicate that fatigue-induced hip weakness increased the motion experienced by the knee, and shifted the moment at the knee in the frontal plane. The hypothesis that hip abductor fatigue would increase knee abduction ROM was supported.

Knee internal adductor moment increased during the cut and the jump, and although the moment shifted in the same direction during the run, this shift resulted in a decrease in internal knee abductor moment. These differences were measured during WA, the period of time when most ACL injuries occur. (2, 35) Additionally, the changes noted in knee angle and moment during the cut and the jump task occurred in the direction previously associated with an increased risk of ACL injury, (17) and with knee injury mechanics (2, 35, 36) suggesting that hip abductor weakness may play a role in knee injury risk.

The hip abductor fatigue protocol had a small effect on all three knee dependent variables. Post-fatigue, the knee started in a more adducted position at IC, then moved to a more abducted position during WA. During the cut and the jump, this shift was consistent with the movement pattern defined in the literature as dynamic valgus of the knee. (9) Correspondingly the frontal plane knee joint moment during the cut and the jump shifted to a greater internal knee abductor moment post-fatigue. The cut and jump tasks are representative of those movements noted during ACL injuries (2, 35). Although the average changes noted are small in magnitude, all subjects individually demonstrated ROM changes in the same direction of knee abduction and all but one demonstrated an increased knee adductor moment post-fatigue (Figures 7 and 8). Withrow et al reported that a 2.49 degree increase in knee abduction increased ACL strain by 30% in vitro. (39) While there are substantial differences in study design and the participants / specimens used, there is indication that small movements into knee abduction may be important to knee injury mechanics. Interestingly, although these changes occur in the same direction during all tasks, the changes during the run moved the knee toward a more neutral position or less adducted position, and the abductor moment decreased during this task.

Similar task differences were noted for the frontal plane knee moment. During the cut and the jump, the frontal plane moment shifted to a greater internal knee adductor moment. The increases observed in frontal plane knee adductor moment during these two tasks are in agreement with the results of the computer model used to evaluate frontal plane knee forces with changes in hip abductor stiffness, (6) which demonstrated that a 50% decrease in hip abductor stiffness resulted in increases in the frontal plane knee moment in the direction of increased internal knee adductor moments in response to axial loading of the joint. This affect was most pronounced when the valgus angle of the knee was increased. However in the current study, with pre and post differences in this small range, we cannot rule out that measurement error during motion analysis from skin movement over osseous structures or a systematic shift in marker position during the fatigue protocol did not account for the differences noted. We did not collect a post-fatigue standing trial to ensure that markers did not shift during testing. Every precaution was taken to prevent this occurrence, but we acknowledge the possibility that this type of error occurred.

One previous study reported that hip abductor fatigue increased knee abduction angle in the frontal plane at initial contact, but not the maximum frontal plane angle. (5) They utilized a combination of isometric open and closed chain hip abduction exercises to produce fatigue, and measured frontal plane movement during a bilateral drop landing using electrogoniometers. The present study does not support these findings, as the frontal plane angle at initial contact was more varus post fatigue, and then collapsed into more valgus throughout WA. The contradictory findings are perhaps because of differences in the task, fatigue protocol, and data collection equipment. Generally, the force required from the hip abductors increases greatly during a unilateral task due to the increased torque applied to the hip by body weight. With a bilateral task, demands on the hip abductors are sub-maximal, and changes in hip abductor force production due to the fatigue may not be apparent as the demands on the muscle may not reach a critical level. The single-leg tasks in the present study were thought to be demanding on the hip abductors, requiring both ballistic eccentric control of the body during a forceful landing and immediate concentric activity to propel the individual in the desired post-landing direction. Differences in measurement accuracy of the three-dimensional camera system compared to the electrogoniometers, particularly in the frontal plane, could also account for the conflicting results. Finally, although the combination of open and closed chain exercises used previously may have greater practical or functional application, our use of repeated concentric and eccentric open chain hip abduction as the fatiguing activity more likely isolated the hip abductor muscle group and is likely to have produced greater fatigue in that specific group.

Of note is that absolute angles are reported in this study. This is a representation of an individual's anatomy based on surface markers. There may be small errors in marker placement for the identification of joint centers, which is a limitation to this technique of capturing human movement. The anatomic angles identified in the standing calibration were not cross-checked with imaging studies. However, the markers were not removed between the pre- and post-fatigue trials, so error due to marker placement is minimized. The results of this study also document the change from pre to post fatigue regardless of the initial anatomic position of the knee. While that may or may not increase the risk of knee injury to those individuals who are anatomically adducted initially, the results demonstrate that hip fatigue-induced weakness would move someone who is initially in a valgus or neutral position to a further valgus position at the knee, and therefore may increase the risk of injury for those marginal individuals.

Leetun reported that hip abductor strength was different between collegiate athletes who experienced lower extremity injuries and those who did not in a prospective study on the effect of core strength on injury rates, (27) although hip external rotator strength difference was the only predictor of lower extremity injury. Many other cross-sectional studies have reported impaired strength or function of the hip abductors of injured individuals or of the injured lower extremity. (4, 10, 23, 33) The results of the present study lend insight into the possible mechanical effects by which hip abductor weakness increases knee injury risk.

Interestingly, hip abductor fatigue in this study created a very small change toward an adducted (varus) knee position (0.5° change) and an abducted position of the hip (1.6° change) at IC, possibly indicating an anticipatory response to the acute hip abductor weakness. While this positional change is very small in magnitude, the results were consistent enough to reach statistical significance. The sensation of hip abductor fatigue may have caused participants to alter their movement patterns in a compensatory effort to maximize force absorption time and ROM. Previous studies have identified kinematic and kinetic differences between anticipated and unanticipated maneuvers. (20) Had unanticipated tasks been tested, participants may not have been able to compensate for hip abductor insufficiency prior to task initiation, and the results may have been altered. We also cannot rule out that these small positional changes are not from a systematic shift in marker position during the fatigue protocol, and may in fact represent artifact from such an occurrence.

In addition to small alterations in frontal plane knee joint mechanics, alterations in hip joint variables were also noted post-fatigue. Hip abductor moment was expected to decrease post fatigue as the muscle could not produce the same force as in the unfatigued state, and that was indeed observed. The hip joint ROM in the frontal plane was increased post-fatigue, due largely to an increase in the IC abduction angle. Hip abduction angle at IC increased an average of 1.6 degrees (Table 1), while hip ROM through WA increased 0.7 degrees.

Stefanyshyn et al. (38) reported that prospectively, runners who demonstrated a larger internal knee abductor impulse were more likely to develop PFPS over the course of a season. Participants in the current study did not demonstrate changes in knee moment in the direction described above by Stefanyshyn. The knee moment changes in this study post-fatigue were in the direction of greater knee adductor moments, which is the opposite direction of the differences described by Stefanyshyn. (38) The run task evaluated in the present study was chosen because it did not introduce the uncertainty of whether or not the foot would fall naturally on the force plate during the time-limited post-fatigue data collection. Pilot testing demonstrated that this task appeared kinematically and kinetically similar to actual running. Pre-fatigue values for knee angle and moment appear consistent with the kinematic and kinetic patterns reported in previous running studies, (29, 38) the major difference being an increased vertical GRF component during WA due to the height that the current participants started the task from. However, it is likely that the run task used in the present study did not truly represent running, and that our results are not indicative of running as an activity. The length of the stride and the vertical acceleration while coming off of the platform may have created more focus on the individual stride landing than during over-ground running, thus altering knee behavior. It is also possible that the mechanism behind the development of PFPS in runners in the Stefanyshyn et al. study is different than the mechanism by which hip weakness potentially influences the development of PFPS. Stefanyshyn et al. did not report hip strength measures for their participants, so the role of hip strength as it relates to the development of PFPS will require further study.

In this study, force decrements associated with fatigue were used to represent force decrements that occur with muscle weakness of the hip abductors. It should be noted that the kinematic and kinetic changes noted with muscle fatigue may not be the same as those seen with muscle weakness. Muscle weakness occurs over an extended time period, allowing for the development of compensation patterns in response to the weakness. Those long term changes can not be detected by this study design. Additionally, decreases in the force producing capacity of the muscle produced by fatigue are accompanied by other neuromuscular changes as well. (14) Fatigue was used to alter the force producing capability of the hip abductor muscles in an attempt to draw conclusions about the effect of hip weakness on lower extremity motion. Although muscle force was affected with the fatigue protocol, it can not be elucidated whether the findings in the present study represent changes due to weakness, due to alterations in neuromuscular control of the fatigued muscle, or due to some other component of fatigue. Additionally, we did not test the response of the fatigued hip-abductor muscle to stretch-shortening type of activities. The response to a stretch-shortening type activity, like the ballistic tasks used in this study, may be different for a fatigued muscle than a chronically weak muscle. This is a limitation of this study design. Hip abductor fatigue also does not occur in isolation during athletic activity, and this study sought to specifically and selectively fatigue just the hip abductor muscle group. This limits the generalizability of these results during athletic activity.

The tasks in this study were taught to participants on the orientation day only after they demonstrated satisfactory performance of the fatigue protocol. A recovery period was allowed, but never the less, participants thus learned the tasks while their hip abductors were not fully recovered. This may have ultimately affected the initial performance of the tasks on Day 2, the test day, and thus impacted the results of this study.

Consideration must be given to why the differences in post-fatigue knee variables were not greater, and if in fact the small magnitude of the changes means that hip weakness is indeed not a major factor in knee injuries. The small changes noted here are not of sufficient magnitude to be clinically meaningful, and could be the result of undetected systematic artifact. It could be concluded from these results that hip abductor fatigue does not affect knee mechanics in a meaningful way. However, neuromuscular control of voluntary movement is a complex topic, and the fact that statistical changes were noted at the knee despite the fact that participants knew the task and the direction of movement is of interest. Further study utilizing these techniques with unanticipated tasks or directions of movement would be a logical progression of this work.

In summary, the purpose of this study was to identify the acute effects of hip abductor weakness, simulated by an isolated fatigue protocol, on knee mechanics during strenuous unilateral athletic activities. Small changes were noted in the frontal plane dependent variables, the plane of the hip abductors main force producing ability. While in the fatigued state, during the cut and the jump task, participant's demonstrated greater knee abduction ROM and a shift in the knee moment to a greater internal adductor moment across tasks during WA. The postfatigue changes at the knee during these two tasks were in the direction identified in the literature as increasing knee injury risk, particularly for ACL injury. Further evaluation of the effect of hip abductor weakness on knee mechanics is warranted.

Conflict Of Interest

None

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Table 1. Mean (standard deviation) hip and knee frontal plane angle at initial ground contact (IC), Range of Motion during WA (ROM), and

moment for cut, jump, and run tasks. Effect size (d) is based on standardized differences.

TABLE 1. Mean ± SD hip and knee frontal plane angle at IC, ROM during WA, and moment for cut, jump, and run tasks.

		Angle at IC (°)				ROM (°)				Joint Moment (N·m)			
		Hip	d	Knee	d	Hip	d	Knee	d	Hip	d	Knee	d
		*,†		†		*		*,†		*,†		*,†	
Cut	Pre	−23.8 ± 5.3	0.34	−0.5 ± 3.9	0.10	5.6 ± 2.6	0.46	1.1 ± 1.7	0.82	−33.4 ± 21.6	0.09	4.0 ± 17.0	0.38
	Post	−25.6 ± 6.4		−0.1 ± 4.1		6.8 ± 2.6		2.5 ± 1.6		−31.4 ± 20.6		10.5 ± 17.5	
Jump	Pre	−21.0 ± 6.7	0.18	−0.6 ± 3.3	0.18	6.4 ± 2.4	0.25	0.3 ± 1.5	0.93	−45.2 ± 26.9	0.19	−3.4 ± 16.7	0.51
	Post	−22.2 ± 6.9		0.0 ± 3.9		7.0 ± 2.5		1.7 ± 1.9		−40.1 ± 24.1		5.0 ± 16.5	
Run	Pre	−15.7 ± 8.4	0.23	3.1 ± 3.5	0.17	6.6 ± 2.9	0.10	0.7 ± 1.8	0.72	−36.7 ± 19.6	0.29	−8.4 ± 9.9	0.72
	Post	−17.6 ± 7.6		3.7 ± 4.4		6.9 ± 2.2		2.0 ± 1.6		−31.1 ± 19.4		−1.3 ± 11.1	
Total	Pre	−20.2 ± 6.1	0.26	0.7 ± 3.4	0.15	6.2 ± 2.2	0.32	0.7 ± 1.5	0.93	−38.4 ± 21.7	0.19	−2.6 ± 13.3	0.55
	Post	−21.8 ± 6.3		1.2 ± 3.9		6.9 ± 2.0		2.1 ± 1.6		−34.2 ± 20.0		4.7 ± 14.1	
P	Fatigue × task	0.586		0.992		0.243		0.756		0.482		0.607	
	Fatigue	<0.001		<0.001		0.461		0.007		<0.001		<0.001	
	Task	<0.001		0.032		0.006		<0.001		0.016		<0.001	

Effect size (*d*) is based on standardized differences.

* Significant main effect of fatigue ($P < 0.05$).

† Significant main effect of task ($P < 0.05$).

Figure 1. Participant flow diagram.

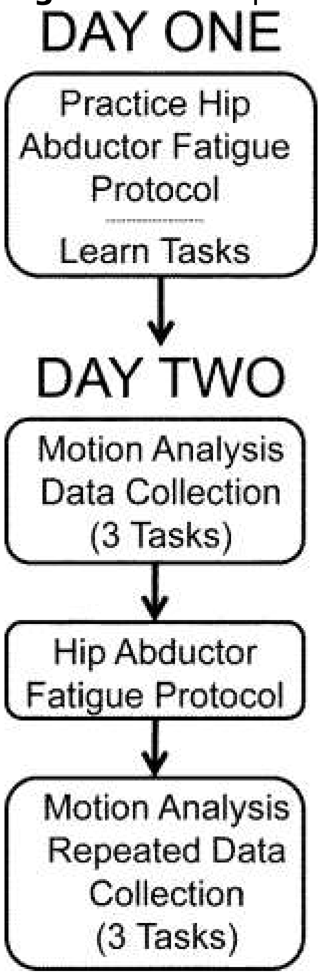

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Figure 2. Positioning on Biodex for fatigue protocol.

Figure 3. Study tasks. Participants started on the elevated box, leaped forward landing unilaterally on the test leg (Left shown), then performed either a side-step cut (shown), a straight vertical jump, or continued to run straight forward from that point.

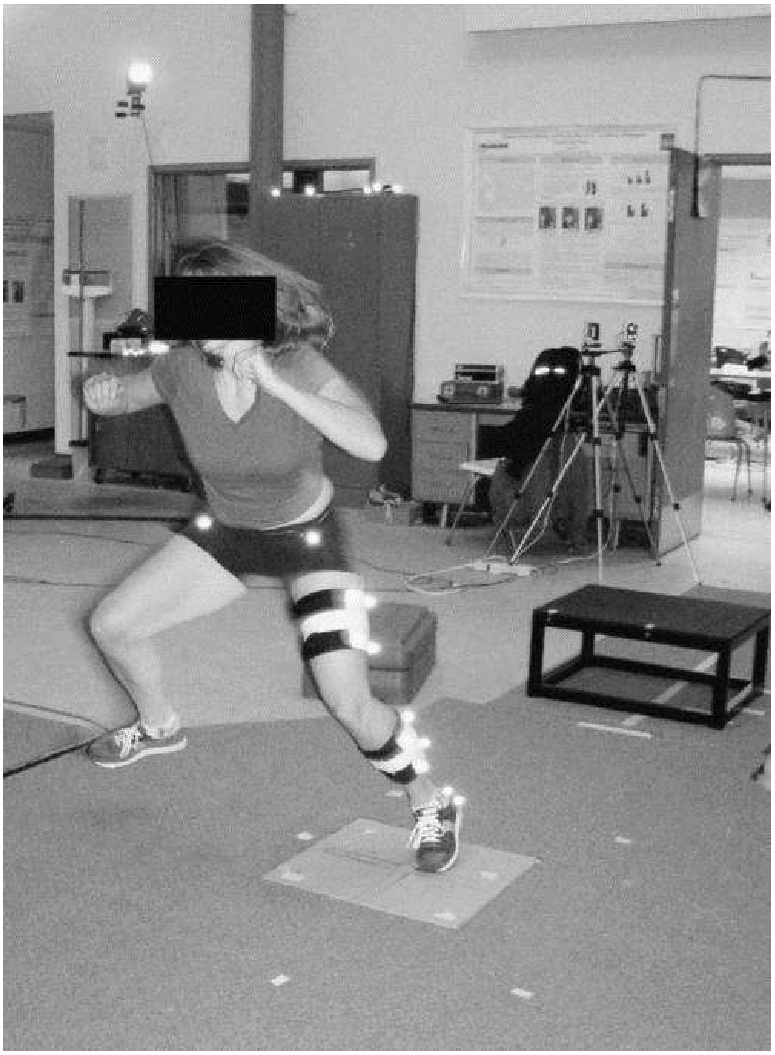

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Figure 4. Torque produced by the hip abductors prior to the fatigue protocol, at cessation of the fatigue protocol, and 2 minutes after cessation of the fatigue protocol. Pilot testing demonstrated that the recovery profile on the test day at 2 minutes after cessation of the protocol mirrored the recovery timeline documented on the orientation day. ("*" indicates significant difference (p<0.05) from baseline (max) that day.)

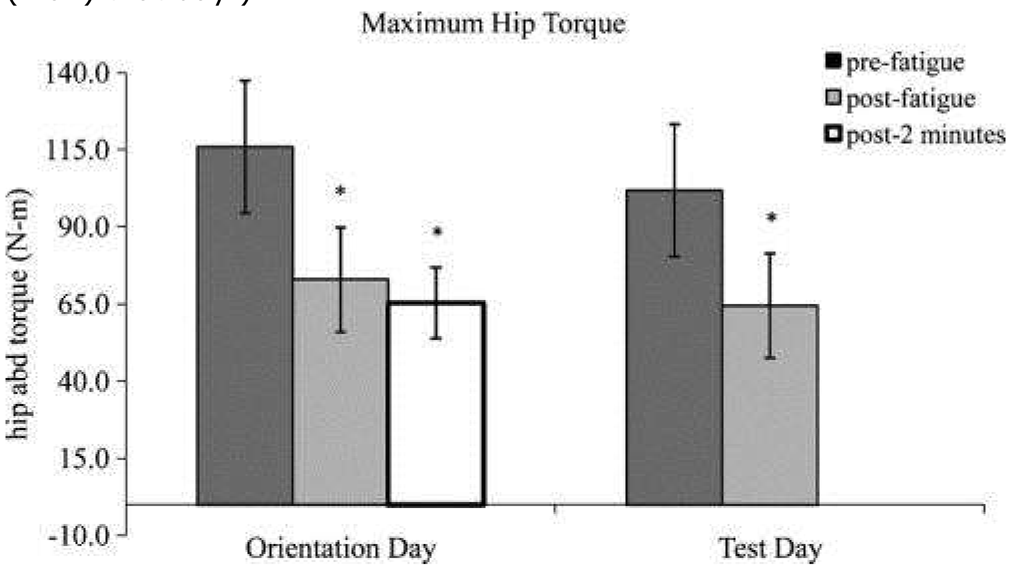

Figure 5. Frontal plane hip and knee angles for the cut, run, and jump over stance phase (normalized to 100%). Thick black line denotes the average end of the WA phase.

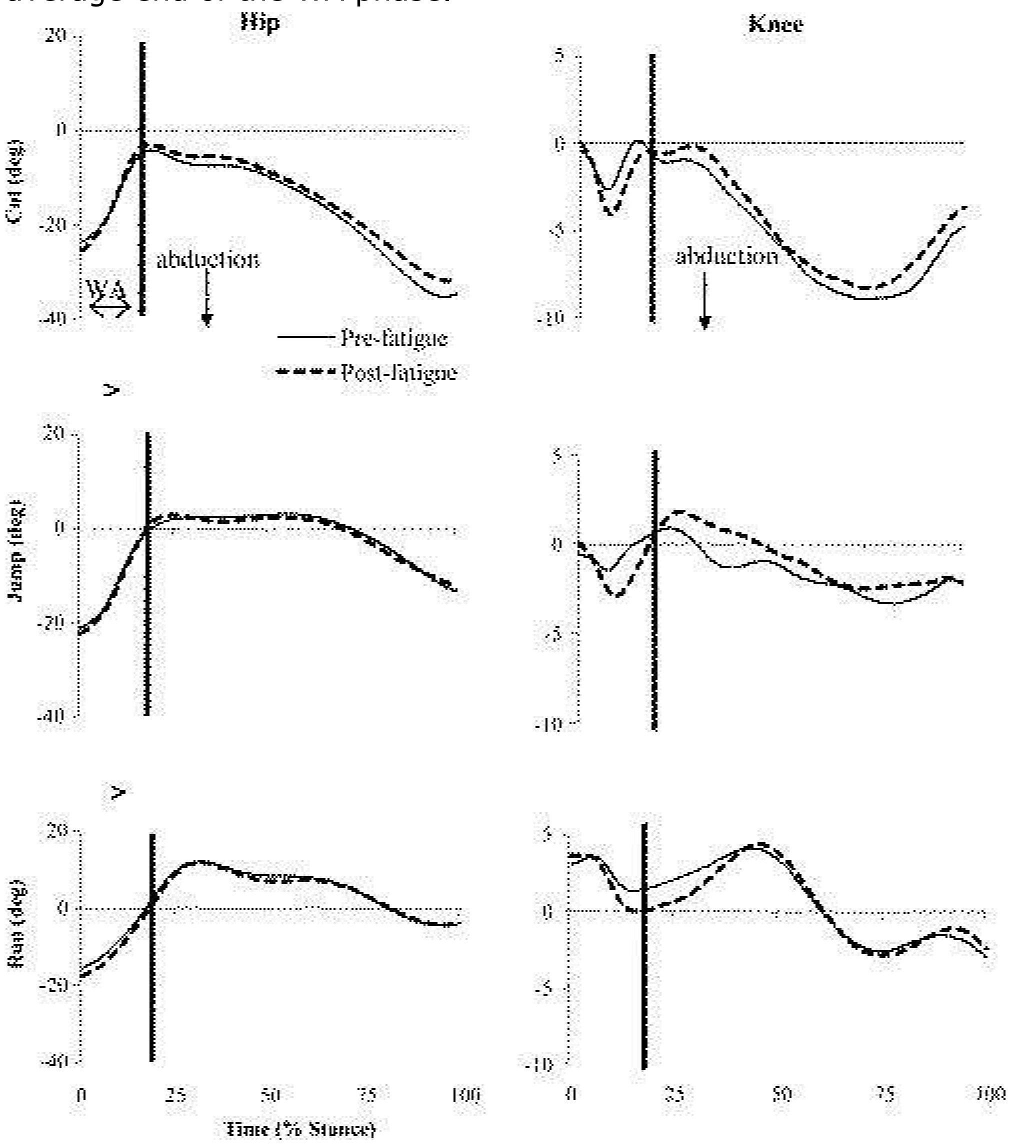

Figure 6. Frontal plane hip and knee moments for the cut, run, and jump over stance phase (normalized to 100%). Thick black line denotes the average end of the WA phase.

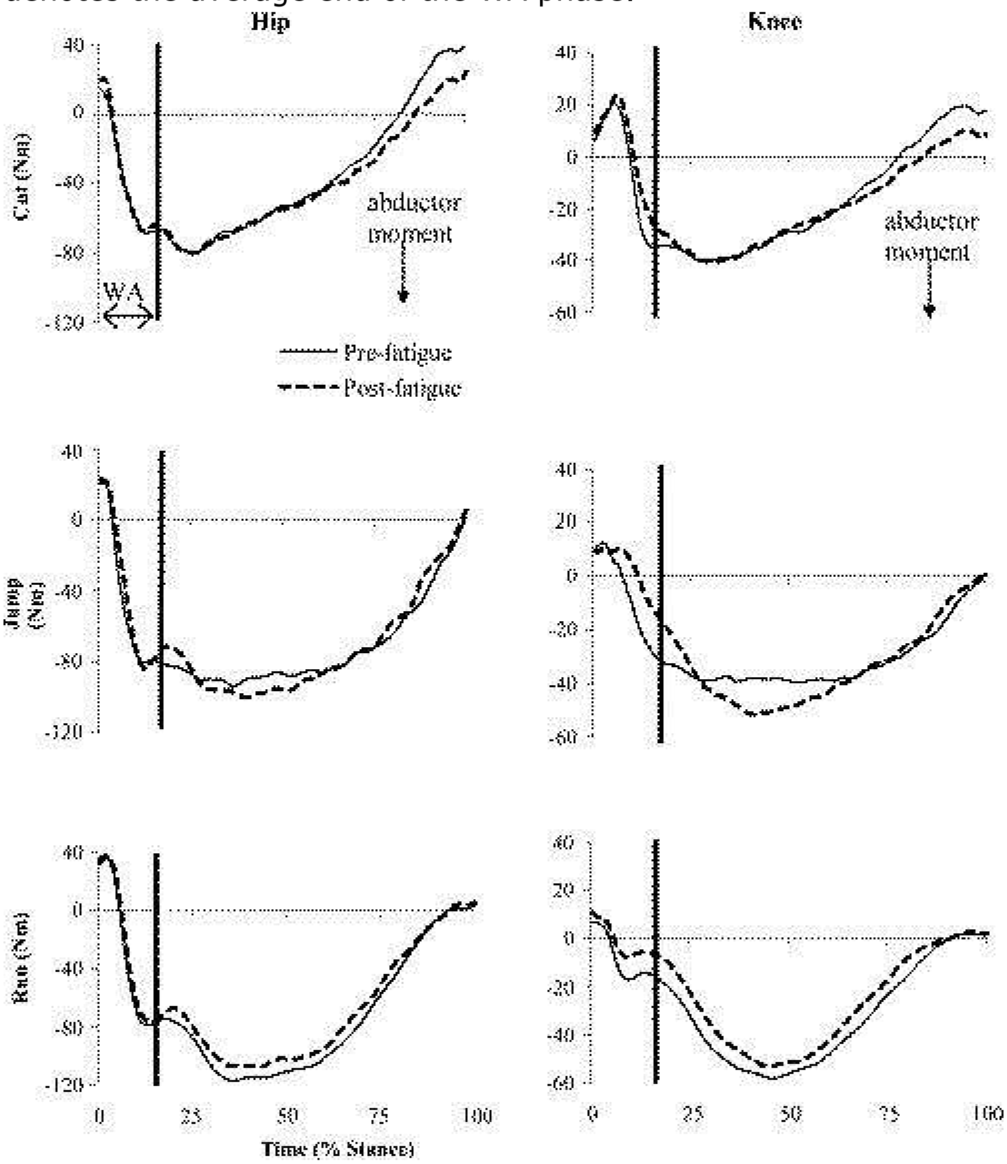

Figure 7. Change in frontal plane knee ROM (post-fatigue minus pre-fatigue) for individual participants across all tasks. Negative numbers indicate a participant demonstrated greater knee ROM, from a more adducted position to a more abducted position when the hip abductors were fatigued.

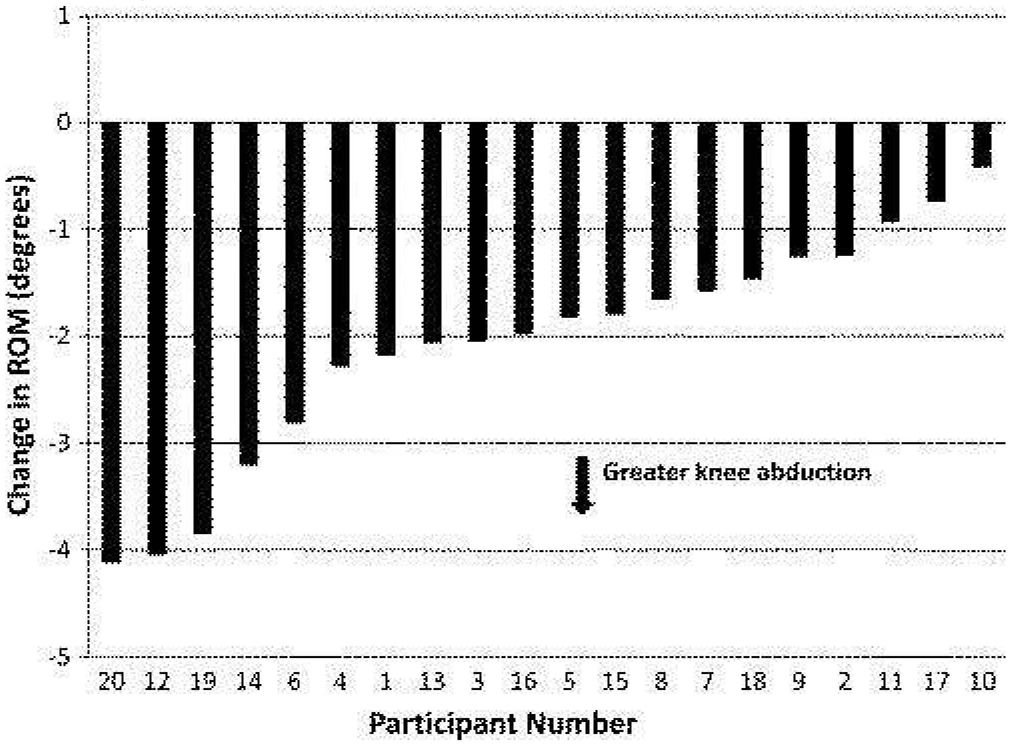

Figure 8. Change in frontal plane knee moment (post-fatigue minus pre-fatigue) for individual participants across all tasks. Positive numbers indicate a greater internal knee adductor moment when the hip abductors were fatigued.