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Reduced hamstring strength increases anterior cruciate ligament loading during anticipated sidestep cutting

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ABSTRACT

Background: Dynamic knee stability is considered a critical factor in reducing anterior cruciate ligament loads. While the relationships between hamstring force production and anterior cruciate ligament loading are well known in vitro, the influence of hamstring strength to anterior cruciate ligament loading during athletic maneuvers remains unknown. Therefore, the purpose of this study was to determine the influence of hamstring strength on anterior cruciate ligament loading during anticipated sidestep cut.
Methods: Seventeen recreationally active females were recruited to perform sidestep cutting maneuvers pre/post an acute hamstring strength reduction protocol. Kinematics and kinetics were calculated during the cut and a musculoskeletal model was used to estimate muscle, joint, and anterior cruciate ligament loads. Dependent t-tests were conducted to investigate differences between the two cutting conditions.
Findings: Anterior cruciate ligament loading increased by 36% due to reduced hamstring strength. This was mostly due to a 44% increase in sagittal plane loading and a 24% increase in frontal plane loading. Post strength reduction sidestep cuts were also performed with decreased anterior tibiofemoral shear force, an outcome that would theoretically reduce anterior cruciate ligament loading. However, the overall decrease in hamstring force production coupled with a more axial hamstring line of action yielded a net increase in anterior cruciate ligament loading.
Interpretation: These results suggest that decreased hamstring strength significantly increases anterior cruciate ligament loading during anticipated sidestep cutting. Additionally, these results support the premise that preseason screening programs should monitor hamstring strength to identify female athletes with potential deficits and increased injury risk.

1. Introduction

Anterior cruciate ligament (ACL) injury is a common sports-related injury, with between 80,000 and 250,000 injuries annually in the United States alone, and is associated with debilitating short and long term consequences (Griffin et al., 2006). Nearly 70% of all ACL injuries are non-contact in nature (Boden et al., 2000), occurring in the absence of physical contact with another player or a direct blow to the knee. Lack of active neuromuscular control, as evidenced by increased knee abduction motion and torque (Hewett et al., 2005), and passive stability of the joint as evidenced by increased general joint laxity (Myer et al., 2008), may destabilize the knee and are predictive of increased ACL injury risk in female athletes. ACL injury likely occurs under conditions of high dynamic loading of the knee joint, when active muscular restraints do not adequately compensate for and dampen joint loads (Beynnon and Fleming, 1998). Decreased neuromuscular control of the joint may place stress on the passive ligament structures that exceed the failure strength of the ligament (Li et al., 1999). Neuromuscular control of high-load movements is required to maintain dynamic knee stability during "high-risk" sporting maneuvers that incorporate sudden deceleration and/or rapid speed or direction changes, such as sidestep cutting (Colby et al., 2000).

Co-activation of hamstrings and quadriceps may be critical in protecting the ACL from rupture when a load is applied as hamstring recruitment is thought to reduce ACL loads from excessive quadriceps forces (Beynnon and Fleming, 1998; Li et al., 1999). Withrow et al. (2008) found in vitro that increasing hamstring muscle force during a simulated jump landing significantly reduced peak relative ACL strain. Through compressive and posteriorly directed shear forces, the hamstrings provide dynamic knee stability by limiting anterior tibial translation (Imran and O'Connor, 1997) and torsional loading (Li et al., 1999), thereby protecting the ACL. Moreover, Myer et al. (2009) prospectively reported that female athletes who went on to suffered ACL injury had a combination of decreased hamstring strength but not quadriceps

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strength compared to males. Thus it appears that deficits in relative hamstring strength may contribute to increased ACL injury risk in female athletes.

While the relationships between muscle strength and recruitment to knee joint stability and ACL loading have been investigated in vitro, and decreased hamstring muscle strength relative to quadriceps muscle strength has been identified prospectively as a risk factor, the influence of these relationships to ACL loading during athletic maneuvers such as sidestep cutting remains unknown. Therefore, the purpose of this study was to determine the influence of hamstring strength on ACL loading during a sidestep cut through a musculoskeletal modeling approach. It was hypothesized that peak ACL loading would increase when hamstring strength was reduced via an acute hamstring strength reduction protocol.

2. Methods

Seventeen female volunteers (age: 21 (1) years, mass: 61.7 (6.8) kg, height: 1.66 (0.05) m) participated in this investigation. Participants were physically active (participation in running and cutting activities (i.e., soccer, volleyball, tennis, basketball) at least 30 min per day, 3 days per week) and had no history of lower extremity or back injury within the 6 months prior to participation or surgery in either lower extremity. Additionally, participants were required to be pain free in the lower extremity on testing days. Participants read and signed an informed consent document approved by the University's Institutional Review board prior to testing.

Participants were asked to come to the lab on two different occasions. The first visit was a practice session. During this time, participants practiced a 45° anticipated sidestep cutting maneuver until they could comfortably complete the task. All cuts were performed on the right foot regardless of foot dominance (Brown et al., 2009) and approach speed was controlled to be 4.5–5.0 m s^{-1} (O'Connor and Bottum, 2009). Approach speed was monitored by two timing gates placed 2 m apart and positioned along a 1 m wide runway. After planting their right foot on the force plate, participants were instructed to cut to the side along a 1 m wide path oriented at 45° to the line of progression. The 1 m wide path ensured participants would maintain a cutting angle of 40–50°. The participants then practiced isokinetic strength testing to scale the musculoskeletal model at 30 $deg \cdot s^{-1}$ on an isokinetic dynamometer (Biodex Inc., New York, NY). These tests included supine hip flexion and extension with the knee flexed at 90°, side lying adduction and abduction with knee fully extended, prone knee flexion with the hip fully extended, seated knee extension with the hip flexed at 90°, and seated ankle plantarflexion and dorsiflexion with hip flexed 30° and knee fully extended. Three sets of three repetitions for each test were completed through a full range of motion with 2 min of rest between sets and tests. Test order was randomized between participants to eliminate systematic variation. Finally, the participants practiced one set of the hamstring strength reduction protocol which consisted of forty repetitions of maximum effort concentric knee flexion on the isokinetic dynamometer at an angular velocity of 180 $deg \cdot s^{-1}$.

All testing was conducted during the participants' second visit. This testing session was scheduled within one week of the practice session. Participants first completed a 5 minute warm-up on a treadmill, followed by peak isokinetic strength testing at 30 $deg \cdot s^{-1}$ of the hip flexors and extensors, hip adductors and abductors, knee flexors and extensors, and ankle plantarflexors and dorsiflexors. Three sets of three repetitions for each test were completed through a full range of motion with 2 min of rest between sets and tests. Test order for each participant was consistent with their practice session but was randomized between participants. After strength testing, differential surface electromyography (EMG) electrodes (Vermed, Bellow Falls, VT, USA) with an interelectrode distance of 22 mm were placed over the participants' right vastus medialis, rectus femoris, biceps femoris, and medial hamstrings (semimembranosus/semitendinosus) according to the guidelines provided by Rainoldi et al. (2004). Electrodes and leads were secured to the skin using tape to minimize motion artifact. Electrode sites were shaved if necessary, abraded, and cleaned with isopropyl alcohol to maximize the electrode adherence to the skin and minimize skin impedance. Electrode placements were confirmed via isometric contractions against manual resistance. Forty-eight retro-reflective skin markers were then placed bilaterally on the participant. Markers used exclusively for the standing calibration trial (calibration markers) included left and right acromioclavicular joints, iliac crests, greater trochanters, medial and lateral epicondyles of the knees, medial and lateral malleoli, and the first and fifth metatarsal heads. Locations of calibration markers were noted with an eyeliner pencil to ensure proper reapplication. Additional tracking markers included the anterior–superior iliac spines, posterior–superior iliac spines, rigid plates with four markers attached to the thoracic spine, bilateral thighs, shanks and heel of the shoes.

A three second standing calibration trial was then collected after EMG electrodes and retro-reflective markers were attached in their proper locations. Calibration markers were then removed and participants completed five successful 45° anticipated sidestep cutting maneuvers. A successful trial was defined as one during which approach speed was maintained, participant's entire right foot came into contact with the force plate, and the participant stayed in the 1 m wide path. During all trials, retro-reflective marker trajectories were collected at 200 Hz with a 10 camera Motion Analysis Eagle System (Santa Rosa, CA, USA). Synchronously, ground reaction forces (GRF) were collected at 1000 Hz with an AMTI OR6-5 force plate (Watertown, MA, USA) and muscle excitations were at 1000 Hz using a Noraxon Telemyo system (Scottsdale, AZ, USA).

Following completion of these anticipated sidestep cutting trials an isokinetic dynamometer was utilized to produce an acute reduction in right leg hamstring strength (Rozzi et al., 1999). Prior to the strength reduction protocol, the right shank marker cluster was removed. The protocol then began with five warm-up concentric knee flexion and passive extension contractions with 75% effort. Next, a five repetition maximum concentric knee flexion test was recorded at an angular velocity of 180 $deg \cdot s^{-1}$. The participants then completed three sets of maximum effort repetitions, separated by a 40 second rest interval. The first two sets consisted of 40 repetitions, and the final set was continued until 3 consecutive repetitions fell below 25% of the participants' peak isokinetic knee flexion torque at 180 $deg \cdot s^{-1}$. Immediately following the strength reduction protocol participants' peak isokinetic knee flexion strength was measured at 30 $deg \cdot s^{-1}$, the right shank marker cluster was reattached and participants completed five additional 45° anticipated sidestep cutting maneuvers. After post-strength reduction trials were completed the calibration markers were reapplied on the marked locations and another three second standing calibration trial was collected. Anticipated sidestep cutting was chosen to minimize the time between the strength reduction protocol and post-strength reduction cutting trials. An average of 69 s elapsed between completion of the strength reduction protocol and the start of the sidestep cutting trials.

Raw three-dimensional marker coordinate and GRF data from the pre- and post-strength reduction sidestep cutting trials were low-pass filtered using a fourth-order, zero lag, and recursive Butterworth filter with a cutoff frequency of 20 Hz (Kristianslund et al., 2012). A kinematic model, comprised of eight skeletal segments (trunk, pelvis, and bilateral thighs, shanks, and feet) was created from the standing calibration trial using Visual3D (v4.86, C-Motion Inc., Rockville, MD) (Weinhandl et al., 2010). Hip joint centers were placed at 25% of the distance from ipsilateral to contralateral greater trochanter marker (Weinhandl and O'Connor, 2010). Knee joint centers were the midpoint between femoral epicondyle markers (Grood and Suntay, 1983) and ankle joint centers were the midpoint between malleoli markers (Wu et al., 2002). Segment coordinate systems were defined to describe segment position and orientation using an unweighted least squares procedure (Spoor and Veldpaus, 1980). An inverse kinematics algorithm was used to solve for the joint angles that minimized soft tissue artifact and