The effects of isometric and isotonic training on hamstring stiffness and anterior cruciate ligament loading mechanisms

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ABSTRACT

Greater hamstring musculotendinous stiffness is associated with lesser ACL loading mechanisms. Stiffness is enhanced via training, but previous investigations evaluated tendon rather than musculotendinous stiffness, and none involved the hamstrings. We evaluated the effects of isometric and isotonic training on hamstring stiffness and ACL loading mechanisms. Thirty-six healthy volunteers were randomly assigned to isometric, isotonic, and control groups. Isometric and isotonic groups completed 6 weeks of training designed to enhance hamstring stiffness. Stiffness, anterior tibial translation, and landing biomechanics were measured prior to and following the interventions. Hamstring stiffness increased significantly with isometric training (15.7%; p = 0.006), but not in the isotonic (13.5%; p = 0.089) or control (0.4%; p = 0.942) groups. ACL loading mechanisms changed in manners consistent with lesser loading, but these changes were not statistically significant. These findings suggest that isometric training may be an important addition to ACL injury prevention programs. The lack of significant changes in ACL loading mechanisms and effects of isotonic training were likely due to the small sample sizes per group and limited intervention duration. Future research using larger sample sizes and longer interventions is necessary to determine the effects of enhancing hamstring stiffness on ACL loading and injury risk.

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1. Introduction

Neuromuscular training programs have demonstrated modest efficacy in reducing anterior cruciate ligament (ACL) injury risk (Gilchrist et al., 2008; Hewett et al., 2006; Mandelbaum et al., 2005; Yoo et al., 2010). However, these programs incorporate numerous components, and there is little-to-no evidence regarding which components are effective or even necessary (Hewett et al., 2006; Yoo et al., 2010). This large number of components requires a substantial time commitment which may lead to poor compliance. As compliance is paramount for success, future ACL injury prevention programs should be streamlined to minimize the time requirement, thus maximizing efficiency, compliance, and efficacy.

The components included in ACL injury prevention programs should be selected based on evidence identifying (1) characteristics that influence ACL loading, (2) which of these characteristics are modifiable, and (3) the effects of modifying these characteristics on ACL injury risk. ACL-deficient individuals with greater hamstring musculotendinous stiffness (MTS) possess greater functional ability than those with more compliant hamstrings (McNair et al., 1992). Healthy individuals with greater hamstring MTS display less anterior tibial translation during controlled perturbations compared to those with more compliant hamstrings (Blackburn et al., 2011). Greater hamstring MTS is also associated with more favorable landing biomechanics in terms of ACL loading as evidenced by smaller anterior tibial shear forces and frontal plane knee moments, and greater knee flexion at the instants of peak kinetic ACL loading mechanisms (Blackburn et al., 2013). Furthermore, peak frontal plane knee moments predict ACL injury risk prospectively (Hewett et al., 2005), suggesting that greater hamstring MTS may be associated with lesser injury risk. MTS can be enhanced via training, thus modifying this single neuromuscular characteristic may reduce ACL loading and injury risk.

Increases in stiffness have been demonstrated with a variety of training modes (Burgess et al., 2007; Grosset et al., 2009; Kubo et al., 2000a,b; 2001a, 2001b, 2007, 2006, 2009; Pousson et al., 1990), with isometric and isotonic training producing the largest increases. However, all but two of these investigations measured tendon stiffness rather than that of the musculotendinous unit as a whole (i.e. MTS), and none involved the hamstrings, thus it is unclear if these training mechanisms would have the same effects on hamstring MTS. As greater hamstring MTS is associated with...
lesser ACL loading mechanisms (Blackburn et al., 2013; 2011), demonstrating the ability to enhance this neuromuscular characteristic may inform the development of ACL injury prevention programs. Therefore, the primary purpose of this investigation was to evaluate the effects of isometric and isotonic training on hamstring MTS. A secondary purpose was to determine if increasing hamstring MTS alters ACL loading mechanisms consistent with reduced injury risk.

2. Methods

This investigation utilized a single-blind randomized controlled experimental design. Thirty-six healthy volunteers (18 males, 18 females) were assigned to isometric (IsoM; n = 12), isotonic (IsoT; n = 12), or control (CON; n = 12) groups in a stratified random manner (i.e. equal sex distribution). Subjects had no history of ACL injury, neurological disorder, or lower extremity surgery or injury within the 6 months prior to participation, and completed at least 20 min of physical activity 3 per week. IsoM and IsoT groups completed 6 weeks of training designed to enhance hamstring MTS, while the CON group continued their normal physical activity habits throughout the intervention. The principal investigator was blinded to group assignment. Hamstring MTS, anterior tibial translation, and landing biomechanics were assessed within 1 week prior to and following the interventions. Hamstring MTS does not differ between limbs in healthy individuals (Jennings and Seedhom, 1998), thus all data were sampled from the right leg only. All subjects read and signed an informed consent document which was approved by the university’s institutional review board.

2.1. Procedures

Hamstring MTS was assessed via the damped oscillatory technique (Blackburn et al., 2013; 2011; Granata et al., 2002; McNair et al., 1992). Subjects were positioned prone with the hip and knee in 30° of flexion and the foot secured to a load cell (Honeywell Sensotec model 41, Columbus, OH, USA) which permitted measurement of hamstring force (Fig. 1). EMG electrodes (DelSys Inc. Bagnoli-8, Boston, MA, USA) were positioned over the biceps femoris long head to evaluate hamstring activity. Subjects performed a 5s maximal voluntary isometric contraction (MVIC) during which load cell and hamstring EMG data were sampled. The foot was then freed from the loading device, permitting knee flexion/extension, and a load equal to 45%MVIC was secured to the shank (Fig. 2). The investigator then aligned the shank with the horizontal, and the subject contracted the hamstrings isometrically to maintain this position (i.e. 30° of knee flexion). The investigator then applied a downward manual perturbation to the calcaneous, extending the knee and initiating oscillatory flexion/extension. The force used to produce this perturbation is manual, and is, therefore, not controlled experimentally. However, MTS demonstrated excellent intra-session reliability and precision for all subjects at pre-test (ICCs1 = 0.82; SEM = 2.90 N/m kg⁻¹) and excellent inter-session reliability across the intervention in the control group (ICCsx = 0.87; SEM = 1.69 N/m kg⁻¹), and previous research (Blackburn et al., 2011) indicates that MTS is independent of perturbation magnitude.

The damped oscillatory knee flexion/extension motion was characterized in the tangential acceleration of the shank segment captured by an accelerometer (PCB Piezotronics model 356A32, Depew, NY, USA) fixed to a splint secured near the ankle. The period between the first two oscillatory peaks in the acceleration was used to calculate the damped oscillatory frequency (Fig. 3), which was then used to calculate MTS via the equation $MTS = \frac{4\pi^2 mf^2}{k}$, where $m$ is the system mass (shank and foot segment (Dempster et al., 1959) + 45%MVIC) and $f$ is the damped oscillatory frequency. Five trials were averaged for analysis and normalized to subject mass (Blackburn et al., 2009; Granata et al., 2002).

An electromagnetic motion capture system (Ascension Technology Corp. miniBIRDS, Burlington, VT, USA) was used to sample knee kinematics during a double-leg landing from a 30 cm height positioned 50% of subject height from two force plates (Bertec Corp. model 4060, Columbus, OH, USA) from which ground reaction forces and moments were sampled. Sensors were placed on the pelvis, thigh, and shank segments, and a segment-linkage model was created by digitizing the medial and lateral malleoli and
femoral epicondyles, and the left and right anterior superior iliac spines. Subjects landed with each foot centered on a single force plate, and performed a maximal vertical leap immediately following ground contact. Kinetic, kinematic, and anthropometric (Dempster et al., 1999) data were combined via an inverse dynamics solution (Gagnon and Gagnon, 1992) to derive net joint forces and internal moments (i.e. the internal response to an external moment). In accordance with literature demonstrating the influence of hamstring MTS on landing biomechanics (Blackburn et al., 2013), peak anterior tibial shear force (ATSF) and internal knee varus moment (KVM), and the knee flexion angle at peak ATSF, internal KVM, and internal knee extension moment (KEM) were assessed during the loading phase of landing (i.e. from initial ground contact to peak knee flexion). Moments were normalized to the product of height and weight, and forces were normalized to weight. The average for each variable was calculated across five trials.

Anterior tibial translation (ATT) was assessed via a custom perturbation device (Blackburn et al., 2011) (Fig. 1). Subjects were positioned as in hamstring MVICs and produced hamstring force equaling 45 ± 5%MVIC which was verified via biofeedback provided on a computer monitor. A cuff was secured to the proximal shank and connected to a load equal to 20% body weight. This load was initially supported by a trigger, but was released following hamstring contraction, allowing the load to be applied abruptly to the posterior shank, producing ATT. ATT was calculated as the peak anterior displacement of the shank relative to the thigh obtained from the electromagnetic coordinate data, and was averaged across five trials.

The training interventions were based on protocols developed by Kubo et al. (2009, 2001a,b, 2007, 2006). Subjects were positioned as in MTS assessment (Fig. 2), and weights equaling 70%MVIC were secured to the shank. For the IsoM intervention, subjects contracted the hamstrings to support the shank on the horizontal (hip and knee in 30° of flexion). For the IsoT intervention, a digital metronome set to 60 bpm was used to control movement velocity and define the concentric (1 s duration) and eccentric (3 s duration) phases over the full knee flexion/extension range of motion. Subjects in both groups reported to the laboratory for training 4× per week for 6 weeks. All training sessions were supervised by research assistants to ensure blinding of the principal investigator to group assignment. The details of each protocol are provided in Table 1. Compliance was calculated as the percentage of training sessions each subject completed out of the 24 total possible sessions.

### 3. Results

The MTS value for 1 male in the IsoM group was identified as a statistical outlier (i.e. ≥2 sd beyond the mean), thus this subject was excluded from statistical analyses. While all subjects in both intervention groups completed the post-test assessment, 2 males in the CON group did not. Compliance in the IsoM and IsoT groups was 88% and 89%, respectively, and did not differ between groups (p = 0.869). Demographic characteristics for subjects included in the statistical analyses are presented in Table 2. All demographic and dependent variables were similar between groups at pre-test (p > 0.05).

The change in hamstring MTS across the intervention did not differ between groups (p = 0.325 for group × time interaction effect). However, the main effect for Time was significant (p = 0.028). Inspection of the data (Fig. 4) suggested the interventions were effective, but that the variability associated with the small sample sizes per group prevented identification of a significant interaction effect. Mean changes in MTS across the intervention were 15.7% (IsoM), 13.5% (IsoT), and 0.4% (CON). We, therefore, performed one-tailed dependent-samples t-tests to compare pre-test and post-test hamstring MTS within each group. These exploratory analyses indicated that stiffness increased significantly in the IsoM group (p = 0.006), and that the change in stiffness in the IsoT group approached significance (p = 0.089; observed power = 0.56), but not in the CON group (p = 0.471).

Hamstring strength and EMG amplitudes were similar for all groups and did not change across the intervention (p > 0.05). Because only the IsoM group demonstrated a significant increase in MTS, correlations between the changes in MTS, strength, and EMG activity were limited to these subjects. Similar to the MTS data, we conducted exploratory analyses on these data using a priori planned exploratory analyses.
change in MTS was not correlated with changes in strength in the IsoM group. Furthermore, the

\( r = 0.348, p = 0.293 \) did not change significantly in the IsoM group. Furthermore, the change in MTS was not correlated with changes in strength in the IsoM group. The effect size (0.75) for MTS; however, the observed power for this effect was 0.56, indicating that 25 subjects would have seen similar improvements in neural function via more robust methods. These findings suggest that changes in MTS were likely attributable to changes in material and/or architectural musculotendinous properties and improved neural efficiency rather than improved strength. Furthermore, ACL loading mechanisms are correlated with hamstring MTS, but not with hamstring strength (Blackburn et al., 2013; Blackburn et al., 2011), and injury prevention programs which incorporate hamstring training decrease ACL loading mechanisms and injury risk (Gilchrist et al., 2008; Hewett et al., 1996; Kiani et al., 2010). These findings suggest that enhancing hamstring MTS, and not specifically hamstring strength, may reduce ACL loading and injury risk.

The most common application of ACL injury prevention programs is to athletic teams, and they are typically performed in the practice environment. The isometric hamstring training in this investigation is not likely feasible in these settings unless training is implemented outside the practice environment. However, training similar to the isometric protocol in this investigation in the form of Nordic hamstrings exercises (Mjolsnes et al., 2004) could be implemented into warm-up sessions for athletic teams. These exercises begin with the individual positioned upright on his knees with a teammate standing behind him to secure the feet, followed by eccentric hamstring action as the individual lowers himself to the ground, and concentric hamstring action to return to the starting position. Just as Nordic hamstring exercises emphasize eccentric action, the isometric training in this investigation emphasized the eccentric phase of the activity (i.e. 1 s concentric, 3 s eccentric). Though not statistically significant, isometric training increased hamstring stiffness 13.5% (\( p = 0.089 \), slightly less than that following isometric training (15.7%). Isometric training resulted in a large effect size (0.75) for MTS; however, the observed power for this effect was 0.56, indicating that 25 subjects would have been necessary to provide statistical power of 0.80 for \( x < 0.05 \) (Portney and Watkins, 2009). Therefore, it is likely that a larger sample size would have resulted in a significant increase in hamstring MTS following isometric training.

Greater hamstring MTS is associated with more favorable biomechanics in terms of ACL loading (Blackburn et al., 2013; Blackburn et al., 2011). As such, increasing hamstring MTS via isometric or isometric training may reduce ACL injury risk. While none of the changes in landing biomechanics across the intervention were statistically significant in the IsoM group, ATT, ATSF and KVM all decreased, and knee flexion angle at peak ATSF, KVM, and KEM increased. These findings suggest that increasing hamstring MTS may alter knee joint biomechanics in manners consistent with reduced ACL loading. The effect sizes for these analy-
ses ranged from small to medium (0.11–0.51) and the observed power was low (0.074–0.303). We suggest that the lack of significant findings was due, in large part, to the small sample size per group (n = 12) and short intervention duration (6 weeks). While no data specific to hamstring MTS are available, increases in tendon stiffness as great as 30–71% have been observed following 12 weeks of training (Kubo et al., 2009; Kuko et al., 2007), changes which are substantially greater than the 13–15% increases in MTS we observed following only 6 weeks of training. A 12 week training duration reflects that of neuromuscular training programs demonstrated to reduce ACL injury risk (Gilchrist et al., 2008). Additionally, McNair et al. (1992) demonstrated that ACL-deficient individuals with greater hamstring MTS possessed greater functional ability. These individuals all elected to undergo conservative rather than surgical management of their injuries and were tested, on average, 20 months post-injury. As such, they likely experienced rehabilitation and/or training and adaptation over a period of time substantially greater than our intervention. Additionally, the orientation of the ACL in the knee joint space exposes it to loading influences from multiple planes of motion (Markolf et al., 1995). Because we did not directly measure ACL loading, the summative effect of the individual changes in these plane-specific loading mechanisms on the total load experienced by the ACL cannot be determined. These findings support the need for future research involving longer interventions and larger sample sizes to elucidate the effects of increasing hamstring MTS on ACL loading mechanisms and injury risk. However, this investigation provides an important first step in evaluating the potential for enhancing hamstring MTS as part of ACL injury prevention efforts.

The limitations of this investigation should be considered when interpreting the results. First, the sample size per group was relatively small, thus the presence of extreme scores may have influenced the data. While we employed data screening procedures to identify statistical outliers, the efficacy of these procedures is limited with small sample sizes due to the presence of relatively large standard deviations. Second, while the principal investigator was blinded to group assignment, the subjects were not, thus it is possible that performance was influenced by knowledge of group assignment. Third, the interventions were of relatively short duration, and it is unclear if longer durations would have resulted in larger MTS increases and changes in ACL loading mechanisms. Lastly, only isometric and isotonic training were evaluated, thus it is unclear if other training modes would produce different effects.

Conflict of Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References


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