HAMSTRING STIFFNESS IS RELATED TO ANTERIOR TIBIAL TRANSLATION WHEN TRANSITIONING FROM NON-WEIGHT BEARING TO WEIGHT BEARING

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Anterior tibial translation (ATT) loads the anterior cruciate ligament (ACL) as the knee transitions from non-weight bearing (NWB) to weight bearing (WB). Therefore, any factors able to effectively reduce ATT during initial WB would theoretically reduce ACL loading. This study evaluated the extent to which hamstring musculo-articular stiffness (K_{HAM}) is associated with ATT as the knee transitions from NWB to WB in 10 healthy females (19.9 ± 1.5 yrs, 1.65 ± 0.06 m, 62.3 ± 6.3 kg). Linear regression revealed that K_{HAM} predicted 48.6% of the variance in ATT (R^2 = .486, p = .025), with higher K_{HAM} being associated with less ATT. K_{HAM} is modifiable through training, and thus may be an important factor to consider from ACL injury prevention and rehabilitation perspectives.

KEY WORDS: Musculo-articular stiffness; Anterior cruciate ligament; Knee biomechanics

INTRODUCTION: Noncontact anterior cruciate ligament (ACL) injuries often occur when the knee transitions from non-weight bearing (NWB) to weight bearing (WB) during cutting and landing maneuvers with the knee relatively extended (< 30° flexion) (Krosshaug et al., 2007). This transition to WB naturally results in anterior tibial translation (ATT), which is restrained by the ACL (Torzilli & Warren, 1994). When this transition to WB occurs with the knee closer to extension during movements that produce high ground reaction forces and internal knee extensor moments, the resultant ATT can become excessive and lead to higher loads placed on the ACL (Sell et al., 2007; Yu, Lin, & Garrett, 2006). Thus, any factors able to effectively resist ATT could theoretically reduce ACL loading and noncontact ACL injury risk.
Cadaver research has shown that simulated hamstring muscle contraction helps control anterior and rotary tibiofemoral motion (Victor, Labey, Wong, Innocenti, & Bellemans, 2010). However, the hamstrings ability to resist ATT during functional loading tasks has not been demonstrated *in vivo*. In this regard, a property of the hamstrings that may play a critical role in resisting ATT and ACL loading is hamstring musculo-articular stiffness (K_{HAM}). K_{HAM} is a modifiable neuromechanical property that quantifies the resistance of the hamstring musculo-articular unit to lengthening in response to an applied load (Blackburn & Norcross, 2014). Healthy individuals with lower K_{HAM} display more ATT during controlled perturbations (Blackburn, Norcross, & Padua, 2011), and greater anterior tibial shear force during bilateral landing tasks, than those with higher K_{HAM} (Blackburn, Norcross, Cannon, & Zinder, 2013). Further, females display less K_{HAM} (Blackburn, Riemann, Padua, & Guskiewicz, 2004) and are at a substantially greater risk for noncontact ACL injury than males, which suggests that K_{HAM} may contribute to ACL loading and injury risk. A limitation of previous work, however, is that the relationship between K_{HAM} and ACL loading has not been examined within a single-sex cohort. Because K_{HAM} is highly correlated with sex, this makes it difficult to tease out the unique contribution of K_{HAM} to ACL loading versus other sex-dependent factors. Additionally, initial trunk position (Blackburn & Padua, 2009) and hip and knee flexion angles (Sell et al., 2007; Yu, Lin, & Garrett, 2006) are predictive of anterior tibial shear; however, these variables have not been controlled for in previous investigations. Therefore, the purpose of this study was to experimentally evaluate, within a single-sex cohort, the extent to which K_{HAM} is associated with ATT as the knee transitions from NWB to WB. We hypothesized that, after experimentally controlling for initial trunk and lower-extremity positioning, higher K_{HAM} values would be associated with less ATT.

METHODS: Measures of K_{HAM} and ATT were obtained from 10 physically active females (19.9 ± 1.5 yrs, 1.65 ± 0.06 m, 62.3 ± 6.3 kg), following a 5 min warm-up. Participants were free from lower-extremity injury for at least 6 months prior to enrollment and without any history of knee ligament injury or surgery. This study was approved by the University's Institutional Review Board and written informed consent was obtained from all participants.

Hamstring Stiffness (K_{HAM}): K_{HAM} was assessed via the free-oscillation technique, whereby the damping effect that the hamstring muscles impose on oscillatory flexion/extension of the knee joint is quantified following a brief perturbation (Blackburn et al., 2011). Participants were positioned prone with the trunk and thigh supported in 30° of hip flexion and the shank was free to move (Figure 1A). A thermoplastic splint was secured to the plantar aspect of the foot and posterior shank to standardize ankle position, and 10% body mass load was then attached to the distal shank. The participant's shank was then passively positioned so that the knee was in approximately 30° of flexion, and the participant was required to maintain this position via isometric hamstring contraction. Real-time knee joint angle data were displayed on a monitor via an electrogoniometer, giving participants a visual target to maintain. Within 5 s of the participant holding this position, an downward perturbation was manually applied to the calcaneus, resulting in slight knee extension and subsequent damped oscillatory knee flexion/extension (Blackburn et al., 2011, 2004). This damped oscillatory motion was characterized as the tangential acceleration of the shank and foot segment, captured via a triaxial accelerometer attached to the thermoplastic splint (Figure 1A). Accelerometer data were sampled at 1000 Hz and then low pass filtered at 5 Hz with a fourth-order zero lag Butterworth filter. The time interval between the first two oscillatory peaks (t_1 and t_2) was used to calculate the damped frequency of oscillation [$1/(t_2 - t_1)$] and K_{HAM} using the equation $K_{HAM} = 4\pi^2 m f^2$, where m is the summed mass of the shank and foot segment and the applied load, and f is the damped frequency of oscillation. Participants were instructed not to interfere with or voluntarily produce the oscillations following the perturbation, and to attempt to keep the hamstrings active only to a level necessary to support the mass of the shank and foot segment and applied load in the testing position. Following 3-5 practice trials, 5 test trials were recorded. K_{HAM} values were then normalized to body mass and subsequently averaged for analysis. Prior to this study, we established good day-to-day measurement consistency for K_{HAM} ($ICC_{2,5} = 0.71$, SEM = 1.26 $N/m{\cdot}kg^{-1}$).

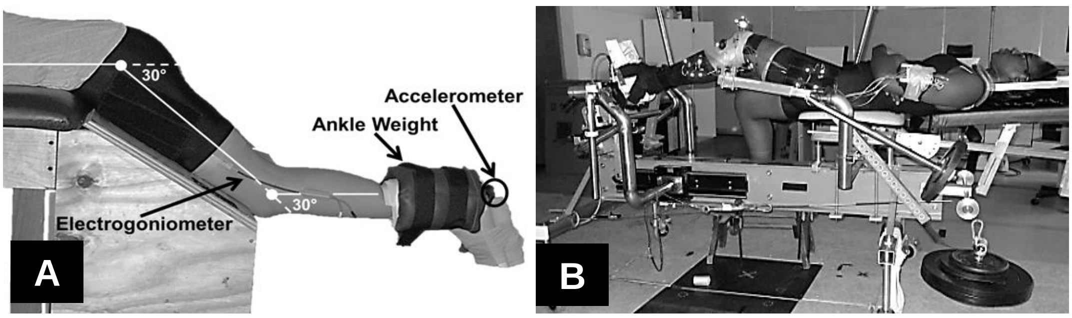

Figure 1. A) Participant positioning during hamstring musculo-articular stiffness (K_{HAM}) assessments. B) The Vermont Knee Laxity Device (VKLD).

Anterior Tibial Translation (ATT): ATT was assessed via the Vermont Knee Laxity Device (VKLD; Figure 1B) using methods previously described (Shultz et al., 2006). Briefly, the VKLD measures the displacement of the tibia relative to the femur as the knee transitions from NWB to WB, and characterizes the anterior-posterior load-displacement behavior of the knee during this transition. Additionally, the VKLD provides the ability to control trunk position and hip, knee, and ankle angles upon weight acceptance, the tibiofemoral shear loads acting at the knee prior to the application of WB loads, and the magnitude and direction of the WB load acting in a reproducible manner through the ankle and hip joint centers of rotation. Participants were instrumented with four clusters of optical LED motion capture markers placed on the lateral thigh, anterior patella, anterior proximal tibial, and lateral shank. Three-dimensional kinematic data were obtained via an eight-camera IMPULSE motion tracking system, and the lower-extremity was then modeled using Motion Monitor Software. Participants were positioned supine with the left foot strapped to a foot cradle connected to a six degree-of-freedom force transducer. The second metatarsal was then visually aligned to the anterior superior iliac spine, and the greater trochanter was aligned to the mechanical

axis of rotation of a thigh counterweight system. This counterweight system was applied in order to offset the gravity loads acting on the thigh segment. The participant's ankle and knee were then flexed to 90° and 30°, respectively, and participants were asked to completely relax their leg muscles. Three anterior-posterior forces were then manually applied to the proximal tibia to standardize the neutral position of the knee joint at the beginning of each trial. Additionally, an initial zero compressive load to the lower-extremity was confirmed prior to each trial via the force transducer attached to the foot cradle. Once initial joint positioning and zero compressive loading were achieved, a compressive load equal to 60% body weight was applied by the release of the load via a pulley system, which acted through the ankle and hip joint axes to simulate the transition from NWB to WB. Participants were unaware of when the load would be released and were instructed to: (1) not anticipate the release of the applied load, and (2) respond to the axial load as quickly as possible by attempting to maintain the initial knee position. Prior to data collection, 3-5 practice trials were performed. Kinematic data were collected at 240 Hz and then low-pass filtered at 5 Hz (fourth-order zero lag Butterworth). A segmental reference system quantified the three-dimensional kinematics as the knee transitioned from NWB to WB. For each segment, the +Z axis was directed laterally, the +Y axis superiorly, and the +X axis anteriorly. Euler's equations described joint motion about the knee with a rotational sequence of Z Y′ X′′. ATT was calculated as the anterior displacement of the proximal tibia with respect to the patella from the initial position during NWB to peak ATT during WB. Knee flexion angles were obtained at the start of each trial and at peak ATT to quantify the change in knee flexion upon weight acceptance, as this could potentially change the relative orientation between markers in the sagittal plane and underestimate the measurement of ATT. The average of 5 test trials was used for analysis.
Statistical Analysis: Linear regression examined the relationship between K_{HAM} (IV) and ATT (DV) while also accounting for any change in knee flexion angle (suppressor variable).

RESULTS: Descriptive statistics (mean ± SD) for K_{HAM} and ATT were 14.7 ± 2.4 N/m·kg^{-1} and 5.2 ± 2.1 mm, respectively. Knee angle data confirmed that participants began each ATT trial at or near 30° of flexion (28.7 ± 5.2°) and flexed their knee an average of 16.8 ± 6.2° from the onset of the applied load to peak ATT. Linear regression revealed that K_{HAM} predicted 48.6% of the variance in ATT (p = .025; Figure 2). The change in knee flexion angle explained less than 1.0% of the additional variance in ATT and the F change was not significant (p = .934).

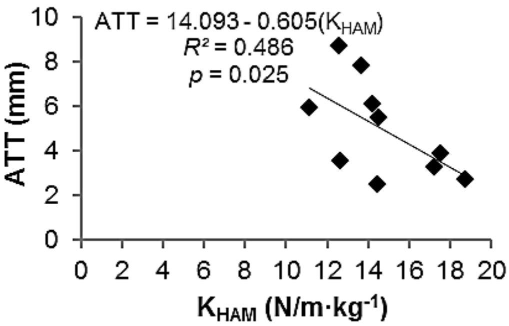

Figure 2. Scatterplot depicting the relationship between K_{HAM} and ATT.

DISCUSSION: Although cadaveric research has shown that simulated hamstring forces reduce ATT (Victor et al., 2010), relatively little is known about the hamstrings ability to resist ATT *in vivo*. Given that K_{HAM} quantifies the resistance of the musculo-articular unit to lengthening in response to an applied load, it is theorized that, for a given load, relatively stiffer hamstrings will permit a smaller change in length compared to more compliant hamstrings. In support of this theory, higher K_{HAM} has been associated with less ATT (Blackburn et al., 2011) and anterior tibial shear (Blackburn et al., 2013) during controlled perturbations and bilateral drop landings, respectively. However, the inclusion of males and females in the same analyses and lack of control over differences in body position upon landing have made it difficult to tease out the extent to which K_{HAM} uniquely contributes to biomechanical indicators of reduced ACL loading. Additionally, the association between K_{HAM}

and ATT has not been examined during a functional WB task. The current investigation expands on previous research by examining the relationship between K_{HAM} and ATT within a single-sex cohort through the use of a functional WB model that allows for standardized compressive axial loading and experimental control over initial body position.
In support of our research hypothesis, K_{HAM} predicted 48.6% of the variance in ATT, with higher K_{HAM} being associated with less ATT. This finding is in agreement with that of Blackburn et al (2011), and provides additional evidence to support the theory that higher K_{HAM} may play a critical role in resisting ATT during initial WB, thereby protecting the ACL from deleterious loading. Further, K_{HAM}.is modifiable, with increases in K_{HAM} of 15.7% reported following 6 weeks of isometric resistance training (Blackburn & Norcross, 2014). Based on the slope (~0.6 mm) of our prediction equation in Figure 2, a 15.7% increase in K_{HAM} could theoretically result in an approximate 1.4 mm reduction in ATT, which may be clinically meaningful in terms of injury prevention and rehabilitation. Hence, targeted training strategies aimed to increase K_{HAM} could potentially result in reduced sagittal plane ACL loading and noncontact injury risk. We acknowledge that the conditions under which we simulated the transition of the knee from NWB to WB are different from the way in which the knee is loaded during dynamic cutting and landing tasks. However, we felt that using a model that could effectively control for initial trunk and lower-extremity positioning, initial zero compressive and tibiofemoral shear loads, and both the magnitude and direction of the axial load applied, was an important first step in establishing a functional relationship between K_{HAM} and ATT. Future studies that incorporate more dynamic tasks are planned.

CONCLUSION: Our main finding was that higher K_{HAM} was associated with less ATT as the knee transitioned to WB. Because ACL injuries likely occur too rapidly for a reflexive response to adequately protect the ACL, this finding suggests that the initial stiffening response of the hamstrings may play a critical role in ACL loading by helping resist initial ATT. Future studies that examine the relationship between K_{HAM} and ACL loading parameters during more dynamic tasks will help further elucidate the role of K_{HAM} as an injury risk factor that can be modified through training.

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