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# Effect of Varying Hamstring Tension on Anterior Cruciate Ligament Strain During in Vitro Impulsive Knee Flexion and Compression Loading

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**Background:** The hamstring muscles are well positioned to limit both anterior tibial translation and anterior cruciate ligament strain during the knee flexion phase of a jump landing. We hypothesized that systematically increasing or decreasing hamstring tension during the knee flexion phase of a simulated jump landing would significantly affect peak relative strain in the anterior cruciate ligament.

**Methods:** Ten cadaveric knees from four male and six female donors (mean age [and standard deviation] at the time of death,  $60.3 \pm 23.6$  years) were mounted in a custom fixture to initially position the specimen in  $25^\circ$  of knee flexion and simulate axial impulsive loading averaging 1700 N to cause an increase in knee flexion. Quadriceps, hamstring, and gastrocnemius muscle forces were simulated with use of pretensioned linear springs, with the tension in the hamstrings arranged to be increased, held constant, decreased, at “baseline,” or absent during knee flexion. Impulsive loading applied along the tibia and femur was monitored with use of triaxial load transducers, while uniaxial load cells monitored quadriceps and medial and lateral hamstring forces. Relative strain in the anterior cruciate ligament was measured with use of a differential variable reluctance transducer, and tibiofemoral kinematics were measured optoelectronically. For each specimen, anterior cruciate ligament strains were recorded over eighty impact trials: ten preconditioning trials, ten “baseline” trials involving decreasing hamstring tension performed before and after three sets of ten trials conducted with increasing hamstring tension, constant hamstring tension, or no hamstring tension. Peak relative strains in the anterior cruciate ligament were normalized for comparison across specimens.

**Results:** Increasing hamstring force during the knee flexion landing phase decreased the peak relative strain in the anterior cruciate ligament by  $>70\%$  compared with the baseline condition ( $p = 0.005$ ). Neither a constant hamstring muscle force nor the absence of a hamstring force significantly changed the peak strain in the anterior cruciate ligament relative to the baseline condition.

**Conclusions:** Increasing hamstring muscle force during the knee flexion phase of a simulated jump landing significantly reduces the peak relative strain in the anterior cruciate ligament in vitro.

**Clinical Relevance:** It may be possible to proactively limit peak anterior cruciate ligament strain during the knee flexion phase of jump landings by accentuating hip flexion, thereby increasing the tension in active hamstring muscles by lengthening them.

The hamstring muscle group has the ability to limit both anterior tibial translation and anterior cruciate ligament strain or force<sup>1-7</sup>. In vivo studies have shown that anterior cruciate ligament strain is significantly affected by rela-

tive hamstring and quadriceps muscle activity<sup>8,9</sup>. Beynon et al.<sup>10</sup> found that isometric hamstring contractions did not increase the level of anterior cruciate ligament strain compared with that in the relaxed condition at  $15^\circ$ ,  $30^\circ$ ,  $60^\circ$ , and  $90^\circ$  of

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knee flexion; in contrast, experiments involving isolated quadriceps contractions showed an increase in anterior cruciate ligament strain. These findings provide evidence that hamstring function may be a critical component in the understanding of injuries of the anterior cruciate ligament and their prevention. The type of hamstring contraction state should also be important.

Forcible stretching of an active muscle can result in up to twice as much muscle tension, with no reflex time delay, as compared with that under isometric or shortening conditions<sup>11,12</sup>. The resistance of the muscle-tendon unit to forcible lengthening (the measured increase in force divided by the increase in length, or muscle stiffness) is known to be proportional to the percentage of actively contracting muscle<sup>13</sup>.

We investigated the effect of the hamstring muscle action state on the relative strain in the anteromedial region of the anterior cruciate ligament during the knee flexion phase of a simulated drop jump landing in a cadaver model by testing three hypotheses. Our hypotheses were that, when compared with the baseline condition (landing conducted with pre-tensioned quadriceps, hamstring, and gastrocnemius muscle-equivalents), (1) an increase in hamstring muscle tension (the lengthening hamstring condition) significantly reduces the peak relative strain in the anteromedial region of the anterior cruciate ligament, (2) isotonic hamstring muscle tension (the isotonic hamstring condition) significantly decreases peak relative strain in the anteromedial region of the anterior cruciate ligament, and (3) an absence of hamstring muscle tension (the no-hamstring condition) significantly increases the peak relative strain in the anteromedial region of the anterior cruciate ligament. The lengthening hamstring condition simulates a "lengthening" muscle contraction, a term used throughout this paper instead of "eccentric" contraction for the reasons given by Faulkner<sup>14</sup>.

## Materials and Methods

### *Specimen Procurement and Preparation*

Eighteen cadaver limbs were acquired from the University of Michigan's Anatomical Donations Program and were fresh-frozen at  $-20^{\circ}\text{C}$  until twenty-four hours prior to testing. All specimens were visually checked for scars and other indications of surgery, malalignment, or deformities prior to preparation and were confirmed to have normal anterior drawer behavior.

The dissection of each specimen was done in a stepwise manner. First, the skin and subcutaneous fat were removed to visualize each muscle. Next, the proximal portion of the quadriceps and hamstring muscles and the distal portion of the gastrocnemius muscles were removed to leave approximately 23 cm of the quadriceps tendon and 15 cm of the hamstring and gastrocnemius tendons available to be mounted in cryoclamps. Each knee specimen was cut 15 cm proximal and distal to the knee joint, and the exposed osseous ends were potted in 10-cm-diameter polyvinyl chloride cylinders with use of a polymethylmethacrylate compound.

Four specimens could not be used for testing because of degenerative joint changes (one) or a nonfunctional anterior

cruciate ligament (three), and four more were eliminated because the testing protocol was not completed, as a result of an anterior cruciate ligament rupture (one), a tibial plateau fracture (one), a quadriceps tendon failure (one), or a hamstring tendon failure (one). This left ten specimens, from four male and six female donors (mean age [and standard deviation] at the time of death,  $60.3 \pm 23.6$  years), that met the inclusion criteria and completed the testing protocol.

### *Knee Testing Apparatus*

A custom 2.5-m-high loading frame was built to mount the specimen in a knee flexion angle that simulated the position of a single extremity as it initially strikes the ground when an individual lands on one foot from a jump (Fig. 1). The specimen was set up with static pre-impact simulated muscular tensions to simulate the in vivo muscular behavior prior to known impact landings<sup>15</sup>. Pre-impact muscle tensions were set to 180 N for the quadriceps muscle ("Q" in Figure 1) and 70 N each for the medial and lateral hamstring muscles ("H" in Figure 1) and the medial and lateral gastrocnemius muscles ("G" in Figure 1). Aircraft cable (3 mm in diameter and with a tensile stiffness of 7 kN/cm; McMaster-Carr, Aurora, Ohio) was used to mimic the spring-like in vivo dynamic resistance of the active quadriceps, hamstring, and gastrocnemius muscle-tendon units under stretch loading. The four hamstring muscle-tendon unit states were created by varying the location of the ground connection point of the hamstring muscle for the specific configuration being tested. For the shortening (or baseline) configuration, the hamstring muscle-tendon unit attachment was affixed to the femoral construct, so that the muscle-tendon unit was allowed to shorten as the knee flexed under impact. For the lengthening hamstring muscle-force condition (Fig. 1), each hamstring muscle-tendon unit cable was attached to the baseplate so that, when the knee was flexed under the impulsive load, the medial and lateral hamstring muscle-tendon unit lengths, and hence forces, increased in proportion to the knee flexion angle. For the constant hamstring force, or isotonic configuration, the proximal end of the hamstring muscle-tendon unit was fixed to the femoral construct, but through a 100-N constant force spring (McMaster-Carr) so that the muscle tension was held at a near-constant force independent of the angle of knee flexion. Lastly, both the medial and the lateral hamstring muscle-tendon units were disconnected for the no-hamstring-tension loading condition.

The initial knee flexion angle was set at  $25^{\circ}$  for all trials. In every trial, this angle increased under the flexion moment component of the impulsive loading. The choice of this angle was based on our pilot radiographic studies, which showed that knee flexion angles of  $>25^{\circ}$  obviate any possibility of notch interference with the differential variable reluctance transducer as well as on evidence of a knee angle of  $27^{\circ}$  at the time of heel contact when an individual lands from a maximum-height jump<sup>16</sup>. A 150-N weight ("W" in Figure 1) was dropped vertically in line with the specimen from a fixed height (75 mm) to strike the end of the impact rod. This loaded the distal part of the tibia with an impulsive compressive force

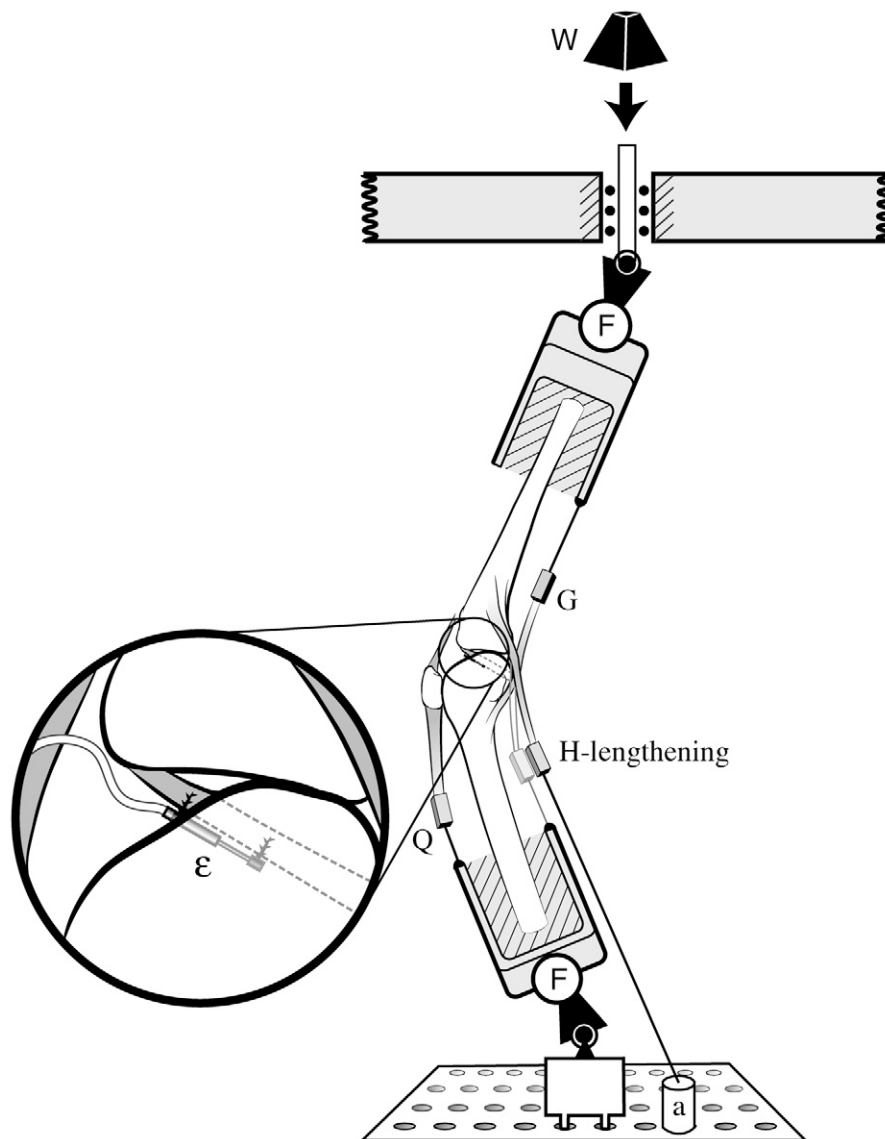


Fig. 1

Schematic of test setup, showing the knee mounted for testing as well as the applied impulsive loading (W) and three-axis load cells (F). Three of the five cables representing pre-impact tensions in the quadriceps (Q), medial and lateral hamstring (H), and medial and lateral gastrocnemius (G) muscle-tendon units are also visible. Two hamstring cable configurations are shown: the longer cables attached to point "a" represent the pair of hamstring cables used for the lengthening condition test, while the shorter cables attached to the lower mounting pot represent the pair of hamstring cables used for the baseline test condition. The latter were replaced by constant force springs for the isotonic hamstring force condition. The inset drawing shows the differential variable reluctance transducer attached to the anteromedial region of the anterior cruciate ligament in order to measure the relative strain ( $\epsilon$ ).

(reaching a peak in  $<40$  ms<sup>17</sup> and averaging at least 1700 N, to simulate ground impact forces recorded during a jump landing<sup>18</sup>). The initial direction of the impulsive force was 4 cm posterior to the knee-joint center in all trials, so it exerted a flexion moment about the knee joint that resulted in a sudden increase in the knee flexion angle and femoral angular mo-

mentum. Two three-axis load cells (AMTI, Watertown, Massachusetts) ("F" in Figure 1) measured the three-dimensional forces and moments delivered to the distal tibial end of the construct as well as the three-dimensional femoral reaction forces and moments. A 3-mm differential variable reluctance transducer (MicroStrain, Burlington, Vermont) was mounted

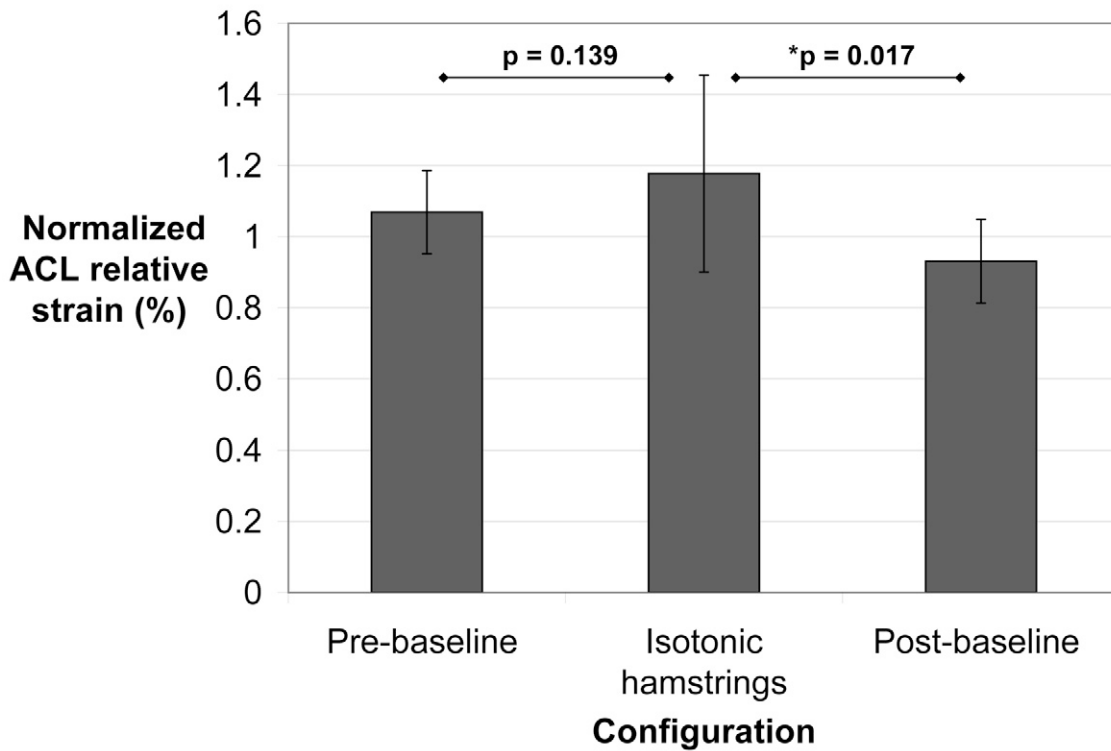


Fig. 2

Comparison of the mean peak relative strain (and standard deviation) in the anteromedial region of the anterior cruciate ligament for the isotonic hamstring condition with the immediate pre-baseline and post-baseline results in the ten knees.

midsubstance on the anteromedial region of the anterior cruciate ligament to record relative strain (“ $\epsilon$ ” in Figure 1). The differential variable reluctance transducer recorded the average relative strain in the superficial layer of the anteromedial bundle that extended to the tips of two 2.5-mm-long barbs used to mount it to the ligament. Impulsive forces, quadriceps and hamstring muscle forces, and anterior cruciate ligament strain data were recorded at 2 kHz with use of a 16-bit analog-to-digital converter board. The calibration constants obtained from the factory calibration of the input-output relationships were used for all force transducers, and forces were measured to the nearest newton. Six infrared-emitting diodes, three each mounted rigidly to the tibia and femur, were tracked with an Optotrak Certus System (Northern Digital, Waterloo, Ontario, Canada) to synchronously record tibiofemoral kinematics at 400 Hz to the nearest millimeter and degree.

#### Testing Protocol

An A-A-B-A-C-A-D-A repeated-measures testing protocol was used. In this experimental design, “A” represents the baseline condition trial block involving ten trials with decreasing hamstring force. The “B,” “C,” and “D” blocks each represent ten trials under specific hamstring loading conditions: constant hamstring force (isotonic), increasing hamstring force (lengthening), and absence of hamstring force, respectively. Hence a total of eighty trials were conducted on each specimen. Data from the first baseline trial block (A) were not used for analysis

because this block acted to precondition the specimen. Data from the last five trials in each of the remaining seven blocks (A-B-A-C-A-D-A) were averaged by block for further analysis.

#### Definition of Anterior Cruciate Ligament Strain

Ligament strain is usually defined as the change in ligament length divided by its original length. The definition of its initial length, needed to define the zero-strain state, is difficult in *in vivo* studies<sup>19</sup>. In our setup, nominal muscle preloads were needed to maintain the initial 25° angle of knee flexion prior to impact, so the unloaded zero-strain state was not known. We therefore defined the initial length of the differential variable reluctance transducer as the length of the transducer in the initial 25° pre-impact posture under simulated muscle loads. The change in transducer length from this initial length, divided by the initial length, was used to estimate the relative strain in the anteromedial region of the anterior cruciate ligament under impulsive loading. The peak relative strain in the anterior cruciate ligament for each of the three hamstring condition blocks was normalized by dividing it by the mean peak relative anterior cruciate ligament strain obtained during the pretest and posttest baseline blocks (the blocks immediately before and after that trial block).

#### Statistical Analyses

The primary (null) hypotheses were that (1) the peak relative strain in the anteromedial region of the anterior cruciate lig-

**TABLE I Mean Impulsive Force, Measured Muscle Forces, and Strain in the Anteromedial Region of the Anterior Cruciate Ligament Under the Four Test Conditions\***

Configuration	Peak Relative Strain in Anteromedial Region of Anterior Cruciate Ligament (%)	Peak Impulsive Force (N)	Peak Quadriceps Force (N)	Peak Medial Hamstring Force (N)	Peak Lateral Hamstring Force (N)
Baseline	3.0 ± 1.1	1,755 ± 275	1,579 ± 203	168 ± 68	183 ± 62
Lengthening of hamstrings	0.8 ± 0.6	2,093 ± 370	1,161 ± 231	338 ± 118	394 ± 83
Isotonic hamstrings	3.6 ± 1.1	1,777 ± 256	1,546 ± 186	92 ± 29	103 ± 31
No hamstrings	2.9 ± 1.3	1,702 ± 224	1,514 ± 169	NA	NA

\*The values are given as the mean and standard deviation. NA = not applicable.

ament under the lengthening hamstring muscle-tendon unit condition would not differ from that under the baseline (neutral loading) condition, (2) the peak relative strain in the anteromedial region of the anterior cruciate ligament under the isotonic hamstring condition would not differ from that under the baseline (neutral loading) condition, and (3) peak relative strain in the anteromedial region of the anterior cruciate ligament under the no-hamstring condition would not differ from that under the baseline (neutral loading) condition. In determining the number of specimens that would be needed,

we focused our sample-size calculations on the achievement of adequate statistical power to test the primary hypothesis. To estimate requisite sample sizes, and to test for significance throughout the study, an alpha level of 0.05 and a power of 0.80 were used. An effect size of 2.06 was found during a pilot study on the lengthening hamstring condition, which required four specimens per group to reach adequate power. A non-parametric Wilcoxon signed-rank test with exact significance was used to test the null hypothesis. An alpha level of 0.05 was chosen for the level of significance.

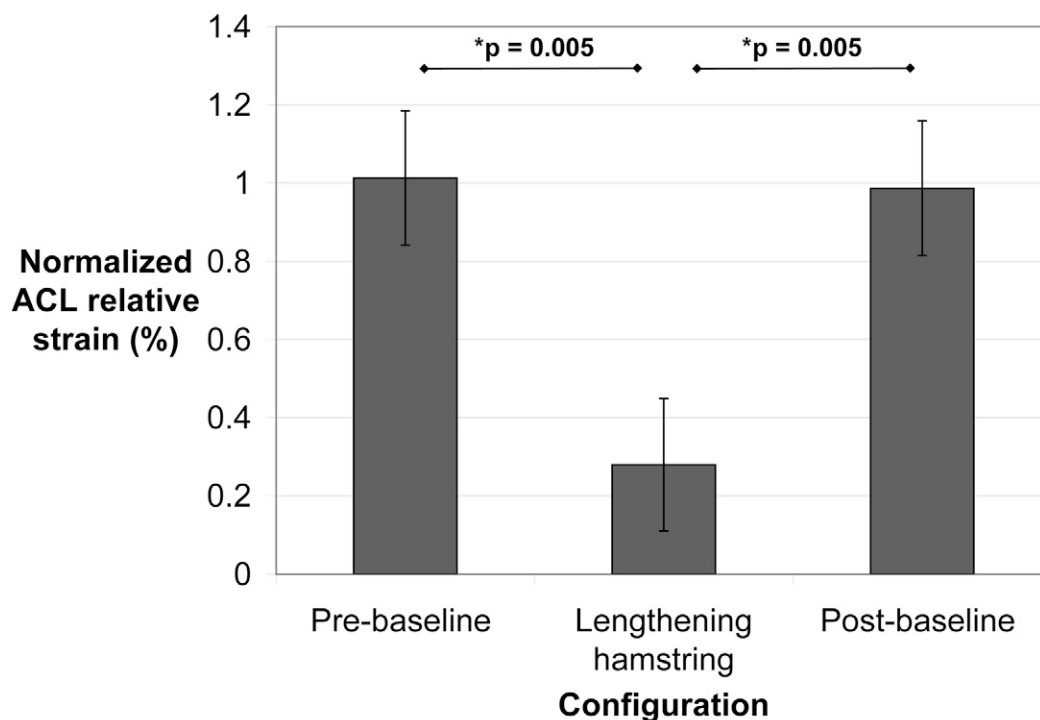


Fig. 3

Comparison of the mean peak relative strain (and standard deviation) in the anteromedial region of the anterior cruciate ligament for the lengthening hamstring condition with the immediate pre-baseline and post-baseline results in the ten knees.

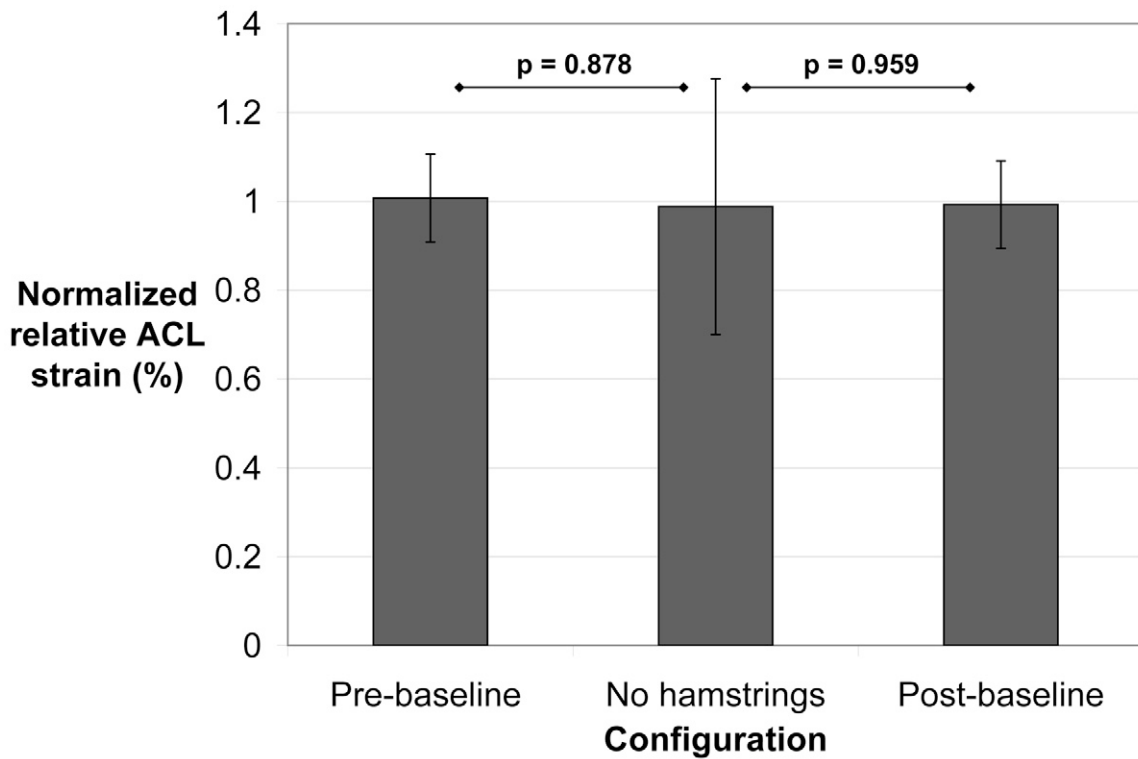


Fig. 4

Comparison of the mean relative strain (and standard deviation) in the anteromedial region of the anterior cruciate ligament for the no-hamstring condition with the immediate pre-baseline and post-baseline results in the ten knees.

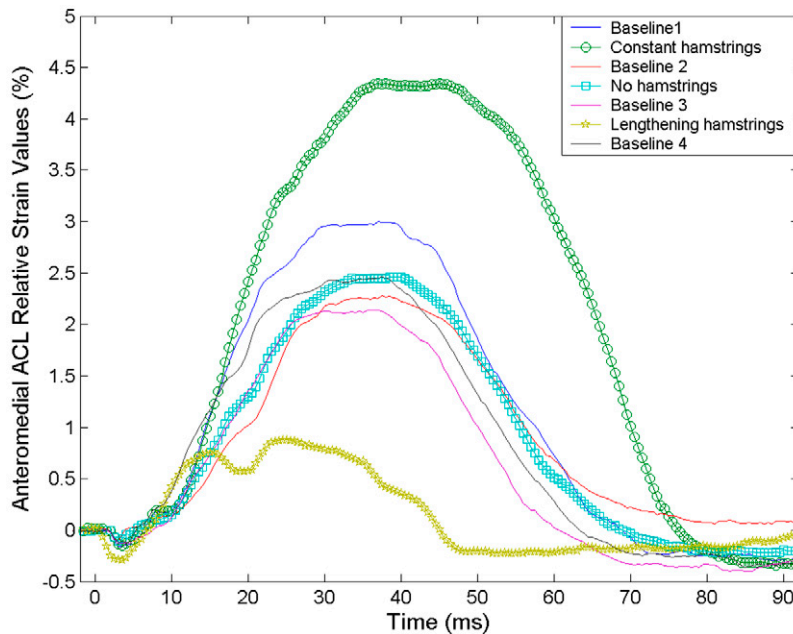


Fig. 5

Sample data for a single knee. Normalized strain in the anteromedial region of the anterior cruciate ligament versus time for all configurations (baseline 1, isotonic hamstring tension, baseline 2, no hamstring tension, baseline 3, lengthening hamstring condition, and baseline 4).

TABLE II Mean Changes in Knee Kinematic Variables Under Impulsive Loading\*

Configuration	Change in Flexion Angle (deg)	Change in Valgus Angle (deg)	Change in Tibial Rotation (deg)	Tibial Translation (mm)
Baseline	5.9 ± 1.4	1.8 ± 2.0	1.9 ± 1.5	4.3 ± 1.4
Lengthening of hamstrings	5.5 ± 1.2	1.1 ± 0.8	1.0 ± 0.5	3.1 ± 1.4
Isotonic hamstrings	6.0 ± 1.1	2.3 ± 1.0	2.8 ± 1.5	4.2 ± 1.0
No hamstrings	6.1 ± 1.3	2.2 ± 1.1	2.5 ± 1.4	4.8 ± 1.2

\*The change in flexion was measured from the initial (25°) flexion angle. The change in valgus angle was the increase in the valgus angle from the initial limb neutral position. The increase in internal tibial rotation was measured with respect to the femur, and tibial translation was measured as the anterior motion of the tibia with respect to the femur. The values are given as the mean and standard deviation.

## Results

The peak relative strain in the anteromedial region of the anterior cruciate ligament in the isotonic hamstring condition did not differ from that found in the pre-baseline test condition ( $p = 0.139$ , Fig. 2 and Table I) but it was significantly greater than that in the post-baseline state ( $p = 0.017$ ). No significant difference in the anterior cruciate ligament strain was found between the pre-baseline and post-baseline conditions ( $p = 0.139$ ).

The increase in hamstring force caused by the lengthening hamstring condition reduced the peak relative strain in the anteromedial region of the anterior cruciate ligament by a mean of >70% ( $p = 0.005$ , Fig. 3 and Table I). Both the pre-baseline and the post-baseline anterior cruciate ligament strains were significantly greater than those found after the addition of the lengthening hamstring condition ( $p = 0.005$  for both), confirming that the anterior cruciate ligament was not damaged during testing. No difference in strain was found between the pre-baseline and post-baseline conditions ( $p = 0.799$ , Fig. 3).

No significant difference in the peak relative strain in the anteromedial region of the anterior cruciate ligament was found between either the pre-baseline or the post-baseline condition and the no-hamstring condition ( $p = 0.878$  and  $p = 0.959$ , respectively; Fig. 4 and Table I). The strain did not differ significantly between the two baseline conditions ( $p = 0.646$ ).

An increase in the hamstring force during the knee flexion phase decreased the peak strain in the anteromedial region of the anterior cruciate ligament (Fig. 5). No major differences were observed in the kinematic changes in the knee joint between hamstring loading conditions (Table II). However, the small sample size and limited power precluded statistical tests of these data.

## Discussion

The results of this in vitro study support our primary hypothesis that stretching spring-like representations of contracted hamstring muscles, while the knee flexes under an impulsive flexion and compression load, significantly decreases the peak relative strain in the anteromedial region of the anterior cruciate ligament compared with that under a simulated

shortening-hamstring-muscle condition (Fig. 3). This decrease in the anterior cruciate ligament strain was found despite the fact that the impulsive force applied under the lengthening condition was significantly greater than that under any other test condition ( $p < 0.001$ , Table I). It is noteworthy that this decrease in the peak relative strain in the anteromedial region of the anterior cruciate ligament was associated with a lower rise in quadriceps force compared with those in the other test conditions; this would have reduced the increase in anterior force pulling on the tibia through the quadriceps tendon and the patellofemoral mechanism. This reduction in peak quadriceps tension may be explained by a stiffening of the knee construct under the increased hamstring tension, which itself helped to limit the rise in relative strain in the anteromedial region of the anterior cruciate ligament during the impulsive loading. The decrease in the anterior cruciate ligament strain was probably not due to an injury to either the anterior cruciate ligament or a secondary restraint because no difference in anterior cruciate ligament strain was found between the pre-baseline and post-baseline states ( $p = 0.799$ ). In a computer simulation similar to this experimental paradigm, Pflum et al.<sup>17</sup> reported that a shortening hamstring condition resulted in hamstring forces near 700 N, which is comparable with the hamstring forces observed in the lengthening hamstring loading condition in this experiment (732 N). Thus, our simulation of hamstring states in this experimental study appears to be reasonable. The mean peak relative anterior cruciate ligament strains in this study ranged from 0.8% to 3.6%. These values are consistent in magnitude with the relative anterior cruciate ligament strains found by Heijne et al. in a study of in vivo closed kinetic chain isometric quadriceps contractions<sup>20</sup>.

We chose a standardized initial flexion angle (25°) for the three impacts so that the testing conditions would be comparable. In general, the greater the knee flexes, the more the hamstrings act to pull the tibia posteriorly; the more the knee extends, the more the hamstrings act to compress the joint<sup>1,21,22</sup>. Therefore, the greater the initial knee flexion angle, the more pronounced the effects of hamstring loading could become. It would be worthwhile to repeat these experiments with other initial flexion angles, both greater and less than 25°.

The impulsive loading represented by this test scenario is similar to that occurring when an individual lands from a jump, at which time the reaction force initially acts 4 cm behind the knee in the sagittal plane. This corresponds to a “vertical” landing in which the hip is essentially over the ankle joint, the knee is flexed 25°, and the vertical component of the reaction force is 1700 N (see Materials and Methods) and the friction force component under the foot is negligible. However, it also corresponds to a landing on one foot with considerable forward body momentum, which is arrested by the landing limb being steeply enough inclined so that the hip lies substantially posterior to the ankle joint, the knee is flexed 25°, and the posteriorly acting friction force acting on the shoe from the ground causes the resultant ground reaction to also incline such that it again acts 4 cm posterior to the knee. It would also pertain to landing scenarios intermediate between these two extremes.

Factors that affect the level of hamstring force in vivo include muscle length, muscle moment arms, knee and hip joint angles and their rate of change (angular velocity), training and conditioning, muscle central activation state, and muscle fatigue<sup>1,23-26</sup>. The position of the trunk and pelvis also has an effect on hamstring activation<sup>27</sup>. Since hip flexion lengthens the hamstrings and knee flexion shortens them, one could reduce anterior cruciate ligament strain by inducing a lengthening contraction of the hamstrings during the knee flexion phase of a jump landing while flexing the hip joint substantially more than the knee joint. In the present study, stretching of the spring-like muscle-tendon units immediately increased their tension as happens in the case of the quadriceps during a lengthening contraction condition in vivo. In the present model, shortening gastrocnemius states always occurred as the knee flexed under the impulsive load.

Several points are worth noting when comparing the relative strains in the anteromedial region of the anterior cruciate ligaments under the different hamstring conditions (Table I). First, the nominal value of the peak anteromedial ligament strain under the lengthening condition was less than that under the other testing conditions (0.8% compared with 2.9% to 3.6%). Second, this reduction in the strain cannot be explained by a decrease in impulsive force because the average impulsive force during the lengthening condition was actually significantly greater than the other impulsive forces (2093 N compared with 1702 to 1777 N). Third, the sum of the forces recorded in the hamstring load cells during the lengthening hamstring configuration (732 N) was greater than that recorded in either the baseline (shortening) state (351 N) or the isotonic state (195 N). Fourth, the lengthening hamstring condition reduced the quadriceps load, as evidenced by the resulting decrease in maximal quadriceps force (1161 N compared with 1514 to 1579 N). This may underlie the reduction in the peak relative strain in the anterior cruciate ligament under the lengthening hamstring condition.

Although this study had limitations, it is likely that none changed the overall findings. One limitation was that we could only measure the relative strain in the anteromedial region of

the anterior cruciate ligament. Femoral notch geometry prevented the insertion of a separate differential variable reluctance transducer into the posterolateral region of the anterior cruciate ligament without incurring artifacts in both measurements. In addition, we were able to estimate the average relative strain only over the length of the anteromedial region corresponding to the length of the differential variable reluctance transducer. This estimate cannot necessarily be extrapolated to the more proximal or distal regions of the anteromedial region of the anterior cruciate ligament, or to the local strain at any point along the length of the anteromedial region.

Another limitation was our inability to measure absolute anterior cruciate ligament strain. However, the reference strain that was measured is a conservative estimate and we are probably underestimating absolute strain because the five muscle forces preloaded the specimen prior to impact.

Although the five muscles physically only acted across the knee in the present model, our lengthening hamstring test condition actually represents the biarticular movement situation in vivo, in which hip flexion exceeds knee flexion. When the effect of hip flexion exceeds that of knee flexion, then a lengthening hamstring state can result, as demonstrated by Thelen et al. during sprinting<sup>28</sup>. Similarly, biarticular motions can also modulate the lengths of three of the four quadriceps muscles as well as the gastrocnemius muscles, so it would be worthwhile to investigate these effects in the future. While we cannot exclude the possibility that the change in anterior cruciate ligament strain under the simulated lengthening contraction could have been partially due to a change in the hamstring moment arm about the knee when the hamstring muscle-tendon unit was attached to the baseplate, we believe that this effect was minor in comparison with the measured change in hamstring tension during this test. Finally, given the interest in how coactivation of the quadriceps and hamstrings affects anterior cruciate ligament strain<sup>4,6,22</sup>, it would be useful to measure the effect of varying the relative magnitudes of the five muscle forces, prior to impact, on the relative strain in the anterior cruciate ligament.

The clinical relevance of this study is that it may be possible for athletes to proactively limit the peak strain in the anterior cruciate ligament during the knee flexion phase of jump landings by accentuating the increase in hip flexion, thereby increasing tension in the active hamstring muscles without neural delay by lengthening them. ■

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