Acta Orthop Scand 1995; 66 (3): 261–265

Effect of quadriceps or hamstring contraction on the anterior shear force to anterior cruciate ligament failure

An in vivo study in the rat

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We studied the effect of quadriceps or hamstring contractions on the anterior tibial shear load to anterior cruciate ligament failure in an in vivo rat model. In both knees of 20 Wistar rats the joint capsule and ligaments, except the anterior cruciate ligaments, were cut and the menisci resected. In 10 rats the right ligament was loaded to failure by anterior translation of the tibia relative to the femur in a testing device during hamstring contraction induced by electrical stimulation of the ischiatic nerve. In the other 10 rats, the right ligament was loaded to failure correspondingly during quadriceps contraction induced by electrical stimulation of the femoral nerve. The loading rate was 2.5 mm s^{-1} (~0.6^{-1}). The knee flexion during testing was 30°. As control, the anterior cruciate ligament of the left knee was loaded correspondingly with relaxed muscles. The ultimate load for the ACL tested during hamstring contraction was 1.5 times higher than when tested with the hamstrings relaxed, more than double the energy was absorbed at failure and the linear stiffness was 1.2 times higher. During testing with quadriceps contraction, no differences in the structural properties were found, compared to testing with the quadriceps relaxed. Our findings show that hamstring contraction helps to resist anterior tibial shear force at 30° knee flexion in rats thus protecting the anterior cruciate ligaments. Quadriceps contraction in this situation does not affect anterior shear force to ligament failure.

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Submitted 94-11-26. Accepted 95-02-21

Quadriceps contraction can cause an anterior translation of the tibia relative to the femur when the knee is near extension (Yasuda and Sasaki 1987a, Hirokawa et al. 1992). The anterior cruciate ligament provides the primary restraint to an anterior shear load on the tibia (Butler et al. 1980). From case studies of skiing injuries, it has therefore been speculated that quadriceps contraction can cause anterior cruciate ligament rupture (McConkey 1986, Feagin et al. 1987). The anterior tibial shear load generated by a maximum isometric quadriceps contraction in humans is small, however, compared to the strength of the ligament (Howell 1990, Chiang and Mote 1993). The validity of this mechanism of injury has therefore been questioned, but it has been proposed that it is sufficient to cause the final disruption after the ligament has been preloaded by an external shear force trauma (McConckey 1987). On the other hand, a hamstring contraction imposes a posterior drawer load on the tibia (Yasuda and Sasaki 1987a) that unloads the ligament (More et al. 1993).

To our knowledge, no study has been done concerning the effect of hamstring and quadriceps contraction on a simulated anterior shear load to anterior cruciate ligament failure near full extension in vivo. We investigated two null hypotheses. First, a maximum quadriceps contraction cannot resist an anterior tibial shear load to ligament rupture. Secondly, a maximum hamstring contraction cannot resist an anterior shear load to ligament injury.

Animals and methods

Two groups of 10 male Wistar/Han/Mol SPF rats (Møllegård, Copenhagen) with a mean weight of 438 (406–481) g were used. The animals were anesthetized with a combination of Hypnorm (fluanisone 5 mg/mL fentanyl citrate 0.1575 mg/mL, Jansen Pharmaceutica BV, Beerse, Belgium) and Dormicum (midazolam 2.5 mg/mL, Hoffmann La Roche, Basel, Switzerland). The dose was 0.2 mL/100g body weight injected subcutaneously. The experiment conformed to the Norwegian Council of Animal Research Code for the Care and Use of Animals for Experimental Purposes.

A bilateral knee arthrotomy was performed through a medial parapatellar incision under a dissecting stereomicroscope. The patella was subluxed laterally. The medial collateral ligament was divided and the medial meniscus was removed. The posterior cruciate ligament was cut at its insertion on the medial femoral condyle. Then the posterior capsule and the lateral collateral ligament and capsule were divided and the lateral meniscus was removed, leaving only the anterior cruciate ligament and muscle tendons intact. The patella was reduced and a 2 mm pin was drilled from the point of insertion of the medial collateral ligament on the medial femoral condyle transversely through the lateral femoral condyle. Another pin was drilled into the pelvis behind the hip. In the 10 rats tested during hamstring contraction and relaxation, the Achilles tendon was cut to eliminate the stabilizing effect of the triceps surae co-contracting with the hamstrings (Aune et al. 1994).

In the quadriceps group, the femoral nerve was dissected free from the vascular bundle just above the inguinal ligament. A bipolar electrode was connected to the nerve with the cathode placed distally to induce antegrade depolarization. It consisted of two silicone-coated wires (AS 632-biomed wire-Cooner Wire, Chatsworth, CA, U.S.A.) mounted 7 mm apart in an open silicone tube. The tube was placed around the nerve and ligated to prevent displacement during testing. Proximal to the electrode, the nerve was crushed between forceps to prevent retrograde depolarization. The ischiatic nerve was cut.

In the hamstring group, a longitudinal incision was made over the posterolateral aspect of the hip. The ischiatic nerve was dissected from its surrounding layer of connective tissue over a distance of approximately 1.5 cm. The femoral nerve was cut in the groin. The electrode was connected and ligated around the nerve, which was crushed proximal to it. The electrodes were connected to a nerve stimulator (Pulsar 6i, Frederick Haer & Co., Brunswick, ME USA).

The rat was suspended in a coat, leaving the right hindlimb free. A clamp fixed the proximal tibia and a triangle connected the transcondylar and the pelvic pin to a modular test apparatus. The triangle secured a knee flexion of 30° (Figure 1). The test machine was originally developed for the rat femur (Engesæter et al. 1978), but it has also been shown to be suitable for the in vivo testing of the rat tibia (Nordsletten and Ekeland 1993) and the rat anterior

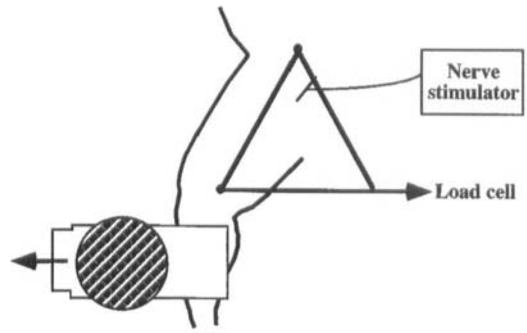

Figure 1. Apparatus for the in vivo testing of the anterior cruciate ligament in the rat hindlimb by anterior shear loading of the tibia.

cruciate ligament in tension (Aune et al. 1994). In this study, the ligament was tested in translation to failure by pulling the tibia anteriorly relative to the femur at a loading rate of 2.5 mm s^{-1} (~0.6^{-1}).

The nerves were supramaximally stimulated throughout the test with 0.5 ms square pulses of 80 Hz with an amplitude of 6 V at the initiation of loading. The load in the test apparatus was measured with a load cell connected to a microcomputer via an amplifier. The load-deformation curves were recorded and calculated on-line in WorkBenchMac (Strawberry Tree Incorporated, Sunnyvale, CA, U.S.A.). Ultimate tensile load, energy absorbed at failure, linear stiffness and ultimate deformation were read directly from the computer recordings. Energy absorbed at failure corresponded to the area under the load-deformation curve. Linear stiffness was defined as the slope of the linear elastic part of the curve, and was read directly from the computer. Ultimate deformation was read from the load-deformation curve as the distance from where the linear part of the curve transected the x-axis to the point of ultimate load (Aune et al. 1994). The failure mode was classified using the stereomicroscope.

The left knees were used as controls. The ischiatic and femoral nerves were isolated and sectioned to ensure that the muscles were totally relaxed during testing. The left hind limb was prepared and placed in the test apparatus, as described above. Thereafter, the anterior cruciate ligament was loaded to failure.

The paired-sample *t*-test (two-tailed) was used for statistical evaluation of differences between testing with muscle contraction or relaxation in each animal. The null hypothesis was rejected at a significance level of $p < 0.05$.

Table 1. Failure data for the right anterior cruciate ligament in rats tested by anterior tibial shear loading during stimulated quadriceps contraction and for the left ligament tested with the quadriceps relaxed. Ratio contracted/relaxed in each animal. Mean, *SD*

	Ultimate shear load (N)		Energy absorption at failure ($J \times 10^{-2}$)		Linear stiffness (N/mm)	
Contracted	58	*6.7*	22	*6*	9.6	*1.6*
Relaxed	61	*6.4*	24	*9*	9.7	*2.6*
Ratio	0.96	*0.11*	1.1	*0.41*	1.1	*0.51*

Table 2. Failure data for the right anterior cruciate ligament tested by anterior tibial shear loading in the intact rat hindlimb during stimulated hamstring contraction and for the left ligament tested with the hamstrings relaxed. Ratio contracted/relaxed in each animal. Mean, *SD*

	Ultimate shear load (N)		Energy absorption at failure ($J \times 10^{-2}$)		Linear stiffness (N/mm)	
Contracted	82	*5.5* [a]	31	*5* [a]	12	*0.9* [b]
Relaxed	55	*7.2*	14	*2*	10	*1.2*
Ratio	1.5	*0.18*	2.4	*0.61*	1.2	*0.2*

[a] P 0.0001, [b] P 0.01.

Results

All the ligaments failed in their substance. Quadriceps contraction did not affect the shear load-to-ligament rupture, unlike loading during quadriceps relaxation (Table 1). The load-deformation curves demonstrated, however, that hamstring muscle contraction substantially increased the structural properties of the bone-ligament-muscle complex, unlike testing with the hamstrings relaxed (Figure 2, Table 2).

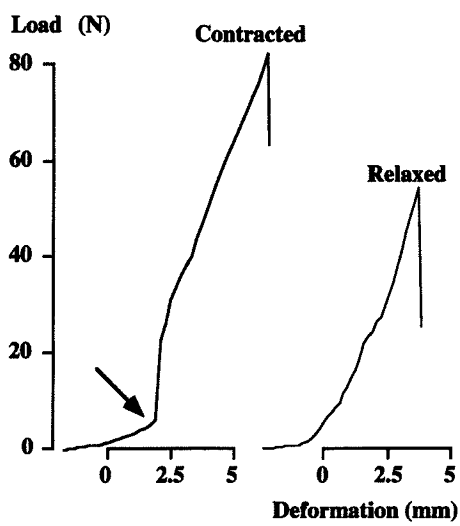

Figure 2. Typical load-deformation curves for the bone-ligament-muscle complex tested in vivo by anterior shear loading of the tibia during electrically stimulated hamstring contraction, compared to that during hamstring relaxation. The arrow indicates the initiation of stimulated muscle contraction.

Discussion

In our study, quadriceps contraction did not affect anterior translation of the tibia to anterior cruciate ligament failure at 30° of knee flexion. Hamstring contraction restricted the tibia to translate anteriorly and protected the ligament against rupture.

Human models have previously been used to examine the effect of muscle contraction on the tibial shear force and anterior cruciate ligament strain under physiologic conditions (Yasuda and Sasaki 1987b, Yasuda and Sasaki 1987a, Howell 1990, Beynnon et al. 1992, Hirokawa et al. 1992, More et al. 1993). To examine any effects of muscle contraction on destructive ligament loads in vivo, an animal model should be used. Our rat model has been shown to be a reliable method for studying the effects of hamstring and gastrocnemius co-contraction on the capacity of the knee subject to ligament failure loads (Aune et al. 1994). However, a limitation on the use of this model is the relevance of the rat knee to the human knee. Rats have been used by other investigators to study anterior cruciate ligament-mechanics because of the similarity of the knee anatomy to that of humans (Cabaud et al. 1980, Larsen et al. 1987, Sakuma et al. 1992). Rat knees differ from humans in their size, the ossified menisci and the habitual flexed position (Evans and Eggers 1960). In pilot studies of the rat knee, a sagittal section showed a four-bar linkage pattern of the cruciate ligaments which is known to explain the mechanics of the human knee (O'Connor et al. 1990).

Peak anterior tibial translation from quadriceps contraction has been reached at about 30° knee flexion in human cadaver and in vivo studies (Howell 1990, Hirokawa et al. 1992). At this angle, the anterior cruciate ligament is the primary restraint to anterior tibial translation (Fleming et al. 1993). The same angle was chosen in this study to create optimal possibilities for a quadriceps force to assist an anterior drawer trauma, because in rats as in humans (Draganich et al. 1987), the angle between the patellar tendon and the perpendicular on the tibial plateau responsible for the anterior shear force increases with knee extension, as observed in a pilot study. Thus, the similarities may indicate the need for a careful extrapolation of the results of this study in the rat to corresponding conditions in humans. At the chosen knee angle, the quadriceps was unable to assist an anterior drawer ligament rupture. With increasing knee flexion, the quadriceps-patellar tendon force becomes perpendicular to the joint surfaces or is directed posteriorly after 60° of flexion and its power to add force to rupture the ligament decreases (Yasuda and Sasaki 1987a, Howell 1990, Hirokawa et al. 1992).

Axial forces through the knee stabilize the knee against translation (Markolf et al. 1981). In this study, the lower extremity of the rat was not subjected to any external axial force during testing to eliminate this effect. However, the main component of the patellar tendon force is directed perpendicularly to the tibial plateu, producing joint compression by quadriceps contraction and stabilizing against femorotibial translation (Torzilli et al. 1994). In the present study, the menisci were removed, thus probably reducing the effect of joint compression. But it is possible that the anterior shear force from quadriceps contraction was controlled by the tibiofemoral compression forces, even if the menisci were absent, since quadriceps contraction had no effect on the translatory load to ligament failure. This study measured the individual effects of the muscle groups. Cocontraction of hamstrings and quadriceps may differ from the sum of the individual effects due to the possible effect of induced axial loading.

The hamstrings are quadricep antagonists that can put a posterior shear force on the tibia and reduce ACL-tension under physiologic conditions (Yasuda and Sasaki 1987a, More et al. 1993). The results of our study showed that this is significant at destructive loads as well. The magnitude of hamstring contraction at the exact time of an injury may vary. The hamstring contraction in this study was limited to a maximum, tetanic contraction. The tests were not performed under dynamic muscle work. Although brief summations and tetanic contractions are principal factors during skeletal muscle work (Nordin and Frankel 1989), dynamic muscle work or relaxation at the moment of an injury produces less tension and reduces the effect of hamstring protection on the knee subjected to ligament injury.

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