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Impingement pressure and tension forces of the anterior cruciate ligament

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Abstract This study examined the impingement behavior of the uninjured ACL and the impingement pressure and tension forces of the ACL to draw conclusions for ACL reconstructions. A miniature pressure sensor was inserted between the ACL and the intercondylar roof of 15 knees of human cadavers before and after a 3-mm notch roof resection (thickness of the sensor); tension of the ACL was measured after attaching the tibial insertion to a load cell. A long-arm goniometer was used to determine corresponding extension angles. The beginning of contact of the ACL with the notch roof was between –1 and –2° of knee extension. Pressure for full passive extension was 855.6±279.1 and 346.4±287.7 kPa, and ACL tension averaged 101.9±38.4 N. Tension forces in passive hyperextension were higher than those detected when a 200-N Lachman test was performed (83.5±25.1 N). There was a significant correlation between extension capability and impingement pressure. Impingement of the ACL was detected in all knees. Full passive extension exerts biomechanical pressure and tension on the ACL. Tension forces of the ACL are higher in passive hyperextension than during a Lachman test with 200 N. The impingement behavior found for the uninjured ACL is simulated in an ACL reconstruction when the center tibial tunnel position is used.

Keywords Knee anterior cruciate ligament impingement hyperextension

Introduction

Impingement of an anterior cruciate ligament (ACL) substitute on the intercondylar notch roof has been demonstrated to be one of the main reasons for graft deterioration [9, 11, 31], formation of a cyclops syndrome [5, 31], and postoperative extension deficit [16, 22, 24]. As a consequence "impingement-free" ACL reconstruction techniques are advocated. Since anterior tibial tunnel placement has been found to be associated with high pressures on the graft [8], customized tibial tunnel placement has been recommended [10]. Other authors conclude that there is no graft impingement when the tibial tunnel is located in the posterior one-third of the ACL footprint. Therefore they recommend using this position in general [21].

Until now the impingement behavior of the uninjured ACL has not been thoroughly investigated. Friedman and Feagin [6] in a cadaver study found that the ACL makes contact with the intercondylar notch roof in passive hyperextension and ruptures from posterior to anterior along its tibial footprint when the knee is forced into further extension. Cinematographic magnetic resonance analysis of knee hyperextension has shown contact between the ACL and the notch roof [14]. The amount of impingement was correlated with the ability of passive hyperextension. Thus it has been concluded that a certain degree of impingement is physiological for the ACL in hyperextension.

Numerous studies have conducted tension measurements of the ACL or ACL substitutes [1, 4, 19, 29, 30]. However, only few investigators have been able to complete tension measurements in full passive or forced hyperextension due to impingement of the sensor [1, 2]. The few examinations that report data for hyperextension have used cadaver knees that were explanted with limited length of femur and tibia [19]. Our previous analysis revealed that measuring extension in this setup overestimates extension by approximately 5° compared with measurements including the centers of rotation of the adjacent joints [13]. The cadavers used for all these studies did not match a population that is operated on for ACL deficiency regarding age and knee conditions (soft tissue properties, passive hyperextension capability).

Biomechanical stress of the graft during hyperextension has not been thoroughly investigated. However, equal extension on both sides has been stressed in commonly used early functional knee rehabilitation protocols, as it has been demonstrated that this approach does not compromise the results in terms of knee stability [25, 27]. However, reports of bone tunnel enlargement following ACL reconstruction have been increasing [15, 17, 28]. Biomechanical stress during rehabilitation could be one of the potential factors contributing to this phenomenon.

The purpose of this study was to investigate the impingement and tension forces of the uninjured ACL that occur in extension and hyperextension of the knee in cadavers that closely match an ACL reconstruction population. The results of this study may be used to simulate impingement behavior of the normal ACL in ACL reconstructions.

Methods

The knees of fifteen human cadavers were examined in the Department of Forensic Medicine of Ludwig Maximilian University in Munich, Germany, for this study. The age was 31.9±10.6 years (range 17–56). The examination took place an average 2.1±1.2 days postmortem (range 0–3). We used the legs of 11 men and 4 women, with a height of 173.0±6.0 cm (range 161–182) and a weight of 72.9±15.4 kg (range 55–106). One knee showed a grade 3 osteochondral lesion of the medial femoral condyle and two specimens grade 2 lesions of the patellofemoral joint. Exclusion criteria were ligament damage or meniscal injuries or general arthritis.

Technical equipment

A miniature pressure load cell (ELFS-B0, Entran Devices, Fairfield, N.J., USA) was customized and mounted with a laser-welded mold with a diameter of 5 mm, i.e., a sensing surface of 19.6 mm^2. The sensor is applicable for loads up to 250 N (8.0 MPa) with an accuracy of 1% in relation to its measurement range. The sensor was connected to a handle that facilitated positioning between the intercondylar notch roof and the ACL (Figs. 1, 2) to obtain pressure loads between the ACL and the intercondylar notch roof.

For tension monitoring a standard load cell from the same manufacturer with a measurement range up to 500 N (0.2% accuracy in relation to its measurement range) was connected to an external

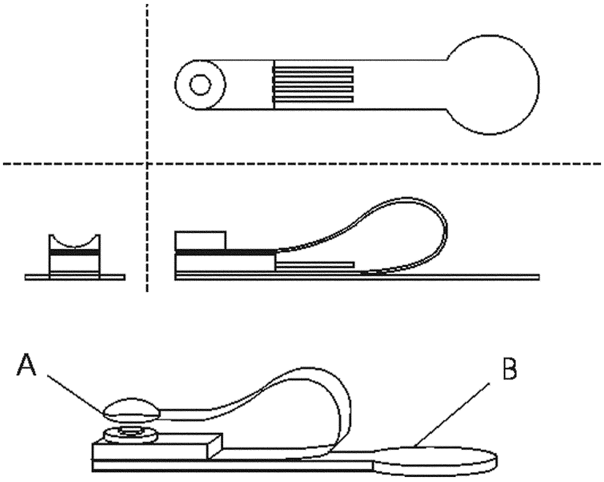

Fig. 1 Dimensions and design of the intercondylar notch roof impingement sensor. A miniature pressure sensor was equipped with a laser welded semicircular mold (*A*) that matched the size of the distal one-third of the ACL. The total height of the sensor was only 3.0 mm and the width 5.0 mm. The sensor was mounted on a positioning handle (*B*)

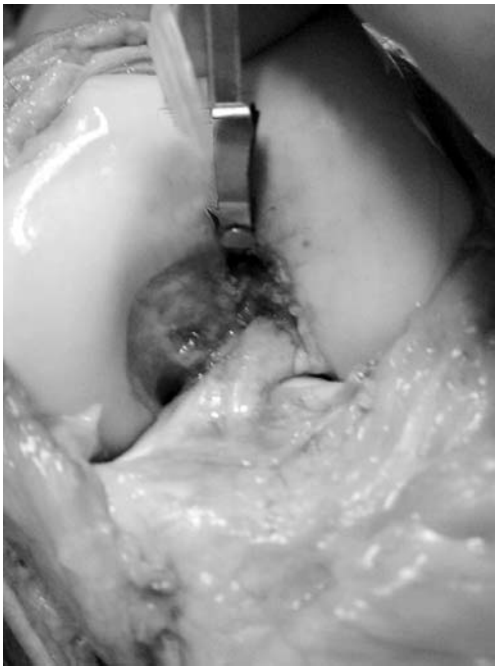

Fig. 2 The impingement sensor was inserted between the intercondylar notch roof, and the knee was taken into full passive extension. Pressure was detected in relation to the knee extension angle. The procedure was repeated after a notch roof resection of 3.0 mm (height of the sensor) was performed

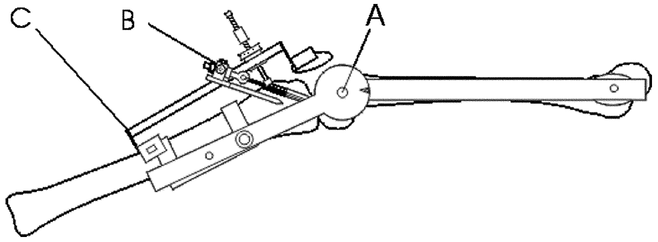

Fig. 3 A long-arm goniometer with molds of the greater trochanter and the anterior tibia was equipped with a digital incremental transducer (*A*) to obtain knee extension angles. The ACLs were reinserted through a tibial drill hole with a polytetrafluoroethylene bushing and connected to a load cell (*B*). Tension was increased until preoperative laxity was restored. Knee laxity was determined with a Rolimeter (*C*) and a maximum manual test

fixator with a calibration device (Fig. 3). Both sensors are temperature compensated and underwent a calibration process before measurements. For the determination of knee extension a precision long-arm goniometer equipped with molds of the greater trochanter and the anterior tibia was connected to a digital increment transducer that produces signals in steps of 0.34°. The accuracy of the device has been determined at 0.6% on a measurement range of 180° in a previously published investigation [13]. All sensors were connected to a CPU, both tension and pressure sensors were temperature compensated. Data was recorded on a RAM chip and transferred to a IBM-compatible notebook PC after each loading cycle.

Cadaver preparation and measurement technique

The knee and hip joints were passively moved through the full range of motion 20 times to reduce tissue stiffness caused by the rigor mortis. A central arthrotomy was used, and the patella was dislocated laterally. The infrapatellar plica and parts of Hoffa's fat pad were resected to facilitate placement of the pressure sensor. An intercondylar notch roof débridement was performed without any bone resection. A precision goniometer was aligned with the axis of rotation of ankle, knee and hip. The goniometer uses molds that rest on defined landmarks (greater trochanter of the femur, anterior tibia inferior to the greater tuberosity; Fig. 3). The authors determined impingement pressure with the sensor on top of the notch roof to provide data that can be used to monitor the impingement behavior of an ACL reconstruction using this sensor in vivo. The pressure sensor was inserted between the ACL and intercondylar notch roof. The knee was taken into full passive extension and the foot positioned on a heel rest. Pressure was recorded starting with passive hyperextension and the joint was taken into 30° of knee flexion at a speed of 5°/s. The procedure was repeated three times.

To investigate the impingement pressure on the anterior prominent part of the intercondylar notch a 6-mm chisel was used to perform a notch roof resection that enabled positioning of the sensor flush with the contour of the intercondylar notch roof (Fig. 2). After insertion of the sensor into the cavity of the resected notch the measurement started with the knees put into forced hyperextension (a force of 500 N was applied anteroposteriorly on height of the knee joint). The measurement of impingement pressure was performed in this position, by analogy with the first part of the investigation.

An instrumented maximal manual Lachman test was measured with a knee arthrometer (Rolimeter, Aircast Europa, Neubeuern, Germany) three times. The mean value was recorded. Lachman testing was performed by the same investigator for each cadaver.

The authors determine strain of the ACL connecting a one-dimensional load cell to the ligament that was reinserted through a drill hole positioned in the posterior one-third of the ACL footprint. This was for three reasons: This procedure has been used by other authors. The results can be compared with existing data. This procedure determines tension forces of an idealized reconstruction, as most recommendations for placement of the tibial tunnel ask for this position. An ACL substitute can be connected to a load cell in the same manner; biomechanical properties of ACL reconstructions can thus be compared with the data of this study.

The ACL was dissected from its tibial bone surface. A 10-mm drill hole was established in the posterior one-third of the tibial insertion using an arthroscopic tibial drill guide (Sulzer, Winterthur, Switzerland). A Teflon bushing with an internal diameter of 8 mm and an external diameter of 10 mm was inserted, and the distal portion of the ACL was connected to a freeze clamp. A Steinmann nail was drilled parallel to the tibial tunnel distally. A tension measurement sensor (Entran Devices) with a custom-made buckle to attach the pin was connected with the clamp. After pretightening the reinserted ACLs were preconditioned applying 20 cycles through the full passive range of motion. Tension was calibrated until the maximal manual displacement determined with the arthrometer was restored to the preoperative value. The maximal manual displacement was controlled after each testing cycle. If there was an increase in displacement, the measurement was repeated after modifying tension.

Lachman testing was performed to compare tension loads in hyperextension with a well examined knee-loading situation. The tension testing protocol started with three repeated measurements from full passive extension (foot on a heel rest) into full flexion. Thereafter a tensiometer was hooked on to a synthetic band that was wrapped around the lower extremity on level of the tibial tubercle. Tension was applied perpendicular to the axis of the tibia in the Lachman position, and tension was recorded at 50, 100, 150, and 200 N anterior joint loading. The same loads were applied posteriorly on level with the joint line with the foot positioned on a heel rest to obtain the tension values for forced hyperextension.

Statistical analysis

The three pressure and tension measurement series were analyzed with regard to reliability of the methods. Pearson's correlation coefficients were calculated. Mean values are reported with standard deviations and ranges. Multiple comparisons of means were conducted with a one-way analysis of variance and a Bonferroni adjusted P level of $0.5/n$ of variables. After performing normality and constant variance tests pairs of values were compared using a single-tailed t test for dependent variables (as only one side of the test was of interest). A P level of 0.05 was taken as indicating statistical significance. Repeated-measurement correlations were analyzed with $\alpha=0.05$ and a desired power of 0.75.

Results

Data reduction and measurement reliability

Due to artifacts of the measurements, one pressure measurement without and two with notch roof resection had to be completely excluded. Pearson's correlation coefficient for pressure measurements was $r=0.93\pm0.05$ (0.77–1.00).

Due to a broken connection cable, tension measurements were impaired in one case. The correlation for the measurements was $r=0.95\pm.07$ (0.75–1.00). There were two knees that had no and one with limited hyperextension ability. These knees were not included in the diagram

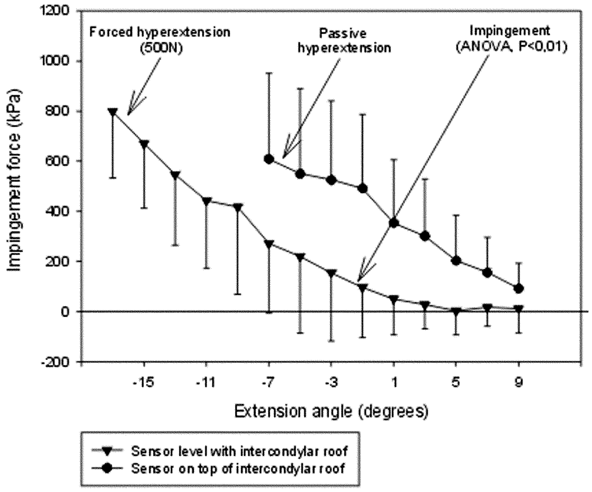

Fig. 4 Impingement pressure between the ACL and the intercondylar notch roof in dependence of knee extension. Values are reported without notch roof resection until full passive extension (*top*) and after a notch plasty that aligned the sensor with the contour of the intercondylar notch roof (forced hyperextension up to 500 N; *bottom*). A significant increase in pressure was determined between –1.0° and –2.0° using a one-way analysis of variance (P=<0.01)

of hyperextension tension and pressure forces (these plots show data obtained from 12 experiments).

Knee extension and stability parameters

Mean extension ability of all 15 knees combined was –4.8±4.7° (–14.0 to –5.0°). The knees used for pressure and tension analysis in hyperextension averaged –7.9±2.4° (–14.0 to –6.2°). Extension increased to –7.2±5.7° (–16.0 to –5.0°) after detaching the ACL and was restored after reinsertion of the cruciate ligament to –4.6±5.2° (–13.0 to 5.0°). Maximal manual displacement of the tibia was 6.2±1.7 mm (4.0 to 10.0) preoperatively and increased to 12.8±1.5 mm (10.0 to 15.0) in the ACL insufficient knees. Preoperative maximal manual displacement values were restored in all cases.

Impingement pressure

Impingement pressure was observed in all experiments of this study. Pressure values are reported without notch roof resection and after notchplasty (sensor on level with the intercondylar notch roof). In passive extension (foot elevated on a heel rest), pressure between the ACL and intercondylar notch roof was 855.6±279.1 kPa (457.9–1268.7) and 346.4±287.7 kPa (11.0–1060.9). In forced hyperextension after notch roof resection, pressure averaged 885.6±259.0 kPa (440.0–1187.7). The complete data are plotted in Fig. 4. The correlation between extension ability and impingement pressure was r=–0.54 (P=0.04).

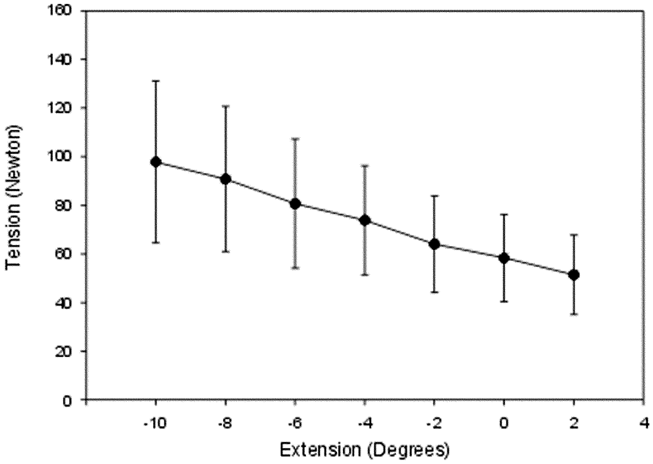

Fig. 5 Tension loads of reattached ACLs in hyperextension. Tension values increase as a function of knee extension

Anterior cruciate ligament tension

We observed a continuous increase in ACL tension from 30° of flexion until full passive and forced extension. Tension of the reattached ACL was determined at 101.9±38.4 N (40.5–166.0) in full passive extension and 64.1±19.9 N (28.5–91.7) at 0° of extension (Fig. 5). Stress testing of fully extended knees with reattached ACLs at 50, 100, 150, and 200 N resulted in an increase in tension to 111.5±43.7 (45.0–190.0), 119.9±47.2 (48.0–205.0), 125.3±51.3 (49.0–225.0), and 129.6±52.7 N (53.0–235.0). In contrast, tension in the Lachman position (25° of flexion) averaged 40.1±21.2 N (0.0–60.0). Stress testing at 50, 100, 150, and 200 N increased tension of the reinserted ACL to 52.0±22.4 (7.0–76.0), 62.3±21.1 (20.0–84.0), 71.1±20.7 (30.0–95.0), and 83.5±25.1 N (40.0–118.0).

Tests for normality for the observed values were determined as P=0.88 for Lachman stress testing and P=0.42 for forced hyperextension data. The single-tailed paired *t* test indicated that passive hyperextension exerted significantly more tension on the reinserted ACL than a Lachman test with a force of 200 N (P=0.02). Accordingly, all other hyperextension stress levels were significantly higher than the ones observed while performing the Lachman test.

Discussion

Graft deterioration and limitation of the postoperative range of motion have been attributed to impingement of the ACL. An anterior tibial tunnel position has been linked with these problems, and “impingement-free” ACL reconstruction has been advocated [7, 10, 11]. Hence full passive hyperextension that is equal on both sides without graft impingement has been stressed as one of the key elements of intraoperative graft performance tests [12, 21, 31]. Immediately postoperative rehabilitation protocols that include exercises to achieve and maintain full side-to-side extension have been published [26, 27]. No significant increase in joint stability has been detected following so-called "early advanced physiotherapy."

Until now no thorough biomechanical investigation with accurate measurements of impingement and tension forces of the uninjured ACL has been performed. Therefore this study was conducted to examine ACL impingement and tension forces in young human cadavers immediately after autopsy. Rigor mortis was eliminated by cyclic conditioning of the lower extremity through the full passive range of motion. In our experience the setup came very close to the intraoperative situation with a patient under general anesthesia. The measurement of impingement with the sensor aligned with the contour of the intercondylar notch roof started with the knees forced into hyperextension. This situation is of clinical relevance as aggressive rehabilitation exercises encourage weight bearing of the knee in full passive extension [27]. Moreover, joint loading was useful for verifying that there is a continuous and linear increase in impingement pressure, as displayed in Fig. 4.

The major concerns of this study were the manual placement of the impingement sensor and the use of an axial tension sensor. We used a load cell connected to the distal end of the ACL guided through a tibial tunnel located in the posterior one-third of the ACL footprint instead of a Hall effect transducer [1, 3]. This was for three particular reasons: Hall effect transducers detect only relative strain. They cannot be used to monitor graft tension intraoperatively in a routinely manner [23]. A measurement of ACL and graft strain in full passive extension is compromised by roof impingement of the sensor [3].

The use of a bone cap with the tibial insertion of the ACL would not have permitted a comparison of the tension values of an ACL graft which can be connected to a tension sensor by analogy. The tension behavior of the ACL observed in this study is very similar to data reported by Markolf et al. [18, 19]. These authors also found a steep increase in tension with the knee taken into extension. Tension at –5° knee extension without quadriceps pull averaged 120 N; the mean value found in this study is within the standard deviation. In contrast to this investigation, their analysis was limited to –5°. All aspects of the tibial forces in the uninjured ACL can be examined only with a three-dimensional force transducer [20]. However, this setup is not useful for monitoring the strain behavior of a graft intraoperatively. In contrast to other examinations, this study population matched closely patients who undergo ACL reconstruction in terms of age, hyperextension capability, and knee laxity.

We decided to investigate a manual placement of the impingement sensor instead of a more rigid fixation [8] for two reasons: The main purpose of the study was to investigate the knee flexion angle when impingement forces occurred. For absolute measurements of impingement pressure it would be necessary to connect the entire notch roof with the sensor and to determine the area of contact. This is not an applicable technique during ACL reconstruction. The procedure introduced in this study can be repeated during an ACL reconstruction in vivo. The only investigation that has examined impingement pressure of ACL grafts in full hyperextension is the work of Goss and colleagues [8]. These authors used a sensor that was firmly attached to the intercondylar notch roof through a drill hole. The purpose of the manual insertion of the sensor used in this study was to examine whether this procedure leads to reproducible results. As indicated, despite of some technical problems with the sensor the results were quite consistent (r=0.93). The pressure lines observed for the center tibial tunnel in the above mentioned study resembles closely the impingement pressure found for the uninjured ACL in this examination.

In contrast to their results for ACL grafts, the tension for 0° determined for the ACL with intact femoral insertion was 20 N less in this study. Further tension monitoring of reconstructions with bone tunnels in the optimum position is required to evaluate whether the tension of ACL reconstructions is more than that determined for an ACL with an intact femoral insertion.

The technique for monitoring ACL strain can be used for procedures using tendons without bone blocks in the tibial tunnel. The load cell and goniometer could be used accordingly. This procedure may be used as a means of intraoperative quality control for ACL reconstructions.

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