Knee mechanics after repair of the anterior cruciate ligament

A cadaver study of ligament augmentation

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An experimental knee-testing system was used to investigate the immediate postoperative mechanical state in knees with nonaugmented and augmented repairs of the anterior cruciate ligament. Ligament, repair tissue, and augmentation forces were measured using buckle transducers, and joint motion was measured using an instrumented spatial linkage during the application of 90 N anteriorly-directed tibial loads to seven fresh knee specimens at 0–90 degrees of flexion. Force and motion data were collected from each knee with an intact and excised anterior cruciate ligament, and after performing (1) a nonaugmented repair and an augmented repair using the Ligament Augmentation Device (3M Company) placed either (2) anatomically through the lateral femoral condyle or (3) in the over-the-top position.

The forces in the nonaugmented repair and the repair with the augmentation in the two positions were greater than the forces in the intact anterior cruciate ligament with the knee under the same anterior loads; this difference from normal was not significant with the over-the-top augmentation. With the augmentation anatomically placed, the load sharing did not reduce the force in the repair tissue as compared with the nonaugmented case. The over-the-top augmentation, on the other hand, lowered the repair tissue forces at extension while avoiding high repair tissue forces in flexion. The tibia was consistently in an externally rotated configuration compared with normal in both the unloaded and anterior load states with all three repair procedures.

Although short-term studies of acute repair of anterior cruciate ligament ruptures report promising results, long-term results have indicated decreasing knee stability and function with time (Balkfors 1982, Feagin and Curl 1976, Odensten et al. 1984, Sandberg 1987). Augmentation methods have been suggested as a possible solution (Bilko et al. 1986, Schabus 1988). However, no data are currently available that document the immediate postoperative mechanical state of the knee with an acute repair of the anterior cruciate ligament or the amount of load sharing that occurs in an augmented repair.

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The goal of this study was to quantify the initial postoperative mechanical state of the knee following nonaugmented and augmented acute repair of the anterior cruciate ligament.

Materials and methods

Experimental system

A testing system (Lewis et al. 1988) was used for the simultaneous measurement of ligament forces and joint motion as external loads are applied to knee specimens. The following is a brief description of the components of the system.

Buckle transducers consist of a crossbar and a frame with two strain gages (Figure 1). The ligament and crossbar are manipulated through the inner portion of the frame so that the crossbar becomes seated upon the frame yet under the ligament. As the ligament becomes loaded, it tends to straighten itself by pushing against the crossbar and frame, produc-

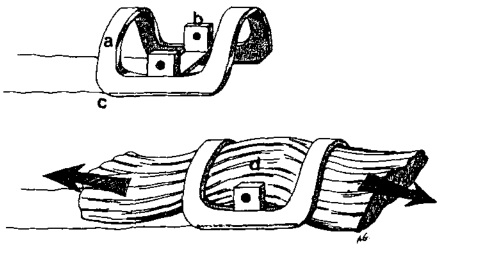

Figure 1. The buckle transducer. Note the frame (a), crossbar (b), wires emanating from strain gages in grooves on the underside of the frame (c), and tension in the ligament with the installed buckle (d).

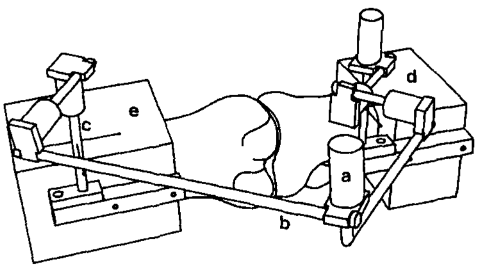

Figure 2. Instrumented spatial linkage (ISL) installed on the load apparatus. Note the potentiometer (a), intermediate link (b), end link (c), tibial clamp (d), and femoral clamp (e).

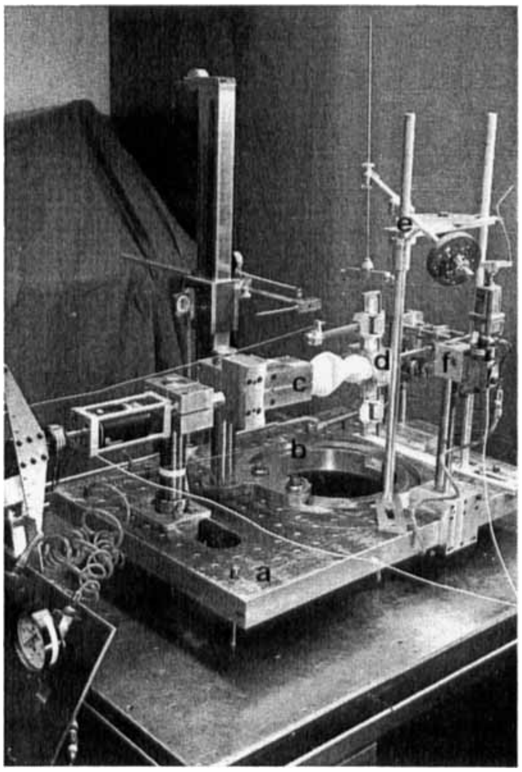

Figure 3. The pneumatic load apparatus. Note the baseplate (a), groove in the baseplate allowing flexion (b), fixed femoral clamp (c), moveable tibial clamp (d), counterbalance assembly (e), and anterior load assembly (f).

ing an electrical response in the strain gages proportional to the tension in the ligament. The buckles are calibrated multiple times during a test period by applying known loads from a high precision spring scale. Impingement of the buckle transducers with surrounding bone is detected and eliminated.

The instrumented spatial linkage used in this study (Figure 2) is an open loop kinematic chain composed of six revolute joints connecting two end links and five intermediate links. By knowing the geometry of the links and the location of the end links relative to the articular surfaces, and by measuring the revolute angles with potentiometers as a specimen joint moves, the motion at the joint can be described in anatomically meaningful parameters.

The specimen load apparatus (Figure 3) consists of a baseplate and tibial and femoral clamps, which hold the potted ends of a knee specimen. The femoral clamp is fixed to the baseplate during application of external loads. The flexion angle can be changed by rotating the femoral clamp within a slot in the baseplate. The counterbalanced tibial clamp is not fixed but rather floats, and is acted upon by cables connected to pneumatic actuators and load cells for the application of unconstrained loads to the tibia.

A detailed error evaluation of the in vitro knee testing system was reported by the authors (Lewis et al. 1988). With a knee under 90-newton anterior-tibial loads, the anterior tibial displacement was repeatable to within an average of 8 percent and anterior cruciate ligament force within an average of 6 percent. The instrumented spatial linkage was able to measure position to within an average of 0.7 mm and orientation to within an average of 0.7°. The effect of tissue creep within a buckle transducer caused the force in the anterior cruciate ligament to decrease less than 4 percent during the period between external load application and transducer recording.

Test protocol

Seven fresh cadaveric lower limb specimens were stored at –20 °C, thawed at room temperature, and prepared by removing all the soft tissue except muscle, capsule, and ligaments. Specimens with evidence of severe degenerative changes or ligamentous insufficiency were not included. The fibula was fixed to the tibia with a screw, and each limb was transected approximately 17 cm distal and proximal to the joint space. The ends of the tibia, fibula, and femur were potted in cylinders of polymethyl methacrylate. A medial capsulotomy was performed, and buckle transducers were installed on the anterior cruciate and lateral collateral ligaments, and on a 1-cm anterior strip of the superficial medial collateral ligament. The knee specimen was installed in the load apparatus. The following knee states were tested.

Normal knee. Knee joint motion and forces in the intact anterior cruciate and collateral ligaments were measured during the application of 90 N anteriorly-directed tibial loads at 0°, 30°, 60°, and 90° of flexion. The force and motion data were also recorded during an unloaded state before application of the anterior load at each flexion angle.

Knee with excised anterior cruciate ligament. The anterior cruciate ligament was excised at its proximal insertion site. The external load sequence was repeated for the excised state, with resulting ligament force and joint motion data again recorded. Note that the buckle transducer remained in place on the ligament remnant during the excised test.

Knee with nonaugmented repair. The knee was removed from the load apparatus and the anterior cruciate ligament was repaired. Four nonabsorbable U-sutures were placed in an anteromedial to posterolateral direction at varying depths in the ligament remnant. A 2.8-mm Steinmann pin was used to drill two fixation holes through the anterior and posterior portions of the femoral attachment site. The sutures emanating from the anteromedial bundle of the remnant were passed through the posterior hole, while the sutures from the posterolateral bundle were passed through the anterior hole. Prior to repair fixation, the buckle transducer on the remnant was calibrated at 30° of flexion by applying the known loads through the two groups of sutures in the fixation holes. The repair tissue was pretensioned at 30° of flexion to prevent more than 5 mm of anterior-posterior tibial translation, and each suture was tied over a cancellous screw on the lateral femoral condyle. The external load sequence was repeated for the repaired state, and force and motion transducer signals were recorded.

Knee with repair augmented anatomically. The nonaugmented repair was taken down, and a 4.5 mm drill hole was placed through the tibia emerging slightly posterior to the anterior cruciate's tibial attachment site. Repair augmentation was provided by the Ligament Augmentation Device (3M Company), which was passed through the hole and sutured distally to the tibial periosteum with eight nonabsorbable sutures. The augmentation device was positioned posteriorly to the remnant and was passed through a slightly widened posterior femoral hole, accompanying the sutures emanating from the anteromedial portion of the remnant. A buckle transducer was installed on the augmentation device, in addition to the buckle already on the repair tissue. The repair tissue was first pretensioned and fixed as described in the nonaugmented case, and then the augmentation device was pretensioned with 67 N and secured to the lateral femoral condyle with a belt buckle staple at 30° of flexion. The external load sequence was repeated.

Knee with repair augmented in over-the-top position. The previous repair was taken down, and the augmentation device and sutures emanating from the anteromedial portion of the repair tissue were passed through a small incision in the posterolateral capsule, so that the device was located proximally in the over-the-top position. The repair tissue and augmentation device were pretensioned and fixed as described in the previous case, and the external load sequence was repeated

Analysis of data

Three-dimensional joint motion and forces in the intact and repaired anterior cruciate ligament, the augmentation device and both collateral ligaments were obtained for each specimen during the loaded and unloaded conditions in the knee states described above. Joint motion was defined in terms of the configuration of the tibia in anterior-posterior translation and internal-external rotation at each flexion angle during the unloaded and anterior load conditions in the different knee states, relative to the tibial configuration at the same flexion angles in the unloaded condition with an intact anterior cruciate ligament. Force and motion data in the excised and repaired states were compared with data from the intact state within the same knee. Because these data are correlated, the paired Student's t-test was used to test the significance of the differences between the force and motion data. Differences were considered to be statistically significant at $P \leq 0.05$. When data are said

Table 1. Force (newtons) in the intact ligament and nonaugmented repair, and total force (newtons) in the augmented repairs at four flexon angles (n 7). Mean *SD*

	0°		30°		60°		90°	
Intact ligament	121	*54*	60	*40*	41	*23*	41	*21*
Nonaugmented	93	*43*	69	*25*	80	*19**	81	*26**
Augmented anatomic	226	*95**	105	*28*	123	*36**	157	*51**
Augmented over-the -top	179	*91*	109	*37*	78	*45*	60	*44*

*indicates that the repair forces were significantly different than forces in the intact ligament at the particular flexion angle

Table 2. Forces in the repair tissue and Ligament Augmentation Device (LAD) normalized to the total force in the repair composite (force ratio) at the four flexion angles, with the augmentation in the anatomic and over-the-top positions (n 7). Mean *SD*

		0°		30°		60°		90°	
Augmented anatomic,	tissue	0.45	*0.13*	0.54	*0.17*	0.65	*0.18*	0.64	*0.17*
	LAD	0.55	*0.13*	0.46	*0.17*	0.35	*0.18*	0.36	*0.17*
Augmented over-the -top,	tissue	0.21	*0.09*	0.47	*0.17*	0.69	*0.20*	0.79	*0.19*
	LAD	0.79	*0.09*	0.53	*0.17*	0.31	*0.20*	0.21	*0.19*

to be different or not different in the following presentation and discussion of results, it means statistically different or not different.

Results

The intact anterior cruciate ligament carried higher forces in extension than in flexion (Table 1). Unlike the intact ligament, the forces in the nonaugmented repaired ligament were isotonic; that is, there was no difference between the forces at the four flexion angles. The nonaugmented repair forces did not differ from normal at extension and 30° of flexion, and were greater than the intact ligament forces at 60° and 90° of flexion. When averaged over the seven specimens and four flexion angles, the forces in the nonaugmented repair were nearly twice as large as the intact ligament.

The forces in the augmented repair composite with an anatomic placement of the device through the femoral condyle were greater than the intact anterior cruciate ligament forces at extension, and 60° and 90° of flexion. When averaged over the seven specimens and four flexion angles, the total repair forces were over three and one-half times greater than forces in the intact ligament.

The forces in the augmented repair composite with the augmentation device in the over-the-top position were similar to the pattern of the intact ligament, with the forces at extension and 30° of flexion greater than at 60° and 90° of flexion. The total repair forces did not differ from normal at any of the four flexion angles.

The load sharing between the augmentation device and the repair tissue varied with procedure and flexion angle (Table 2). With the augmentation in the over-the-top position, the repair tissue carried on the average 21 percent of the total composite force in extension, increasing through the flexion range to an average of 79 percent of the total force in 90° of flexion. The load-sharing profile for the augmentation in the anatomic position showed a more even distribution, with an average of 45 to 65 percent of the force carried by the repair tissue across the flexion range.

The forces in the nonaugmented repair did not differ from the intact ligament force at extension and 30° of flexion, but were greater than normal at 60° and 90° of flexion (Table 3). When the augmentation was located anatomically, the repair tissue forces did not differ from normal except at 90° of flexion, where tissue forces were greater than the intact ligament. There were no differences between the forces in the nonaugmented repair and the repair tissue with the augmentation placed anatomically;

Table 3. Force (newtons) in the intact anterior cruciate ligament, nonaugmented repair, and tissue component of the augmented repairs at four flexion angles (n 7). Mean *SD*

	0°	30°	60°	90°
Intact ligament	121 *54*	60 *40*	41 *23*	41 *21*
Nonaugmented	93 *43*	69 *25*	80 *19**	81 *26**
Augmented anatomic	103 *62*	57 *23*	78 *27*	98 *40**
Augmented over-the -top	40 *35**	56 *32*	57 *42*	79 *44*

* repair forces differed from forces in the intact ligament.

Table 4. Force (newtons) in the collateral ligaments during the normal, excised and repaired anterior cruciate ligament states at four flexion angles (n 7). Mean *SD*

	0°		30°		60°		90°	
	Medial	Lateral	Medial	Lateral	Medial	Lateral	Medial	Lateral
Intact ligament	25 *17*	20 *24*	33 *25*	17 *23*	44 *30*	13 *13*	37 *33*	13 *19*
Excised ligament	74 *45**	29 *43*	89 *50**	21 *25*	75 *42*	28 *24*	75 *29**	49 *47*
Nonaugmented	33 *30*	20 *20*	55 *51*	18 *20*	56 *43*	11 *15*	53 *34*	12 *24*
Augmented anatomic	25 *19*	16 *19*	65 *53**	22 *40*	71 *51*	10 *15*	51 *36*	11 *22*
Augmented over-the -top	25 *28*	27 *58*	60 *48*	23 *45*	72 *50*	16 *20*	73 *52**	26 *37*

* repair forces differed from forces in the intact ligament.

thus, the augmentation located anatomically did not reduce the repair tissue force.

The over-the-top augmentation produced repair tissue forces lower than forces with the nonaugmented repair, as well as the repair forces with the augmentation placed anatomically. With the over-the-top augmentation, the repair tissue forces were lower than with the intact ligament at extension, but did not differ from normal at the other three flexion angles.

The forces in both collateral ligaments increased nearly 3 times after excising the anterior cruciate ligament (Table 4). The collateral forces reapproached normal when the ligament was repaired with all three procedures.

The configuration of the tibia was anterior compared with normal when the anterior cruciate ligament was excised (Figure 4). The anterior-posterior configuration of the tibia returned to within normal limits in the nonaugmented and two augmented repair states. The tibia was externally rotated compared with normal in both the unloaded and the anterior loaded conditions with the three repair procedures (Figure 5).

Discussion

Forces in the nonaugmented repair were near normal at extension, but were greater than normal in flexion, even when the repair was performed in accordance with Noyes et al. (1983), who proposed that the normal 5-mm anterior-posterior translation should be preserved during pretensioning of the graft. If these abnormally high forces occur in vivo, they could lead to suture failure, loosening of fixation, and stretching out the repair and secondary restraints, such as reported clinically (Balkfors 1982, Feagin and Curls 1976, Odensten et al. 1985, Sandberg 1987).

Notably, there was a large variability in the repair forces. Using the identical surgical technique, nonaugmented repair forces were 2–3 times greater than the normal anterior cruciate ligament at 30° of flexion in specimen 1, but were less than normal in specimen 2. The contribution of experimental errors to this variability was described in the Methods section. Because each knee served as its own control, the remaining variability was due to surgically controllable factors. Perhaps the level of control exerted over such variables as location of fixation holes, repair pretension, or the tibial position resulting from

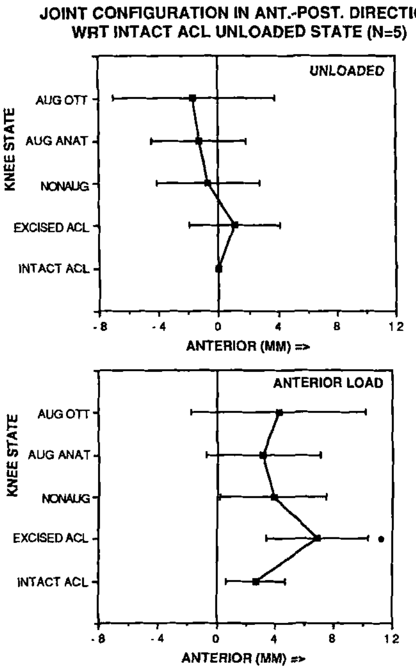

Figure 4. Means and standard deviations of the joint configuration in anterior-posterior tibial translation during unloaded (top) and anterior loaded (bottom) conditions, defined relative to the intact unloaded anterior cruciate ligament state, over all four flexion angles in five of the specimens with the intact and cut ligament (INTACT ACL, EXCISED ACL), the nonaugmented repair (NONAUG) and the augmented repairs with the augmentation located anatomically (AUG ANAT) and over-the-top (AUG OTT).

* Configuration in the excised or repaired states was significantly different than the configuration in the intact state.

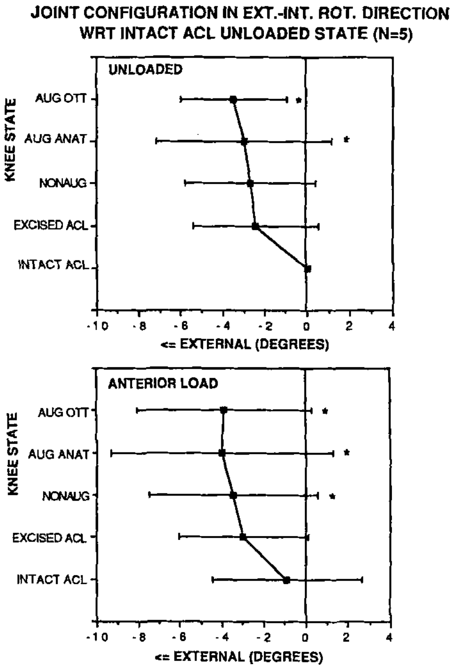

Figure 5. Means and standard deviations of the joint configuration in internal-external tibial rotation during the unloaded (top) and anterior load (bottom) conditions. Abbreviations as in Figure 4.

pretension at the time of fixation was inadequate to ensure reproducibility. The difficulty in obtaining reproducibility experimentally may explain why clinical reports, where control over the above variables is drastically less, are so contradictory.

Both augmentation procedures generated total forces in the repair composites that were greater than the intact anterior cruciate ligament under the same anterior loads. It is a significant observation that augmenting a repair anatomically through the femoral condyle did not produce a reduction in repair tissue force. Thus, it is not evident what is gained by this augmentation. However, this conclusion is specific to the surgical procedure employed in this study. It is possible that a different procedure with an anatomically located augmentation segment could achieve the desired reduced tissue force. The augmentation and sutures from the anteromedial remnant in the over-the-top position did reduce repair tissue forces below those in the nonaugmented repair, and even below normal at extension. Because there was an abnormal fixed external rotation of the tibia for all three repair procedures, there was no obvious advantage of one repair condition over another in this regard. In the immediate postoperative state, the over-the-top augmentation appeared to be the superior of the two methods based on repair tissue force level. The effectiveness of the over-the-top augmentation would be expected to allow for full extension exercises and improved quadriceps rehabilitation, both of which are known to lead to high forces in the anterior cruciate ligament at extension and 30° of flexion (Henning et al. 1985, Renström et al. 1986). The amount of load sharing necessary for augmentation to fulfill its protective role during repair tissue remodeling is presently unknown, as is the question of whether the load sharing obtained in the initial postoperative state will remain during the months where healing occurs.

This study demonstrates that current procedures for repair of acute anterior cruciate ligament ruptures, with or without augmentation, may lead to higher than normal forces in the repair tissue, as well as abnormal configuration. Of special importance are the high forces produced in the repair tissue in flexion, which could potentially lead to repair stretching and failure. The use of a synthetic augmentation device placed in the over-the-top position protects the repair tissue at extension. Although the total forces in the composite repair were considerably higher than in the intact ligament at extension, the forces in the repair tissue segment approached normal when the augmentation device was positioned anatomically through the condyle, and were lower than normal when it was positioned over-the-top.

References

Balkfors B. The course of knee ligament injuries. Acta Orthop Scand 1982;(Suppl 198):1–99.

Bilko T E, Paulos L E, Feagin J A Jr, Lambert K L, Cunningham H R. Current trends in repair and rehabilitation of complete (acute) anterior cruciate ligament injuries. Analysis of 1984 questionnaire completed by ACL Study Group. Am J Sports Med 1986;14(2):143–7.

Feagin J A Jr, Curl W W. Isolated tear of the anterior cruciate ligament: 5 year follow-up study. Am J Sports Med 1976;4(3):95–100.

Henning C E, Lynch M A, Glick K R Jr. An in vivo strain gage study of elongation of the anterior cruciate ligament. Am J Sports Med 1985;13(1):22–6.

Lewis J L, Lew W D, Schmidt J. Description and error evaluation of an in vitro knee joint testing system. J Biomech Eng 1988;110(3):238–48.

Noyes F R, Butler D L, Paulos L E, Grood E S. Intra-articular cruciate reconstruction. I: Perspectives on graft strength, vascularization, and immediate motion after replacement. Clin Orthop 1983;(172):71–7.

Odensten M, Lysholm J, Gillquist J. Suture of fresh ruptures of the anterior cruciate ligament. A 5-year follow-up. Acta Orthop Scand 1984;55(3):270–2.

Renström P, Arms S W, Stanwyck T S, Johnson R J, Pope M H. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med 1986;14(1):83–7.

Sandberg R. Knee ligament injuries. A plan of action. Thesis, University of Lund, Lund, Sweden 1987.

Schabus R. Die Bedeutung der Augmentation für die Rekonstruktion des vorderen Kreuzbandes. Acta Chir Austriaca 1988;20(Suppl 76):4–48.

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