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Change in Meniscal Strain with Anterior Cruciate Ligament Injury and After Reconstruction

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ABSTRACT

Meniscal injury has been well documented in association with injury to the anterior cruciate ligament. The purpose of this study was to evaluate the effect of anterior cruciate ligament transection and reconstruction on meniscal strain. Four differential variable reluctance transducer strain gauges were placed in the medial and lateral menisci of nine cadaveric knees. Each specimen was mounted to a six-degree-of-freedom knee testing device. Testing was conducted with the knee fully extended and at 45° and 90° of flexion, both with and without applied axial load. At each angle of flexion, an anterior and posterior tibial load was applied. Next, the anterior cruciate ligament was transected and the testing sequence was repeated. Finally, the ligament was reconstructed using a central one-third patellar tendon graft and the testing sequence was repeated. The results demonstrated statistically significant increases in meniscal strain in ligament-transected knees compared with intact specimens. A reduction in meniscal strain to a level similar to that detected in the ligament-intact knees was observed after anterior cruciate ligament reconstruction. These results have important clinical implications regarding the potentially deleterious effect of the anterior cruciate ligament-deficient knee on meniscal strain and the potential benefit of anterior cruciate ligament reconstruction.

The meniscus is essential for normal function of the knee because of its ability both to transmit axial loads and to increase the weightbearing surface of the tibiofemoral joint.[13] Its deficiency has been associated with degeneration of the articular surface in the knee joint.[12]

The clinical relationship between ACL deficiency and meniscal injury has been well documented.[9,18] The medial meniscus has been demonstrated to function as a secondary restraint to anterior tibial translation in the ACL-deficient knee.[11] In addition, the meniscus has also been shown to enhance stability under anterior-posterior, varus-valgus, and internal-external rotation load when the ACL is absent.[16,17] In the ACL-deficient knee, it has been shown that lateral meniscal tears are associated with acute injuries, whereas medial meniscal tears are more prevalent after chronic ACL deficiency.[16] More recently, Allen et al.[1] demonstrated that the medial meniscus sustains an increase in anterior-posterior load sharing in ACL-deficient knees.

Despite clinical data documenting a relationship between ACL deficiency and meniscal injury, little biomechanical data exist regarding the relationship between the state of the ACL and meniscal strain under various loading conditions. The purpose of the current study was to record meniscal strain in a cadaveric knee model in the ACL-intact state, after ACL transection, and after ACL reconstruction.

MATERIALS AND METHODS

Knee Loading Device

All specimens were tested using a knee loading device (Fig. 1).[5,6] This device consists of a loading frame capable of applying a load or displacement with six degrees of freedom (anterior-posterior, medial-lateral, proximal-distal, flexion-extension, varus-valgus, and internal-external rotation). Motion is applied through stepper motors that are computer controlled. Force is measured by a six-axis load cell that can measure force and moments in all six components. The computer controls motion in such a way that a specific load can be applied and the knee can be

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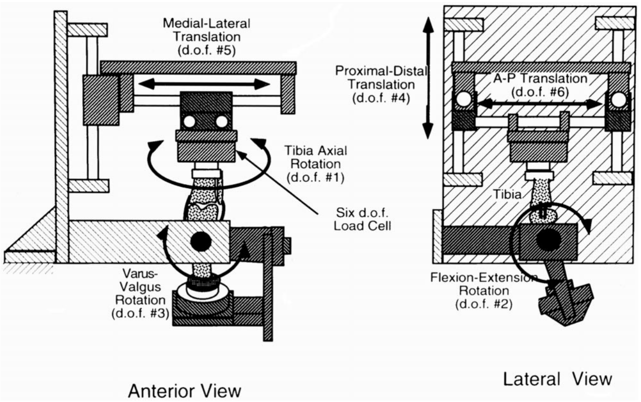

Figure 1. Schematic drawings of the knee testing apparatus. d.o.f., degrees of freedom.

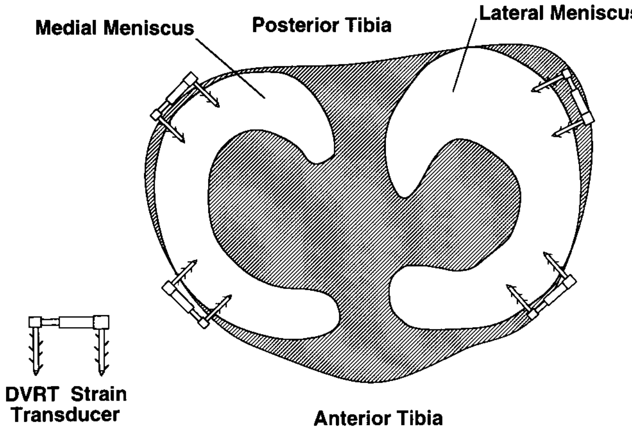

Figure 2. The medial and lateral menisci showing the positions of the strain gauges.

positioned at a predetermined flexion angle. The computer can also simultaneously position the knee while applying a prescribed load. To simulate free motion in an axis, the force set point in that axis is set to zero and the position is adjusted to maintain zero force. In this study, all motions except for the flexion angle were free motions, with the anterior-posterior and axial tibial forces set to the desired level.

Strain Measurement

A technique for real-time strain measurement in the knee meniscus has not been reported. The method of strain measurement chosen for this study was the differential variable reluctance transducer (DVRT) strain gauge (MicroStrain Inc., Burlington, Vermont). This strain gauge has been used successfully in previous studies to measure ligament strain; however, its use in menisci has only been reported in the temperomandibular joint.[2,15] The strain gauge consists of a small tube within which a core slides with changes in length. The device is secured to the meniscus by means of two barbs. The distance between the barbs changes with tissue strain, which is recorded as a change in voltage by a computer equipped with an analog-to-digital converter. Noninvasive optical methods of strain measurement, such as video dimension analysis, were not chosen because it would not be possible to visualize the meniscus in several areas simultaneously. In addition, compared with optical methods, the DVRT strain gauge can better approximate average strain through a thickness of tissue. The use of sutured liquid metal strain gauges was attempted in preliminary studies; however, these strain gauges developed problems with loosening, failure due to bubble formation, and inconsistent calibration. The DVRT strain gauges were placed on the posteromedial and anteromedial areas of the medial menisci and posterolateral and anterolateral aspects of the lateral menisci (Fig. 2).

Test Protocol

Nine fresh-frozen cadaveric knees were obtained from the University of South Alabama anatomical gift program. All specimens were greater than 60 years of age and free of significant tibiofemoral or patellofemoral articular cartilage abnormalities and meniscal damage. Specimens were stored frozen until the day of surgery, at which time they were thawed in a warm water bath. The femur, tibia, and fibula were cut approximately 150 mm from the joint line. Each specimen was dissected to the joint capsule, where care was taken to maintain the meniscocapsular attachments to the tibia. The lateral collateral ligament and the tibiofibular joint were maintained in their entirety. The popliteus muscle and its tendinous insertion onto the femur were left intact. A 10-mm patellar tendon graft with attached patellar and tibial bone plugs was harvested from the central one-third of the patellar tendon. Two No. 1 Surgidec sutures (U.S. Surgical Corporation, Norwalk, Connecticut) were placed through drill holes in each bone plug. The tibia and femur were potted in cylinders using low-melting-point (158°F, 70°C) metal. Cold water was applied to the joint itself to ensure that it was not heated. The fibula was not fixed distally. The DVRT strain gauges were then applied to the anterior and posterior aspects of the medial and lateral menisci. The gauges were placed 1 cm from the medial and lateral collateral ligaments at the midline of the peripheral meniscus and were aligned along the circumference. Although meniscal thickness varied somewhat between different specimens, placing each DVRT 1 cm from the collateral ligaments and at the midline of the meniscus enabled the strain gauges to be reproducibly placed in the different specimens. These locations were chosen because of their accessibility and the high incidence of tears at these locations. Each knee was mounted in the six-degree-of-freedom testing machine with the knee placed in full extension. Extension was determined by applying a 0.6-N·m extension moment to the joint and then flexing the knee until the moment was less than 0.1 N·m. The tibia was loaded through a cycle of 0 N to 38 N anterior to 38 N posterior (anterior-posterior) force and back to 0 N while meniscal strain and tibial displacement were recorded at fixed force increments. The anterior-posterior force was limited by the moment capacity of the load cell. A 200-N axial force was applied to the knee along the axis of the tibia and the anterior-posterior drawer loading was repeated. The testing sequence was repeated at 45° and 90° of knee flexion. The ACL was sectioned completely and the test sequence was repeated.

After testing the ACL-intact and ACL-transected states, a standard one-incision ACL reconstruction was performed using a 10-mm bone-patellar tendon-bone graft. Using a commercial endoscopic guide system (Arthrex, Naples, Florida), the center of the tibial tunnel was placed 5 mm anterior to the posterior cruciate ligament, while the femoral tunnel was placed 1 mm anterior to the posterior femoral cortex. The center of the femoral tunnel was placed at the 11 o'clock position (right knee) or 1 o'clock position (left knee). Both tunnels were reamed to 10 mm and the previously sized graft was pulled into the tunnels. A 9 × 25 mm interference screw was placed in the femoral tunnel. The knee was brought from full extension to full flexion 10 times to prestretch the graft before tibial fixation. The distal bone plug sutures were attached to a commercial tensiometer as the knee was placed in 30° of flexion. While a posterior force of 89 N was applied to the proximal tibia and 67 N of longitudinal tension was applied to the graft through the tibial bone plug sutures, a 9 × 25 mm metal interference screw was placed in the tibial tunnel. During interference screw placement, the tibia was rotationally constrained, thereby enabling only the anterior-posterior tibial translation. Testing was then repeated for the reconstructed knee. Data were statistically analyzed using an analysis of variance (ANOVA) test. The threshold for statistical significance was $P \leq 0.05$.

RESULTS

The results presented are the total changes in strain from 0-N anterior-posterior load during the loading cycle. Knee state, axial load, and meniscal gauge position significantly affected measured strain ($P < 0.05$). Although knee flexion angle had an influence on meniscal strain, it was not significant ($P = 0.17$).

Meniscal strain was significantly increased when the ACL was cut, and a significant decrease in strain was noted when it was subsequently reconstructed ($P < 0.01$). A significant increase in meniscal strain was observed at all angles after ACL transection. When the ACL was reconstructed, meniscal strain returned to levels observed in the ACL-intact state.

The average strain for all gauges during testing increased from 1.2% (SEM, ±0.11%) for intact specimens to 1.7% (SEM, ±0.13%) for gauges in ACL-cut knees. The trend with knee flexion was similar for both intact and ACL-cut knees, with an angle of 45° having the least strain (Figs. 3 through 6).

In the postermedial meniscus, flexion angle and knee state significantly affected meniscal strain (Fig. 3). Specifically, the effect of cutting the ACL was greater at higher flexion angles and with axial loading. Looking at all flexion angles together under axial loading, strain increased approximately 50% after the ACL was transected and was reduced by about 50% after ACL reconstruction ($P < 0.05$). With no axial load, the magnitude of meniscal

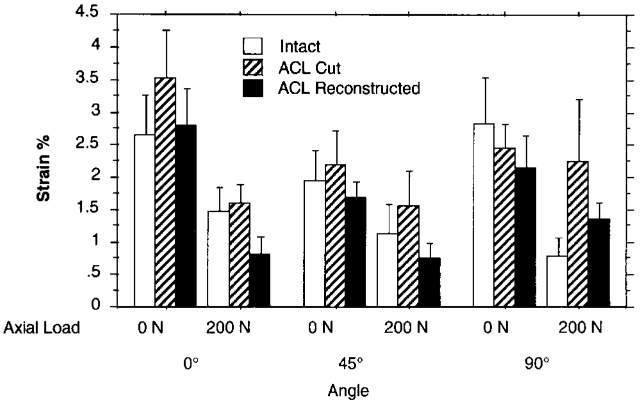

Figure 3. Strain in the posteromedial meniscus for the three tested states. At all flexion angles with axial loading, strain increased approximately 50% after ACL transection and was reduced by about 50% after ACL reconstruction ($P < 0.05$).

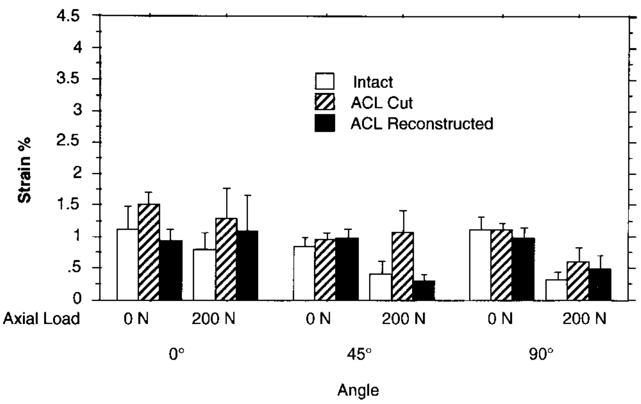

Figure 4. Strain in the posterolateral meniscus for the three tested states.

strain was greater; however, the effect of ACL transection and reconstruction was diminished. Looking at all posteromedial meniscal measurements, there was a significant effect of ACL reconstruction and axial load on strain ($P < 0.05$).

Analysis of the effect of axial load and flexion angle on meniscal strain demonstrated higher strain in all gauges without axial load when compared with the loaded state. These findings were statistically significant in all gauges except those in the anteromedial meniscus. Without axial load at 45° of knee flexion, minimal strain was observed in the posterolateral, posteromedial, and anteromedial meniscal gauges; minimal meniscal strain was observed in the anterolateral meniscal gauge at 0° of knee flexion. With an applied axial load, there was a trend of decreasing strain with increasing flexion angle for all gauges. No angle effect was statistically significant.

Evaluating all tests, there was a significant relationship between gauge location and meniscal strain ($P < 0.0001$). In the medial meniscus, posterior strain was noted to be

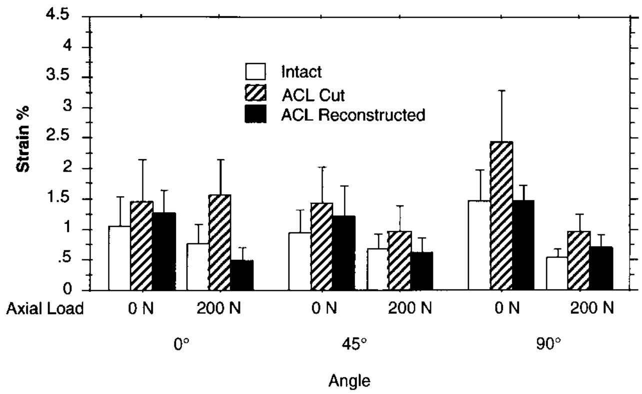

Figure 5. Strain in the anteromedial meniscus for the three tested states.

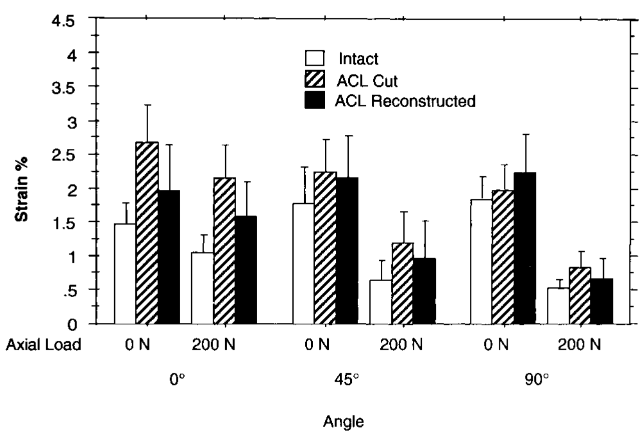

Figure 6. Strain in the anterolateral meniscus for the three tested states.

higher, while in the lateral meniscus, anterior strain was greater.

The trends with respect to knee state were similar between the medial and lateral menisci. Averaging all flexion angles with the knee axially loaded, strain doubled in the posterolateral meniscus with the ACL cut. Reconstruction of the ACL resulted in a return of strain levels to those observed in the ACL-intact state ($P < 0.05$). In the anterolateral and anteromedial meniscus gauges, increased strain was observed with ACL transection, and a trend toward normal strain was observed with ACL reconstruction. This was similar to the observation in the posterior gauges. The strain measured in the anterolateral menisci without axial load was an exception in that it did not tend to return to normal with ACL reconstruction (Fig. 6).

DISCUSSION

The incidence of concomitant meniscal tears reported in patients with an acute tear of the ACL has been reported to be between 19% and 76%, increasing to between 53% and 100% in patients with chronic ACL instability.[8,9,18] Keene and Paterson[8] reviewed 735 knee arthroscopies and noted that patients with chronic ACL injuries had a 100% incidence of meniscal tears. Warren and Levy[17] reported an increased incidence of meniscal injury associated with chronic ACL insufficiency. Indelicato and Bittar[7] retrospectively reviewed records of 100 patients with confirmed ACL damage. The authors noted that the incidence of meniscal tears was 77% in knees with an acute ACL injury and 91% in knees with a chronic ACL injury. Other authors have also noted an increased incidence of meniscal injury in chronically ACL-deficient knees.[4,19]

The current study was undertaken to better understand the causes for the increased incidence of meniscal tears observed in the ACL-deficient knee. The current results demonstrate an increase in meniscal strain after ACL injury. In addition, flexion angle, axial loading, and ACL state were shown to influence meniscal strain in our cadaveric model. The current study supports the hypothesis that an increase in anterior-posterior tibial displacement associated with injury to the ACL may contribute to increased meniscal strain. This observation may help explain the higher incidence of meniscal injuries observed in chronically ACL-deficient patients. Moreover, meniscal repair may not provide significant long-term benefit in the ACL-deficient knee unless the underlying ligament instability is corrected. Cannon and Vittori[3] reported that restoring knee stability can decrease the incidence of meniscal tears. Such clinical data support our laboratory findings that meniscal strain can be restored to normal levels after ACL reconstruction.

The highly significant effect of gauge location in the current study indicates that the meniscus is not simply a radially loaded structure that undergoes pure hoop stress. One would expect circumferential stress applied to a simple hoop to demonstrate uniform strain characteristics around the circumference of the hoop.

Care should always be taken when interpreting laboratory results. The linear strain measurements of the DVRT gauges represent an approximation of the strain in the complex three-dimensional structure of the meniscus. Such measurements are derived from motion recorded between two strain gauge attachment points. This motion represents straight elongation strain of an isolated portion of the meniscus. Therefore, these measurements represent only an approximation of meniscal strain secondary to compression. Moreover, the DVRT provides an accurate strain measurement of fibers that are aligned along the axis of the strain gauge only at that specific location. The higher strain observed in the unloaded knee is most likely due to significantly higher anterior-posterior translation noted in the unloaded knee. Applied axial load stabilized the knee, limiting anterior-posterior translation at the applied force level. This significantly lower displacement for axially loaded knees was also demonstrated by Shoemaker and Markolf.[14] The strain measurements in this study were of a similar magnitude (1% to 2%) as that measured by Krause et al.[10] for a 500-N applied axial load.

The results of this study indicate that the DVRT strain gauge system is capable of measuring circumferential hoop strain on the peripheral surface of knee menisci. The cadaveric dissections performed before strain gauge placement may have slightly diminished the knee stability. Although great care was taken to ensure that all meniscocapsular attachments were left intact, the remaining joint capsule was removed, which probably contributed to a small amount of increased anterior-posterior tibial translation. Although the dissection may have increased meniscal strain levels, it is unlikely that this affected the observed trends.

The loading system used in our study was simplified to enable the comparison of different knee states. We did not attempt to simulate complex in vivo knee loading that involves muscle forces and rolling/gliding of the tibiofemoral joint.

Subject to the study limitations, the current study not only assists in understanding the mechanisms of meniscal injury, but also provides clinically relevant data regarding elevated meniscal strain observed in the ACL-deficient knee. No previous biomechanical study has examined the effect of ACL deficiency and of subsequent ACL reconstruction on meniscal strain. Future extensions of this study may involve the effect of ACL graft positioning, graft tensioning, and graft material on meniscal strain. Another factor to be examined is the effect of knee bracing on meniscal strain. Finally, a mathematical model of the knee joint, including a detailed model of the menisci, could also be developed to relate the meniscal surface strain to strain in other areas of the menisci.

CONCLUSIONS

From the results of this study, we conclude the following: 1) Anterior and posterior meniscal strain in the cadaveric knee are increased after ACL sectioning and anterior-posterior loading. 2) After ACL reconstruction, meniscal strain is returned to levels observed in the ACL-intact knee. 3) Reconstruction of the ACL appears to reduce strain within the menisci, and therefore may diminish the likelihood of meniscal injury and enhance the biomechanical environment for healing of a meniscal repair.

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