

# How Three Methods for Fixing a Medial Meniscal Autograft Affect Tibial Contact Mechanics

Mohammad M. Alhalki,\* MS, Stephen M. Howell,†‡§ LTC, MC, USAF, and  
Maury L. Hull,\*† PhD

*From the \*Biomedical Engineering Graduate Group and †Department of Mechanical Engineering, University of California at Davis, Davis, California, and the ‡Clinical Investigation Facility, David Grant Medical Center, Travis Air Force Base, California*

## ABSTRACT

We evaluated three methods for fixing a medial meniscal autograft to determine which method restored tibial contact mechanics closest to normal. The contact mechanics (maximum pressure, mean pressure, contact area, and location of the center of maximum pressure) of the medial tibial articular surface were determined using pressure-sensitive film while knee specimens were loaded in compression to 1000 N at 0°, 15°, 30°, and 45° of flexion. Pressure was measured for the intact knee, the knee after meniscectomy, and the knee with the original meniscus removed and reimplanted as an autograft using three different fixation methods. The contact mechanics of the autograft reinserted with bone plug fixation were closest to normal; however, the maximum pressure was significantly greater than in the intact knee. Adding peripheral sutures neither improved nor worsened the contact mechanics. Fixation with sutures only did not restore normal contact mechanics. We concluded that medial meniscal transplantation requires anatomic fixation of bone plugs attached to the anterior and posterior horns to restore contact mechanics closest to normal. Fixation of the meniscal horns with sutures alone cannot be recommended.

Removal of either the entire meniscus or a portion thereof may cause degenerative arthritis in the knee.<sup>10, 12, 13, 17, 18, 28</sup>

§ Address correspondence and reprint requests to Stephen M. Howell, MD, 8100 Timberlake, Suite F, Sacramento, CA 95823.

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The cause of the arthritis is increased contact stress on the articular cartilage, which increases in direct proportion to the amount of meniscus removed.<sup>6</sup> Meniscal transplantation is being evaluated as a method to restore normal contact mechanics, with the long-term goal of preventing degenerative arthritis.<sup>19</sup>

One factor affecting the ability of a meniscal transplant to restore normal contact mechanics at the time of implantation is the method of fixation to the surrounding tissues. This factor is important because the menisci are connected to the surrounding tissues by a complex of attachments. The function of these attachments is to provide restraints that limit the movement of the meniscus when it bears load. Consequently, it would be expected that maintaining the restraints is important to the distribution of the compressive load transmitted by the joint.<sup>1</sup> Because the restraints of a meniscal allograft are dictated by the surgical techniques used to fix the graft to the surrounding tissue, the methods of fixation were the focus of this study.

Although previous research has examined the effect of different methods of meniscal fixation on the contact mechanics of the lateral compartment of the knee,<sup>11</sup> we know of no previous research that has made such a study for the medial compartment. Study of the medial compartment is important because the medial meniscus is more commonly torn than the lateral meniscus<sup>16</sup> and hence is more likely to be replaced. Because of anatomic differences between the lateral and medial compartments of the knee, the effect of fixation methods in the medial compartment warrants separate study from the effect of fixation methods in the lateral compartment.

The purpose of this study was to evaluate three methods for fixing a medial meniscal transplant to determine which technique restored contact mechanics closest to normal. The methods studied included inserting bone plugs attached to the meniscal horns in anatomic placed tunnels, suturing the periphery of the meniscal transplant

to the rim of the remainder of the original meniscus in conjunction with bone plug fixation, and suturing the meniscal horns through bone tunnels in conjunction with suturing of the meniscal rim. These three methods were of interest to determine whether adding peripheral sutures to a transplant fixed with bone plugs alone further improved the contact mechanics and if contact mechanics were closer to normal when the transplant was fixed to the tibial plateau either with bone plugs and peripheral sutures or with sutures alone.

Because the performance of a meniscal allograft at the time of implantation depends on a variety of factors including placement, fixation method, geometry, and the material properties,<sup>24</sup> a method was devised to isolate the variable of fixation method for study. To control the variables of placement, geometry, and material properties, the original medial meniscus was harvested with bone plugs and reinserted using each of the three fixation methods.

## MATERIALS AND METHODS

### Specimen Testing

Ten fresh-frozen, human cadaveric knees were obtained from six men and four women with an average age of 70 years (range, 37 to 89). Anteroposterior and lateral roentgenograms and MRI scans were obtained of each knee. There was no evidence of joint space narrowing, osteophytes, chondrocalcinosis, articular wear, meniscal degeneration, or meniscal tears.

Each knee was prepared by transecting the femur 24 cm from the joint line and the tibia 35 cm from the joint line. Soft tissues within 10 cm of the joint line were retained and the rest were removed. To interface the specimen with the testing apparatus, 1.25-cm-diameter steel rods were cemented into the medullary canal of the femur and tibia with polymethyl methacrylate.

Specimens were tested in a six degree-of-freedom, load-application system, a knee joint testing apparatus custom designed and built in our laboratory.<sup>5</sup> The system constrained flexion to a predetermined angle and applied the compressive loads as the tibial contact pressure was measured using pressure-sensitive film. Unconstrained motion was permitted in the remaining degrees of freedom.

The specimens were aligned in the load application system using the functional axes approach, a technique with good repeatability.<sup>5,8,9</sup> After aligning each specimen, the rod-femur and rod-tibia complexes were potted in hollow, rectangular, metal tubes with polymethyl methacrylate. The use of rectangular tubes allowed the specimen to be removed and returned to the test apparatus without the need for realignment. After the alignment procedure, the specimen was removed from the test apparatus and an osteotomy of the medial femoral condyle was performed using a technique described by Martens et al.<sup>22</sup> to allow easy, repeated access to the medial hemijoint. These authors showed that the osteotomy of the medial femoral condyle does not significantly change the pressure and contact area compared with the intact knee.

After the osteotomy, the knee was reassembled and the specimen was replaced in the load application system for preconditioning. A series of preconditioning cycles was applied to the knee to minimize the effects of stiffness resulting from rigor and freezing. The specimen was preconditioned by compressing the knee in 17 equal intervals to 1000 N of load using a ramp-up-plateau format with the load application system. Four complete loading cycles were applied at 0° and 45° of knee flexion.<sup>22</sup>

To serve as a control, the contact pressure on the articular surface of the medial tibia was measured with the intact meniscus in place (intact knee) using a two-layered, pressure-sensitive film (Super-Low Range Fuji Prescale Film; C Itoh, New York, New York). Super-low range film was used because it provides higher pressure resolution than the four other film ranges that are available.<sup>20</sup> This film measures pressure between the nominal limits of 0.5 to 2.5 MPa.<sup>1,22</sup> Custom-sized, 0.25-mm-thick, polyethylene film packets were prepared from a template of the articular surface of the medial tibial plateau. All film packets were sealed at the same ambient conditions for each specimen, which avoided the need to compensate for temperature and humidity.<sup>22</sup>

Four factors were controlled during the exposure of the pressure-sensitive film: shear, orientation, overshoot, and loading time. Because of the high sensitivity of the pressure transducer to shear,<sup>30</sup> a previously tested method was used to avoid shear loads during installation, loading, and removal of the transducer.<sup>22</sup> The film packet was inserted under the medial meniscus with the knee distracted 2 mm at 100° of flexion. While maintaining the load required to distract the knee, the flexion angle was changed to the angle desired for testing. The orientation of the film on the tibial plateau was recorded by inserting two pins through two 1.6-mm-diameter tunnels drilled through the tibia and its articular surface. Two dots appeared near the anterior and posterior margins of the film in regions that were either minimally exposed or unexposed during loading. The compression load was incrementally increased over 15 seconds until 1000 N was reached, held for 5 seconds, and released.<sup>22</sup> The use of incremental load increases avoided overshoot by the load application system.<sup>5</sup> Three pressure measurements were made at each of the randomized flexion angles of 0°, 15°, 30°, and 45°. The knee positions were selected to represent the motion arc of the knee during the stance phase of gait.<sup>27</sup>

The specimen was removed from the load application system. The medial tibial plateau was reexposed by opening the osteotomy to facilitate removal of the medial meniscus with bone plugs. A 2.4-mm-diameter K-wire was drilled from the center of the posterior horn of the medial meniscus across the tibial metaphysis, exiting on the anterolateral aspect of the tibia. Similarly, a second K-wire was drilled from the center of the anterior horn of the medial meniscus across the tibial metaphysis, exiting on the posteromedial aspect of the tibia. A 10-mm cannulated reamer was drilled over the guide wire through the metaphysis to within 15 mm of the joint line. The bone plug attached to the meniscal horns was harvested by advanc-

ing a coring reamer (Acufex, Waltham, Massachusetts), with a 10-mm outside diameter and an 8-mm inside diameter, within the tunnel to the joint line. The peripheral margin of the meniscus was sharply detached within 2 mm of the outer edge.

In a pilot study, the osteoporotic bone plugs failed by the cortical bone separating from the cancellous bone during compression. To prevent failure during these experiments, the diameter of the cancellous bone was trimmed to 6 mm, and a 12.5-mm-long, No. 6, flat-headed machine screw was inserted into the 2.4-mm tunnel from the meniscal side of the plug, across the insertion of the meniscal horn, through the cortical bone, and into the cancellous bone. Polymethyl methacrylate was molded around the screw and bone to create a more durable, reinforced plug 8 mm in diameter and 15 mm long.

As was done when the meniscus was intact, tibial articular pressure was measured with the medial meniscus removed (total meniscectomy) and the medial meniscus reimplanted (autograft) using a randomization protocol. When the autograft was evaluated, contact pressure was measured for each fixation method in the following order: 1) fixation of the anterior and posterior horns by cementing bone plugs using polymethyl methacrylate in their original tunnels, 2) fixation of the horns by bone plugs in conjunction with fixation to the periphery of the meniscus with multiple vertical mattress sutures,<sup>29</sup> and 3) fixation of the horns by passing sutures through bone tunnels and fixation to the periphery of the meniscus with multiple sutures.

Bone plug fixation was performed by disassembling the osteotomy and cementing the bone plugs into the original tunnels to ensure anatomic placement. The osteotomy was reassembled, the preconditioning cycle was repeated to seat the graft, and the pressure was measured. Next, peripheral sutures were added to the bone plug fixation of the autograft after reopening the osteotomy. The outer edge of the allograft was sutured to the remnant of the original meniscus using single, vertical-loop stitches of a 2-0 (metric, 3-0) Ethibond polyester braided suture (Ethicon, Somerville, New Jersey) spaced 10 mm apart and tied snugly with an unmeasured tension.<sup>29</sup> The osteotomy was reassembled and the preconditioning and pressure measurements were repeated. Finally, the autograft was fixed with sutures alone. The anterior and posterior horns were sharply detached from their respective bone plugs. The screw in the bone plug was removed, and a 2.4-mm drill hole was redrilled through the center of each bone plug through the original tunnel. A 2-0 Ethibond suture was sewn to each horn, threaded through the tunnels, and tied snugly with an unmeasured tension over the anterior cortex of the tibia. The peripheral sutures were retained. Preconditioning and pressure measurements were repeated.

#### Data Analysis

To generate a calibration curve for each knee, 14 film packets were exposed under known loads over a range of 0.5 to 3.75 MPa in increments of 0.25 MPa using a mate-

rials testing machine (858 TableTop model, MTS, Inc., Minneapolis, Minnesota).<sup>21</sup> The maximum calibration load was chosen to exceed the upper pressure limit of the film specified by the manufacturer because it has been shown that the film is capable of measuring pressures higher than this limit.<sup>22</sup> The pressures corresponding to color densities of the exposed film packets were quantified using digital imaging techniques (Image v 1.61, National Institute of Health, Bethesda, Maryland) performed on a personal computer. To transfer the image of the exposed film to the computer for analysis, the dye-receiving layers of the film packets were scanned simultaneously with a high-resolution scanner. A calibration curve relating the gray-scale values for each pixel to pressure was derived using regression to determine the best-fit fifth-order polynomial. Pressures related to pixel values in this manner have been shown to have a root-mean-squared error of 0.04 MPa for the super-low range film.<sup>20</sup>

For each knee, five contact variables, the maximum pressure, the mean pressure, the contact area, and the *x* and *y* locations of the maximum pressure were determined at 0°, 15°, 30°, and 45° of flexion for each of the five joint conditions (that is, the intact knee, the knee after meniscectomy, and the knee with the autograft fixed with the three different methods). To make these measurements, 600 film packets (10 specimens × 5 conditions × 4 flexion angles × 3 measurements per angle) were scanned. The 15 film packets exposed at a given flexion angle were scanned simultaneously, thresholded, and then calibrated. The average value for each contact variable was computed from the three films exposed at each flexion angle. Thresholding was used to eliminate scatter and to match the appearance of the scanned image to the original exposed film packets.

Different statistical analysis procedures were used to analyze the results. For the mean and maximum pressures and the contact area, a repeated-measures analysis of variance (RANOVA)<sup>25</sup> was used. The independent variables included two within-specimen factors, joint condition at five levels (intact knee, knee after meniscectomy, and autograft with three fixation methods) and flexion angle at four levels (0°, 15°, 30°, and 45°). The maximum pressure, mean pressure, and contact area were normalized because the contact mechanics of the intact knee varied between specimens. Normalization was performed by computing the difference between the value of a contact variable for a particular joint condition (*A*) and the value of the contact variable for the intact knee (*N*) and dividing by the difference between the value of the contact variable for the joint after meniscectomy (*M*) and the value of the contact variable for the intact knee ( $A - N/M - N$ ). A multiple analysis of variance (MANOVA) was used to determine whether the location of the maximum pressure was significantly different between knees with the intact meniscus and knees with the autograft reimplanted using each fixation method. Where significant differences were indicated ( $P < 0.05$ ), paired comparisons were made using Tukey's method.

## RESULTS

The joint condition significantly affected both the maximum pressure and mean pressure ( $P < 0.0001$ ), but not the contact area. The flexion angle and the interaction of the flexion angle with the joint condition had no significant effect on these three contact variables as analyzed using RANOVA. Highly variable shifts in the location of the maximum pressure occurred for all joint conditions compared with the intact knee. Therefore, as determined by MANOVA, the joint condition, flexion angle, and the flexion angle/joint condition interaction had no significant effect on the location of the maximum pressure ( $P = 0.827$ ,  $P = 0.104$ , and  $P = 0.065$ , respectively).

None of the three fixation methods used to implant the autograft restored the normalized maximum pressure of the medial tibial articular surface to normal (Fig. 1). At 0°, 15°, 30°, and 45° of flexion, the maximum pressure with the autograft fixed with either bone plugs or with bone plugs and peripheral sutures was significantly greater than the maximum pressure in the intact knee. There was no significant difference in the normalized maximum pressure between the two fixations using bone plugs. The greatest difference in normalized maximum pressure occurred when the autograft was fixed with sutures. The normalized maximum pressure with suture fixation alone was significantly greater (Tukey's method) than that both in the intact knee and in the knee with the autograft fixed with either bone plugs or with bone plugs and peripheral sutures. The normalized maximum pressure with suture fixation alone was 75%, 65%, 62%, and 84% greater than the intact knee at 0°, 15°, 30°, and 45° of flexion, respectively.

Only the two fixation methods that used bone plugs to secure the autograft restored the normalized mean pressure of the medial tibial articular surface to normal (Fig. 2). The normalized mean pressure was not significantly different from the intact knee at 0°, 15°, 30°, and 45° of flexion when the autograft was fixed with either bone plugs or with bone plugs and peripheral sutures but was significantly greater (Tukey's method) when the autograft was fixed with sutures alone. The normalized mean pressure with suture fixation alone was 61%, 49%, 56%, and 61% greater than the intact knee at 0°, 15°, 30°, and 45° of flexion, respectively.

All three fixation methods restored the normalized mean contact area to normal (Fig. 3). Even though the normalized mean contact area differed considerably between the five joint conditions, these means were not significantly different because of the wide confidence intervals (Tukey's method). This variability explains why the normalized contact area of the knee after meniscectomy was 40%, 40%, 80%, and 80% less than the intact knee at 0°, 15°, 30°, and 45° of flexion, respectively, and yet not significantly different.

The method of fixation did not significantly affect the average shift of the center of maximum pressure compared with the intact knee (Figs. 4 and 5). Compared with the intact knee, the average shift of the center of maximum pressure of the autograft inserted using bone plug

fixation was lateral and posterior at 0° and 15° but medial and posterior at 30° and 45° of flexion. In contrast, compared with the intact knee, the average shift in the center of maximum pressure for the autograft inserted using sutures only was lateral and posterior at 0°, medial and anterior at 15° and 45°, and medial and posterior at 30° of flexion.

The addition of sutures to the autograft fixed with bone plugs had no significant effect on any of the contact variables (Figs. 1 through 5). However, at 45° of flexion there was a trend toward poorer contact mechanics from the addition of sutures; the maximum pressure increased 26% at 45° of flexion and the mean pressure increased 11% at 45° of flexion compared with the intact knee. Therefore, adding peripheral sutures to bone plug fixation did not improve contact mechanics and had a tendency to increase the maximum and mean pressure to above normal at 45° of flexion.

## DISCUSSION

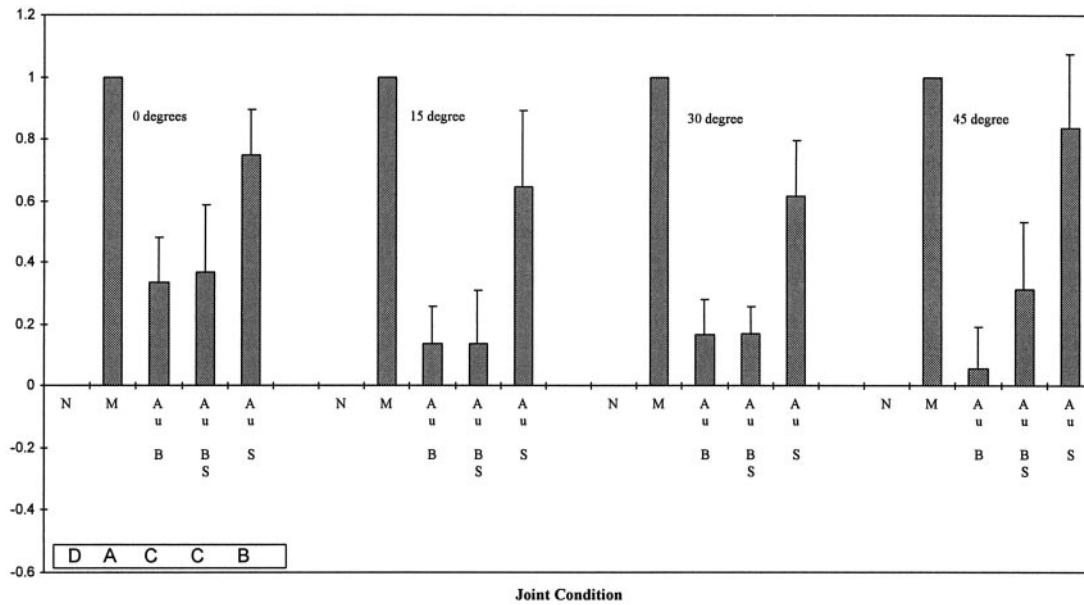
### Methodologic Issues

The purpose of this study was to determine which fixation technique for inserting a medial meniscal autograft restored the contact mechanics closest to normal. By using an autograft instead of an allograft, the effects of fixation were isolated from confounding factors such as differences in meniscus size, shape, and mechanical properties between the donor meniscus and the original meniscus.<sup>11</sup> Furthermore, variability in positioning was minimized by fixing the autograft within the original bone tunnels.

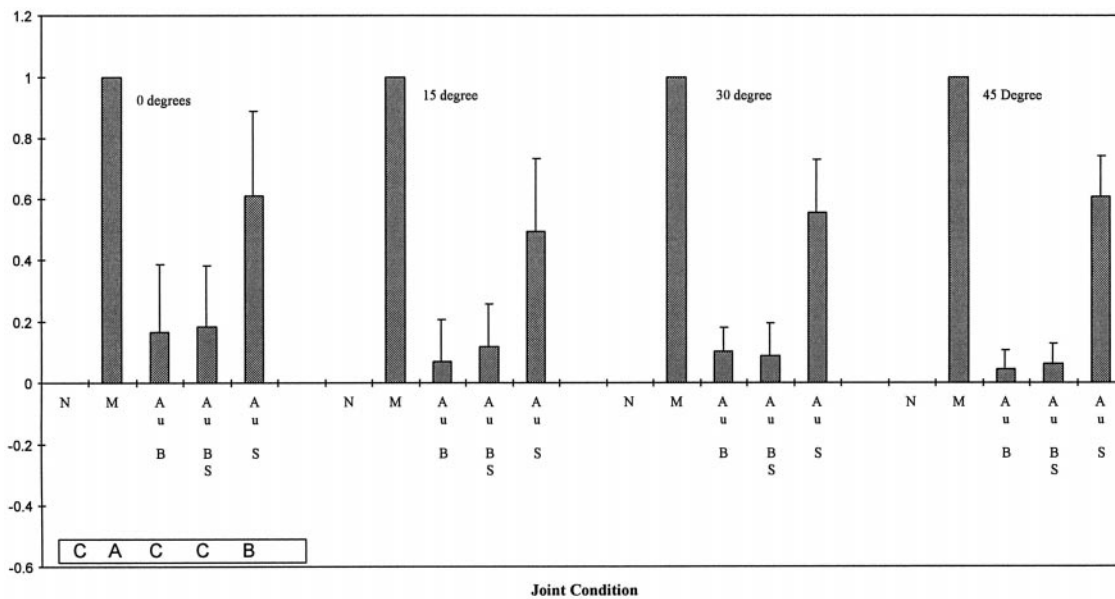
Several issues were considered in the selection of a compressive load for this study. Ideally, the applied compressive load should have been between 1800 and 2000 N (2.5 times body weight) to approximate the load across the knee during walking.<sup>23</sup> Although meniscal allografts from donors less than 48 years of age can tolerate a compressive load of 1800 N,<sup>26</sup> in our study the reinforced bone plugs from the elderly, osteoporotic specimens had a tendency to fail at loads above 1000 N (1.25 times body weight). Even though a load of 1000 N was less than ideal, the conclusions regarding the effectiveness of the three fixation methods are still meaningful because the same load was applied for all knee conditions.

Pressure-sensitive film was chosen as the transducer because it is reliable, provides a high sampling density, and can be easily inserted and removed without disrupting the contact mechanics of the joint; however its use has limitations.<sup>6, 7, 15, 22, 26</sup> A shortcoming of the film is that it is effective only within a certain range of pressure. Pressures lower than the film range will not be detected, which will cause the actual contact area to be underestimated. Pressures that exceed the film range will saturate the film and underestimate the actual maximum pressure. Although the film is rated to measure pressure between the nominal limits of 0.5 to 2.5 MPa, independent calibrations extended this range to 0.5 to 3.75 MPa for the environmental conditions normally present in our laboratory.

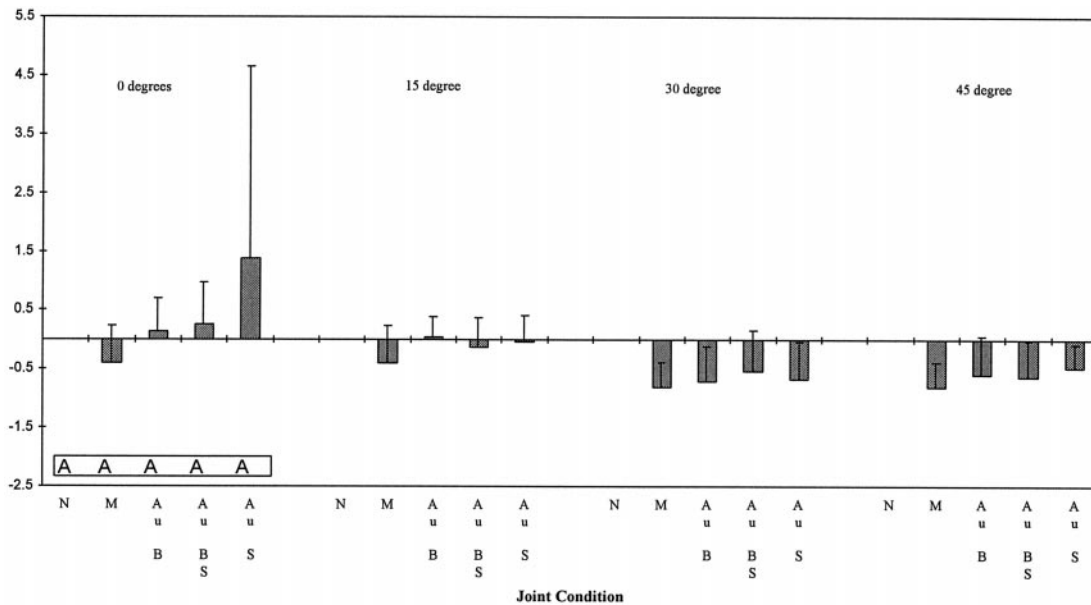
The maximum pressure, mean pressure, contact area,



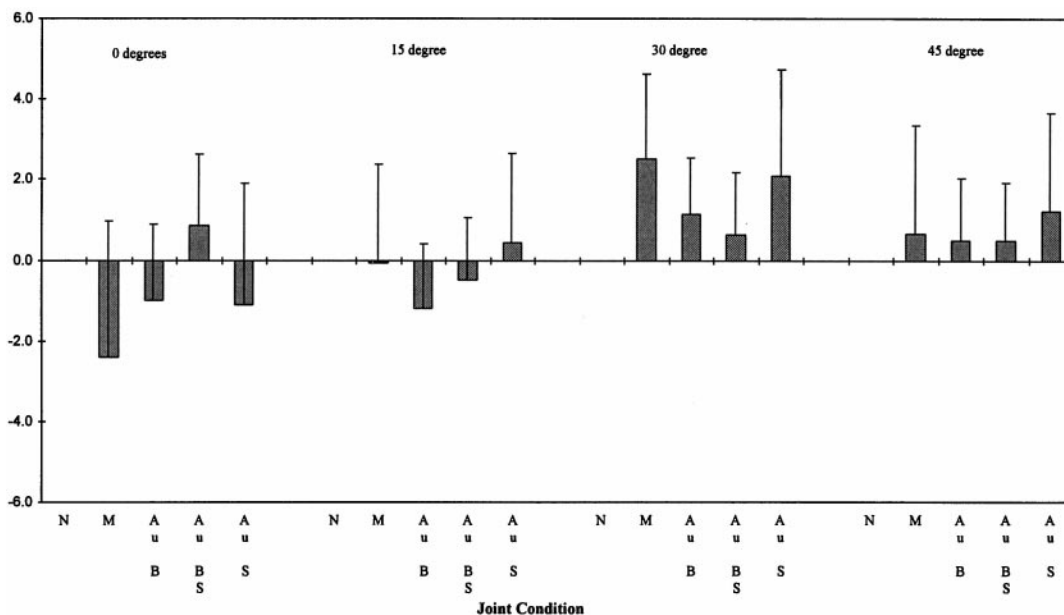
**Figure 1.** The normalized maximum pressure averaged over all of the intact-knee specimens (N) was compared with the normalized maximum pressure averaged over all specimens of 1) the knee after meniscectomy (M), 2) the autograft fixed with bone plugs (AuB), 3) the autograft fixed with bone plugs and peripheral sutures (AuBS), and 4) the autograft fixed with sutures only (AuS) at four flexion angles. Shorter columns indicate a pressure closer to that of the intact knee. Error bars indicate 95% confidence limits. At all flexion angles, there was no significant difference in the normalized maximum pressure between the autograft fixed with either bone plugs (C) or with bone plugs and peripheral sutures (C), but both were significantly greater than the intact knee (D). The normalized maximum pressure for the autograft fixed with sutures (B) was significantly greater than the intact knee (D) and the autograft fixed with either bone plugs (C) or with bone plugs and peripheral sutures (C).



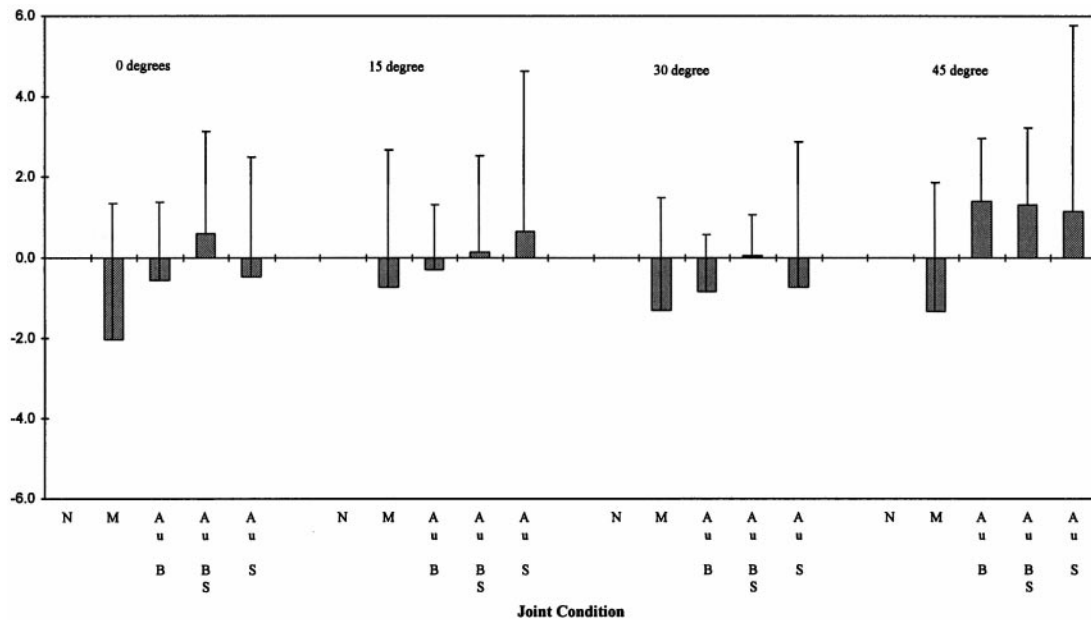
**Figure 2.** The normalized mean pressure averaged over all of the intact knee specimens (N) was compared with the normalized mean pressure averaged over all of the specimens of 1) the knee after meniscectomy (M), 2) the autograft fixed with bone plugs (AuB), 3) the autograft fixed with bone plugs and peripheral sutures (AuBS), and 4) autograft fixed with sutures only (AuS) at four flexion angles. Shorter columns indicate a pressure closer to that of the intact knee. Error bars indicate 95% confidence limits. At all flexion angles, there was no significant difference in the normalized mean pressure between the autograft fixed with either bone plugs (C) or with bone plugs and peripheral sutures (C) and the intact knee (C). The normalized mean pressure for the autograft fixed with sutures (B) was significantly greater than the intact knee (C) and the autograft fixed with either bone plugs (C) or with bone plugs and peripheral sutures (C), but was significantly less than the knee after meniscectomy (A).



**Figure 3.** The normalized contact area averaged over all of the intact-knee specimens (N) was compared with the normalized contact area averaged over all specimens of 1) the knee after meniscectomy (M), 2) the autograft fixed with bone plugs (AuB), 3) the autograft fixed with bone plugs and peripheral sutures (AuBS), and 4) the autograft fixed with sutures only (AuS) at four flexion angles. Shorter columns indicate an area closer to that of the intact knee. Error bars indicate 95% confidence limits. Even though the mean normalized contact area differed considerably between the joint conditions, there was no significant difference in the normalized contact area because of the wide variability in the confidence intervals.



**Figure 4.** The medial (positive values) and lateral (negative values) shift in the center of maximum pressure were averaged over all of the intact-knee specimens (N) and compared with the medial and lateral shift in the center of maximum pressure averaged over all specimens of 1) the knee after meniscectomy (M), 2) the autograft fixed with bone plugs (AuB), 3) the autograft fixed with bone plugs and peripheral sutures (AuBS), and 4) the autograft fixed with sutures only (AuS) at four flexion angles. Shorter columns indicate a location closer to that of the intact knee. Error bars indicate 95% confidence limits. The medial and lateral shifts in the center of maximum pressure were not significantly different between the five joint conditions.



**Figure 5.** The anterior (positive values) and posterior (negative values) shifts in the center of maximum pressure were averaged over all of the intact-knee specimens (N) and compared with the anterior and posterior shifts in the center of maximum pressure averaged over all specimens of 1) the knee after meniscectomy (M), 2) the autograft fixed with bone plugs (AuB), 3) the autograft fixed with bone plugs and peripheral sutures (AuBS), and 4) the autograft fixed with sutures only (AuS) at four flexion angles. Shorter columns indicate a location closer to that of the intact knee. Error bars indicate 95% confidence limits. The anterior and posterior shifts in the center of maximum pressure was not significantly different between the five joint conditions.

and the shift in the location of the center of maximum pressure were evaluated because these contact variables can be measured, and a change from normal may be related to the development of degenerative arthritis. Both the maximum and mean pressures were measured since there is a relationship between increased contact pressure and the development of osteoarthritis.<sup>4</sup> Measurement of the contact area was required to interpret changes in pressure. The measurement of the location of the center of maximum pressure was included because the region of articular cartilage under load may change with a meniscal transplant. Since loaded regions of articular cartilage have a higher proteoglycan content and hence a greater aggregate compression modulus than unloaded cartilage,<sup>3</sup> changes in the location of the center of maximum pressure could cause accelerated articular wear if the cartilage subjected to new loads does not adapt.

In our study, the maximum pressure for the knee after meniscectomy was underestimated in 4 of the 10 specimens because the film was saturated. However, this underestimation did not affect the conclusions of the study. Since the goal of the study was to identify the fixation technique that is most effective at restoring normal contact mechanics at the time of implantation and not whether the contact mechanics for a given fixation method were better than the contact mechanics for the knee after meniscectomy, the conclusions of this study remain valid.

Notwithstanding the underestimation in the maximum pressure for some of the specimens, the maximum pressures measured for the medial tibial articular surface in

this study were similar to those measured by Ahmed and Burke<sup>2</sup> using a plastic microindentation transducer. These authors observed a maximum pressure of 2.0 MPa for the intact knee, and 2.75 MPa for the knee with a medial meniscectomy at a compressive load of 890 N at 30° of flexion. At the same flexion angle and a slightly higher compressive load (1000 N), the present study reported an average maximum pressure of 2.8 MPa for the intact knee and 3.3 MPa for the knee with a medial meniscectomy.

Although the “normal” contact mechanics of a knee from an elderly specimen are likely to be different from the “normal” contact mechanics of a knee from a younger specimen, the use of older specimens (70 years) did not compromise the conclusions of the study. Because the statistical analysis was designed to make comparisons within a knee, each knee served as its own control and the age of the specimen was eliminated as a variable. The two conclusions of the study, that 1) medial meniscal transplantation requires anatomic fixation of bone plugs attached to the anterior and posterior horns to best restore normal contact mechanics and 2) fixation with sutures alone cannot be recommended, were not affected by the age of the specimens.

The purpose of the study was to determine which of three different fixation methods restored contact mechanics closest to normal under physiologic loads using an ideal meniscal transplant (that is, an autograft) and not to determine the durability of the bone plugs. Reinforcement of the fixation was necessary because the compression loads were greater than those expected during the initial

weeks after implantation when the knee is typically immobilized and weightbearing is limited to avoid damage to the bone plugs before biologic bonding occurs. Because only osteoporotic knees were available, the bone plugs were reinforced with a machine screw and polymethyl methacrylate and cemented in the sockets to prevent fragmentation under the 1000-N compressive load required to evaluate the contact mechanics under physiologic conditions.

The cementing of the bone plugs was not analogous to the immediate fixation at the time of implantation. The benefit from cementing the bone plugs was that the contact mechanics could be evaluated without implant failure at physiologic loads. The limitation of cementing the bone plugs was that this fixation differed from the fixation at the time of implantation *in vivo* in which the bone plugs are held less rigidly in sockets with sutures. The contact mechanics resulting from fixing the bone plugs in the sockets by tying sutures over a bridge used at the time of implantation may not be as close to normal as the better-case situation in which the bone plugs are cemented. Although this is possible, it is unlikely as long as the bone plugs fit snugly in the tunnels, because such a fit would inhibit lateral motion of the horns.

#### Clinical Implications

The most important results from this study were that 1) a medial meniscal autograft did not restore contact mechanics to normal, 2) implantation of the autograft with bone plugs resulted in contact mechanics that were significantly closer to normal compared with fixation with sutures alone, and 3) the contact mechanics of the medial tibial articular surface were not improved by suturing the periphery of the meniscus.

Although the method of fixation did affect the contact mechanics at the time of implantation, it is not known whether the initial method of fixation affects the contact mechanics after the meniscal transplant becomes biologically fixed (at 3 to 6 months postoperatively). It could be argued that suture fixation, using the technique described in this study, allows the meniscus to extrude under compression loading because the meniscal horns are not anchored as well as when bone plugs are used. If the suture fixation allows the meniscus to biologically bond in an extruded position, the long-term contact mechanics may be inferior to those after fixation using bone plugs. Further *in vivo* studies are required to determine the importance of the fixation method on the long-term contact mechanics of a meniscal transplant.

Even though the method of fixing the autograft with bone plugs without peripheral sutures is not used clinically, the measurement of the contact mechanics with this fixation technique permitted an evaluation of the respective contributions of the bone plugs and sutures to the contact mechanics. The similarity in contact mechanics between the bone plug fixation with and without peripheral sutures indicated that the contact mechanics were not affected by suturing the periphery of the meniscus. Therefore, anchorage of the meniscal horns was the more im-

portant determinant of the contact mechanics. Efforts to improve contact mechanics should be focused on ensuring anatomic positioning and improvement of the rigidity of the attachment of the meniscal horns.

Because of the extensive peripheral attachments of the meniscus to surrounding tissues of the knee, it was an unexpected finding that the peripheral sutures did not improve the contact mechanics of the transplant fixed with bone plugs. The periphery of the medial meniscus adheres to the joint capsule and is connected to the tibial plateau by the coronary ligament. The function of these various attachments appears to be to constrain the movement of the meniscus when it bears load. Although peripheral sutures were unimportant for restoring contact mechanics from 0° to 45° of flexion at a compressive load of 1000 N, it is possible that the stabilizing effect of sutures could become more important at higher degrees of flexion at which the medial meniscus translates more posteriorly,<sup>14</sup> at higher compressive loads, and under other loads such as internal rotation, for which the medial meniscus provides some restraint.<sup>31</sup>

Although the retention of a 2-mm peripheral meniscal rim to suture the transplant is the technique recommended for meniscal transplantation, the meniscal rim did not prevent extrusion of the meniscal transplant under compressive loads, as evidenced by the poor restoration of contact pressure by fixation with sutures alone. If the peripheral rim were the primary interface preventing extrusion of the meniscus, the restoration of contact mechanics by the autograft should have been just as effective by fixation with sutures alone as by fixation with bone plugs.

Medial meniscal transplants should not be sutured in place without bone plugs. Anchoring the anterior and posterior horns with 2-0 Ethibond sutures through anatomically placed bone tunnels and peripheral sutures does not reestablish the loadbearing function of the meniscus at the time of implantation. A sutured medial meniscal transplant has poorer contact mechanics than those of the intact knee and of the autograft implanted with bone plugs.

The inability of suture fixation to restore normal contact mechanics may have been due to either compliance or relaxation of the sutures (or both) holding the horns of the transplant in place. Either of these conditions would have allowed the horns to separate as a result of the hoop stresses developed under compressive loading. One would intuitively expect that increased separation of the horns would lead to increased contact pressure because of diminished conformity between the meniscus and the medial condyle. Theoretically, the use of multiple sutures in shorter tunnels to anchor the horns of the meniscus instead of a single 2-0 Ethibond suture may increase the stiffness of the fixation and improve the contact mechanics. However, fixation of a medial meniscal transplant with the suture technique used in this study cannot be recommended.

To perform a comprehensive evaluation of contact mechanics, the measurement of the shift in location of the center of maximum pressure was included in this study.



Because of the large variability between specimens, no consistent pattern of migration of the center of maximum pressure from normal was demonstrated either for the autograft with the three fixation methods or for the knee after meniscectomy. However, the shift in the location of the center of pressure of the autograft fixed with bone plugs from the location of the center pressure in the intact knee averaged less than 1.4 mm in the medial/lateral and anterior/posterior directions. It seems unlikely that a shift of this magnitude would relocate the maximum pressure to a relatively unloaded area of cartilage where the higher load may be less well tolerated.

Normal contact mechanics are less likely to be restored consistently in the clinical situation when an allograft is implanted instead of a medial meniscus autograft (that is, an "ideal transplant"). Increased variability in contact mechanics is expected with an allograft because of differences in geometry and material properties compared with the autograft. Current techniques for selecting a medial meniscal allograft do not include matching the shape of the allograft to the original meniscus nor does a method exist for matching material properties. The inability of the autograft to restore normal maximum pressure and the large variability in mean pressure and contact area in knees with meniscal autografts, coupled with the imperfect match between the allograft and original meniscus, suggests that surgeons should not expect a medial meniscal allograft to consistently restore normal contact mechanics at the time of implantation.

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