The Effects of Medial Meniscal Transplantation Techniques on Intra-Articular Contact Pressures

Nikhil N. Verma, MD
Edward Kolb, MD
Brian J. Cole, MD, MBA
Eric Berkson, MD
Ralph Garretson, MD
Jack Farr, MD
Benjamin Fregly, PhD

ABSTRACT: This study aimed to compare medial compartment contact pressures in knees treated with medial meniscal transplantation using either a bone plug or bone trough technique. Peak pressure, mean pressure, and contact area of the medial compartment were determined in 8 cadaveric specimens at 0° and 30° of flexion under a 1000-N load. Contact mechanics were measured for the intact knee, after meniscectomy, and after medial meniscal transplant with either a bone plug technique or a bone trough technique. Total medial meniscectomy resulted in decreased contact area, increased medial contact pressure, and increased medial peak contact pressure. When comparing meniscal transplant techniques at both 0° and 30°, no significant difference (*P*<0.05) was noted regarding contact mechanics after transplantation. The bone trough technique shows similar contact mechanics to the double bone plug technique and maintains the natural hoop stress of the meniscus during medial meniscal transplantation.

[*J Knee Surg*. 2008;21:20-26.]

INTRODUCTION

The importance of the meniscus in normal knee function has been well documented. Most importantly, the meniscus decreases tibiofemoral contact area and contact pressure, thereby functioning in a chondroprotective role. In 1948, Fairbank[12] described radiographic changes including flattening of the femoral condyles as well as joint space narrowing in knees after total meniscectomy. Since then, numerous studies have shown the increased propensity toward early osteoarthritis after total meniscectomy.[4,11,19,20,22,24] Johnson et al[19] reported on 440 patients followed for a mean of 17.5 years; at final follow-up, 74% of meniscectomized knees had at least one Fairbank change, compared with 6% on the contralateral knee. Osteoarthritis was diagnosed in 40% of the meniscectomized knees, compared with 6% in the contralateral knees.

In an attempt to change this natural history, meniscal transplantation was first described by Locht et al[23] in 1984 and has gained popularity over the past decade. The initial transplant described by Locht et al involved replacement of a portion of the tibial plateau with the attached meniscus. Various meniscal transplantation techniques have since been described, including suture technique without bone transplantation, double bone plug technique, and a bone trough and its variant key hole technique.[9,14,30] The current trend is to transplant with attached bone at the meniscal horn sites, as recent studies have shown that load transmission is superior when the meniscal graft is secured with bone.[2,10,25]

Two popular techniques currently used to maintain the bony attachments of the meniscus include a double

---

Drs Verma and Cole are from Rush University Medical Center, Chicago, and Dr Kolb is from Orthopedic and Sports Medicine Center, Bloomington, Ill; Dr Berkson is from Massachusetts General Hospital, Boston, Mass; Dr Garretson is from Blue Ridge Orthopedic Associates, Warrenton, Va; Dr Farr is from OrthoIndy Knee Care Institute, Indianapolis, Ind; and Dr Fregly is from the University of Florida, Gainesville, Fla.

Correspondence: Nikhil N. Verma, MD, Midwest Orthopedics at Rush, Rush University Medical Center, 1725 W Harrison, Ste 1063, Chicago, IL 60612.

Figure 1. K-scan thin film pressure transducer used to measure contact forces across the medial compartment.

bone plug technique or bone bridge (using a keyhole or bone trough) technique. Initially, the bone trough technique was recommended on the lateral side where the meniscal horns were in close proximity, whereas the double bone plug technique was employed on the medial side.[27] However, the bone bridge technique may have theoretical advantages over the double bone plug technique for both lateral and medial transplantation. First, the anatomic relationship of the anterior and posterior meniscal horns are maintained using a bone bridge, which in turn maintains the natural hoop stress property of the meniscus. The adverse effects of posterior horn tunnel misplacement of 5 mm either medially or posteriorly have recently been demonstrated by Sekaran et al.[29] Second, from a technical standpoint, the slot technique eliminates problems with tunnel convergence, which can be particularly problematic in cases with concomitant ligament reconstruction or osteotomy. To date, we are not aware of any biomechanical data comparing the effect of these two medial meniscal transplant techniques on contact mechanics across the knee. One study has specifically reviewed changes in contact mechanics using various transplant techniques for lateral meniscal transplantation.[10] In that study, no significant differences were noted between bone plug and the bone bridge technique.

The purpose of this study was to directly compare the double bone plug transplantation technique with the bone bridge transplantation technique for medial meniscal transplantation. We hypothesized that no significant difference in the contact mechanics across the knee would be found between these two techniques.

MATERIALS AND METHODS

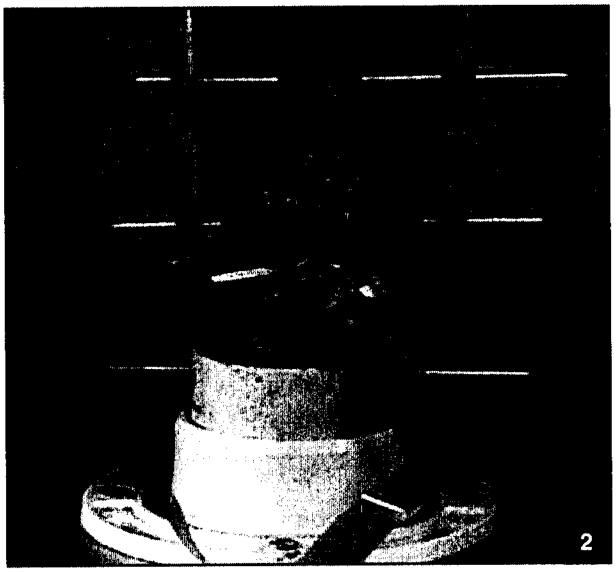

Figure 2. Sample specimen loaded in the Instron machine, with a K-scan sensor within the knee joint.

Eight fresh-frozen cadaveric knees were obtained for testing. All knees were evaluated prior to testing with anteroposterior and lateral radiographs. No specimen had radiographic evidence of early osteoarthritis or any prior surgery. The knees were cut so that approximately 10 cm of tibia and femur above and below the joint line remained. The skin, subcutaneous tissue, fat, muscle, and patella were removed leaving the cruciate and collateral ligaments intact. Limited removal of the joint capsule was necessary to provide access to the medial compartment, although the meniscal attachment to the tibial was preserved in the intact specimen. The femur and tibia were then cemented into 4-inch pieces of polyvinyl chloride pipe. Two parallel tunnels were placed in both the femur and tibia to allow pin insertion for rotational control. The rotational pins provided a reference point for specimen position and allowed easy removal and reproducible replacement of the specimens into the Instron machine (Instron Corp, Canton, Mass).

K-scan 4000 sensors (Tekscan Inc, South Boston, Mass) were used to measure contact pressure and contact area in both the medial and lateral compartments (Figure 1). The K-scan system is composed of a thin-film sensor (pressure transducer) and an interface box and software that produces digitized, real-time recordable data. The knee specimens were prepared by placing the sensors into the medial compartment under the respective meniscus through a limited anterior and posterior arthrotomy. The sensors were secured to the surrounding capsule using an ethibond suture placed through a rim of cloth tape on the periphery of the sensor. The meniscus of the transplanted specimens were not sutured to the periphery. Peripheral suture neither improved nor worsened the contact mechanics across the knee.[2]

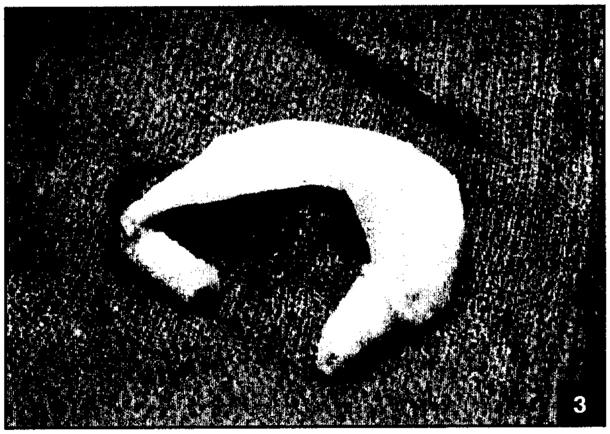

Figure 3. Sample medial meniscal allograft prepared for implantation using double bone plug technique.

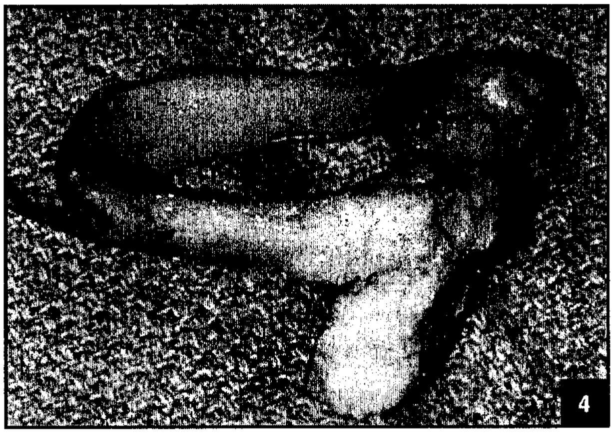

Figure 4. Sample medial meniscal allograft prepared for implantation using bone trough technique.

The specimens were then mounted in an Instron 1321 (Instron Corp) materials testing device (Figure 2). The position of the femur fixture to the applied load was measured using digital calipers to ensure reproducible positioning of the specimens for subsequent tests. The sensor was conditioned by subjecting it to 3 cycles of axial loading from 0 to 2800 N. It was then calibrated at 700 and 2100 N, generating a 2-point calibration curve specific for each knee and sensor combination. The K-scan sensors in our study had an effective stress range from 0.5 to 30 MPa. A load of 1000 N was applied over 5 seconds in positions of full extension and 30° of flexion. The selection of load magnitude was based on previous studies.[2,3] Due to limitations in the testing apparatus, higher degrees of knee flexion could not be tested.

The contact mechanics were tested under various conditions: with the meniscus intact, after meniscectomy, and after meniscal transplant. The specimens were first tested in the intact state for a baseline measurement of the contact pressure and area across the knee. Then the specimens underwent meniscectomy, with the goal of preserving the meniscus for reimplantation later during the study. The meniscectomy was performed preserving two bone plugs for four specimens and a bone bridge in the remaining four specimens. Bone plugs were preserved by passing a guidewire through the anteromedial tibial border and into the anterior and posterior horns of the meniscus using a guidewire. A cannulated coring reaming was then used to remove a plug of bone with the meniscal horn attached. The trough specimens were obtained using an osteotome and saw as needed to remove the meniscus with an associated 7-mm to 8-mm×1-cm bone bridge incorporating both meniscal horns. Given the possibility of graft mismatch, preserving the native meniscus for reimplantation allowed us to assure that the transplanted meniscus was appropriately sized for the knee.

After testing on the meniscectomized knees was completed, a medial meniscal transplant (reimplantation) was performed using a double bone plug (Figure 3) technique in four specimens and a bone trough technique (Figure 4) in the other four specimens. For the bone plug technique, the meniscus was secured with sutures tied over a button on the anterior tibia. For the bone trough technique, the bone bridge was secured within the trough using a biointerference screw placed on the lateral or intercondylar notch side of the bone bridge. Loading cycles were then repeated in both 0° and 30° of flexion.

Each trial was self-calibrated using a 2-point calibration system, calibrating at 200 N and 1000 N. This approach eliminated the significant drift problem present in K-scan sensors. Missing rows or columns of data were interpolated from the adjacent rows or columns. Each stress value was averaged with its adjacent cell to adjust for erroneous stress peaks caused by sensor kinking. A low-end cutoff stress value of 0.05 MPa was used to compensate for the sensitivity of the sensors to any kind of noise, including sensor kinking. The 0.05-MPa cutoff had little effect on the forces and peak stresses across the knee joint.

Contact mechanics across the knee joint under the various loading conditions were recorded. Contact area, mean contact stress, and peak contact stress were compared for each specimen with the intact meniscus, after meniscectomy, and after meniscal transplant. The contact area was defined as the area under the sensor when a 0.05-MPa threshold stress cutoff value was used.

Prior to the conclusion of the study, a power analysis was performed using the calculated standard deviations for each measurement of pressure and surface area reading taken from the trials. A 10% difference

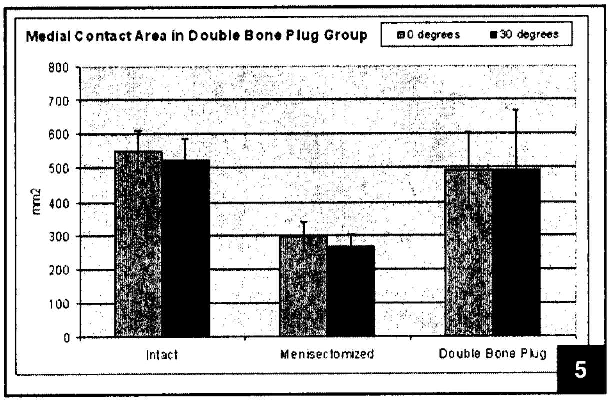

Figure 5. Medial contact area in intact, post-meniscectomy, and transplant specimens for the double bone plug group.

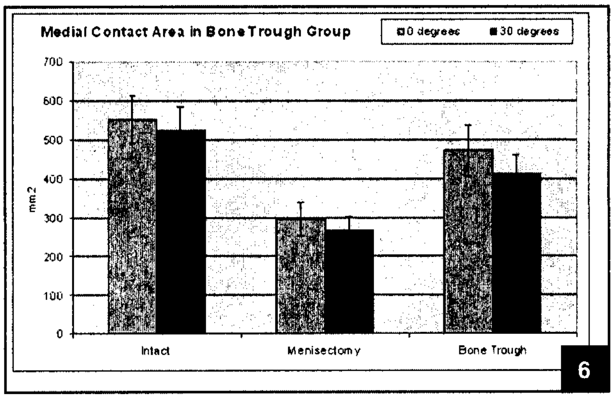

Figure 6. Medial contact area in intact, post-meniscectomy, and transplant specimens for the bone trough group.

between areas and pressures was assumed to be clinically significant. Using a P value <0.05, this power analysis determined an 80% chance of detecting a 10% difference between meniscal transplant techniques with 2N=8.

Statistical analysis was performed using SYSTAT (version 10 for Windows; Systat Software Inc, San Jose, Calif). A repeated measures analysis of variance was used to analyze differences between intact meniscus, meniscectomy, and transplanted menisci. For significant results, a post hoc test was performed using a Bonferoni correction. Differences between individual parameters and between bone plug and bone trough samples were analyzed using a two-tailed paired t test. Percent changes between meniscal states were calculated by averaging the percent change within each specimen. When possible, 95% confidence intervals were calculated for each evaluation.

RESULTS

A total of 144 load transmissions were recorded using the K-scan device. Eight specimens were included in the analysis, four in the bone plug group and four in the bone trough group. Data was recorded and reviewed focusing on three variables: medial contact area, mean medial contact pressure, and peak medial contact pressure.

Medial Contact Area

The mean medial contact area for the intact knee using all eight specimens at 0° and 30° of knee flexion were 551.7±60.7 mm^2 and 521.6±62.4 mm^2, respectively. After meniscectomy, mean contact area at 0° and 30° decreased to 295.9±42 mm^2 and 267.8±35.2 mm^2, respectively. This resulted in a mean 46% (±7%) decrease in contact area among all eight specimens.

After meniscal transplant, significant increases in contact areas in both the double bone plug and bone bridge group were noted. In the double bone plug group, the mean medial contact area of the intact specimen was 549.6±119 mm^2 at 0° and 534.2±82.1 mm^2 at 30° of knee flexion. In the same specimens, meniscectomy resulted in a decrease in mean contact area to 241.2±53.2 mm^2 at 0° of knee flexion and 255.6±51.3 mm^2 at 30° of knee flexion. After meniscal transplantation with the double bone plug technique, mean contact area increased to 494.3±108.1 mm^2 at 0° of knee flexion and 492.2±49.8 mm^2 at 30° of knee flexion (Figure 5).

In the bone bridge group, the mean contact area of intact specimens was 529.08±119.4 mm^2 at 0° of knee flexion and 504.4±93.1 mm^2 at 30° of knee flexion with the intact meniscus. After meniscectomy, mean contact area decreased to 342.33±53.2 mm^2 at 0° of knee flexion and 262.7±49.8 mm^2 at 30° of knee flexion. These values increased to 471.83±65.3 mm^2 at 0° of knee flexion and 411±52.3 mm^2 at 30° of knee flexion after transplantation (Figure 6).

There was a statistically significant difference in mean contact area between the intact and meniscectomized groups (P=0.001) and between meniscectomized and transplanted groups (P =0.005) for both techniques at both 0° and 30° of flexion. No significant difference was noted between transplanted and intact samples for either group (P=0.497).

No statistically significant difference in medial contact area was noted between the double bone plug and bone bridge group at 0° (P=0.740) or 30° (P= 0.712) of knee flexion.

Medial Contact Stress

The mean medial contact stress for all eight specimens with the meniscus intact was 1.30±0.2 MPa, increasing to

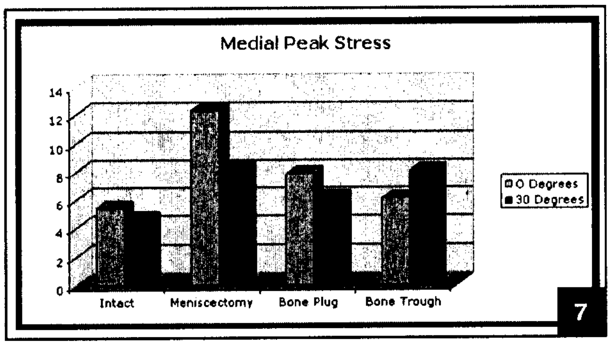

Figure 7. Medial compartment stress and medial peak stress in intact, post-meniscectomy, bone trough specimens.

2.57±0.6 MPa after meniscectomy at 0° of flexion. This resulted in a mean 43% (±8%) increase in medial contact stress among specimens.

For the bone plug group, the mean medial contact stress increased from 1.29±0.30 MPa to 3.40±0.48 MPa at 0° after menisectomy. After meniscal transplantation the mean medial contact stress improved to 1.46±0.40 MPa. In the bone trough group, the mean medial contact stress increased from 1.37±0.30 MPa to 1.99±0.48 MPa at 0° of knee flexion after menisectomy. After meniscal transplantation, the medial contact stress decreased to 1.29±0.20 MPa. Similar results were noted at 30° of knee flexion (Figure 6). A statistically significant difference in medial contact stress between intact and meniscectomized knees (P=0.000) and between meniscectomized and transplanted knees (P=0.001) was found at both 0° and 30° of flexion. No significant difference was noted between transplanted and intact knees (P=0.683). No statistically significant difference was noted between the double bone plug and bone bridge group at 0° (P=0.442) or 30° (P=0.884).

Medial Peak Stress

The mean medial peak stress of the intact meniscus was 5.06±0.90 MPa, increasing to 8.78±2.5 MPa after meniscectomy at 0° for all eight specimens. This resulted in a mean 33% (±13%) increase in medial peak stress.

In the double bone plug group, the medial peak stress increased from 5.41±1.77 MPa to 12.27±2.88 MPa at 0° after meniscectomy. After meniscal transplantation, the medial peak stress improved to 7.83±2.16 MPa. In the bone trough group, the medial peak stress increased from 4.95±1.76 MPa to 6.05±2.87 MPa after meniscectomy at 0°. After meniscal transplantation, the medial peak stress decreased to 6.12±2.13 MPa. Again, similar changes were noted at 30° of knee flexion (Figure 7). No statistically significant differences were noted in the medial peak stress at 0° and 30°.

A statistically significant difference in medial peak stress was found between intact and meniscectomized knees (P=0.034). No significant difference was noted between transplanted and intact knees (P=0.317). No statistically significant difference in medial peak stress was noted between the double bone plug and bone bridge group at 0° (P=0.219) or 30° (P=0.303).

DISCUSSION

Although previous studies have examined the contact mechanics of the medial and lateral compartments of the knee, few studies have examined changes occurring after medial meniscal transplant.* To our knowledge, this is the first study to examine the changes in contact mechanics of the knee in relation to the medial meniscal transplant technique. Various techniques are available to measure pressures across the knee joint.[1,5,13,15] Our study used K-scan sensors (TekScan, Inc), shown by Harris et al[15] to be more reliable and reproducible than Fuji film, allowing us to attain computerized real-time data via the thin film pressure transducer. This technique has been used previously as a method of assessing contact pressure mechanics within knee compartments.

Previous studies have demonstrated the alternation in mean and peak stresses, as well as decreased contact area after meniscectomy.† Our study confirms this result. Total medial meniscectomy resulted in a 46% (±7%) decrease in contact area, a 43% (±8%) increase in medial contact pressure, and a 33% (±13%) increase in medial peak contact pressure. These results were statistically significant and were within the range of those reported by other studies of the medial compartment after meniscectomy.[3,10,25,29] The different shape and joint contour between the medial and lateral compartment is well known and results in compartment-specific changes after meniscectomy. It is imperative, when comparing contact mechanics before and after meniscectomy and among studies, to isolate a single compartment because of the anatomic variation between the two compartments.

Various meniscal transplantation techniques have been described, including suture-only techniques, double bone plug technique, and bone trough or its variant, the keyhole technique. Each of these techniques offers differences in the fixation of the allograft. Studies of biomechanical effects of various meniscal transplant techniques reveal the importance of secure fixation of the meniscal horns, and currently, some form of bone fixation of the meniscal horns is recommended.[2,10]

---

*2, 3, 5-8, *10, 13, 16, 17, 21, 25, 28, 29, 31, 32*

†*2, 3, 5, 7, 10, 18, 24, 26, 29, 31*

Our study examined the contact mechanics of two different meniscal transplant techniques: the bone plug and the bone bridge. The bone bridge technique has been used historically for lateral compartment allograft meniscal replacement due to the proximity of the horns. Although some theoretical advantage may be received by maintaining the anatomic placement sites of the meniscus through a bone bridge transplantation technique, this study demonstrated no statistically significant difference in medial contact area, mean contact stress, and peak stress on the medial side. In both cases, the medial meniscus autograft transplant using either technique restored biomechanical contact pressures and medial contact area to those measurements in an intact meniscus. A more significant disadvantage of the double bone plug technique may have been noted if the tunnels had been placed independently of meniscal harvest. This may have resulted in abnormalities in meniscal horn placement which may have altered hoop stress distribution and load transmission.

In our experience, we have found that there are some clinical advantages in using a trough technique. This technique allows maintenance of an anatomic relationship of the meniscal horns. It has been shown that small changes in meniscal horn placement can results in decreased pressure distribution.[29] From a technical standpoint, the trough technique eliminates the difficulty in obtaining anatomic placement of the posterior horn tunnel and of posterior horn bone plug passage. In addition, the use of a trough technique eliminates problems with tunnel convergence. This can be particularly helpful when performing concomitant ligament reconstruction or osteotomy.

CONCLUSION

Medial meniscus transplantation using a bone trough techniques results in similar improvements in contact area, mean contact stress, and peak contact stress, compared with a double bone plug technique. Currently, we use the trough technique for all meniscal transplantation in both lateral and medial compartments.

REFERENCES

1. Ahmed AM, Burke DL. In-vitro measurement of static pressure distribution in synovial joints. Part I: Tibial surface of the knee. *J Biomech Eng.* 1983;105:216-225.
2. Alhalki MM, Howell SM, Hull ML. How three methods for fixing the medial mensicus autograft affect tibial contact mechanics. *Am J Sports Med.* 1999;27:320-328.
3. Alhalki MM, Hull ML, Howell SM. Contact mechanics of the medial tibial plateau after implantation of a medial meniscal allograft. A human cadaveric study. *Am J Sports Med.* 2000;28:370-376.
4. Allen PR, Denham RA, Swan AV. Late degenerative changes after meniscectomy. Factors affecting the knee after operation. *J Bone Joint Surg Br.* 1984;66:666-671.
5. Baratz ME, Fu FH, Mengato R. Meniscal tears: The effect of meniscectomy and of repair on intraarticular contact areas and stress in the human knee. A preliminary report. *Am J Sports Med.* 1986;14:270-275.
6. Brown TD, Shaw DT. In vitro contact stress distribution on the femoral condyles. *J Orthop Res.* 1984;2:190-199.
7. Bourne RB, Finlay JB, Papadopoulos P, Andreae P. The effect of medial meniscectomy on strain distribution in the proximal part of the tibia. *J Bone Joint Surg Am.* 1984;66:1431-1437.
8. Bylski-Austrow DI, Malumed J, Meade T, Grood ES. Knee joint contact pressure decreases after chronic meniscectomy relative to the acutely meniscectomized joint: A mechanical study in the goat. *J Orthop Res.* 1993;11:796-804.
9. Cameron JC, Saha S. Meniscal allograft transplantation for unicompartmental arthritis of the knee. *Clin Orthop.* 1997;337:164-171.
10. Chen MI, Branch TP, Hutton WC. Is it important to secure the horns during lateral meniscal transplantation? A cadaveric study. *J Arthroscopic Rel Surg.* 1996;12:174-181.
11. Dandy DJ, Jackson RW. The diagnosis of problems after meniscectomy. *J Bone Joint Surg Br.* 1975;57:349-352.
12. Fairbank TJ. Knee joint changes after meniscectomy. *J Bone Joint Surg Br.* 1948;30:664-670.
13. Fukubayashi T, Kurosawa H. The contact area and pressure distribution pattern of the knee. A study of normal and osteoarthritic knee joints. *Acta Orthop Scand.* 1980;51:871-879.
14. Garrett JC, Stevensen RN. Meniscal transplantation in the human knee: A preliminary report. *Arthroscopy.* 1991;7:57-62.
15. Harris ML, Morberg P, Bruce WJ, Walsh WR. An improved method for measuring tibiofemoral contact areas in total knee arthroplasty: A comparison of K-scan sensor and Fuji film. *J Biomech.* 1999;32:951-958.
16. Haut Donahue TL, Hull ML, Rahid MM, Jacobs CR. How the stiffness of meniscal attachments and meniscal material properties affect tibio-femoral contact pressure computed using a validated finite element model of the human knee joint. *J Biomech.* 2003;36:19-34.
17. Huang A, Hull ML, Howell SM. The level of compressive load affects conclusions from statistical analyses to determine whether a lateral meniscal autograft restores tibial contact pressure to normal: A study in human cadavaric knees. *J Orthop Res.* 2003;21:459-464.
18. Ihn JC, Kim SJ, Park IH. In vitro study of contact area and pressure distribution in the human knee after partial and total meniscectomy. *International Orthopedics.* 1993;17:214-218.
19. Johnson RJ, Kettelkamp DB, Clark W, Leaverton P. Factors effecting late results after meniscectomy. *J Bone Joint Surg Am.* 1974;56:719-729.
20. Jorgensen U, Sonne-Holm S, Lauridsen F, Rosenklint A. Long-term follow-up of meniscectomy in athletes. A prospective longitudinal study. *J Bone Joint Surg Br.* 1987;69:80-83.
21. Kettlekamp DB, Jacobs AW. Tibiofemoral contact area: Determination and implications. *J Bone Joint Surg Am.* 1972;54:349-356.
22. Krause WR, Pope MH, Johnson RJ, et al. Mechanical changes in the knee after meniscectomy. *J Bone Joint Surg Am.* 1976;58:599-604.
23. Locht RC, Gross AE, Langer F. Late osteochondral allograft resurfacing for tibial plateau fractures. *J Bone*

Joint Surg Am. 1984;66:328-335.

24. McKinley TO, English DK, Bay BK. Trabecular bone strain changes resulting from partial and complete meniscectomy. *Clin Orthop.* 2003;407:259-267.
25. Paletta, GA Jr, Manning, T, Snell E, Parker R, Bergfeld J. The effect of allograft meniscal replacement on intraarticular contact area and pressures in the human knee. A biomechanical study. *Am J Sports Med.* 1997;25:692-698.
26. Radin EL, de Lamotte F, Maquet P. Role of the menisci in the distribution of stress in the knee. *Clin Orthop.* 1984;185:290-294.
27. Rath E, Richmond JC, Yassir W, Albright JD, Gundogan F. Meniscal allograft transplantation. Two- to eight-year results. *Am J Sports Med.* 2001;29:410-414.
28. Seedhom BB. Transmission of the load in the knee joint with special reference to the role of the menisci: Part I. *Eng Med.* 1979;8:220-228.
29. Sekaran SV, Hull ML, Howell SM. Nonanatomic location of the posterior horn of a medial meniscal autograft implanted in a cadaveric knee adversely affects the pressure distribution on the tibial plateau. *Am J Sports Med.* 2002;30:74-82.
30. van Arkel ER, deBoer HH. Human meniscal transplantation. *J Bone Joint Surg Br.* 1995;77:589-595.
31. Walker PS, Erkman MJ. The role of the menisci in force transmission across the knee. *Clin Orthop.* 1975;109:184-192.
32. Walker PS, Hajek JV. The load-bearing area in the knee joint. *J Biomech.* 1972;5:581-589.