ORIGINAL RESEARCH

Load-Bearing at the Meniscofemoral Joint: An *in vitro* Study in the Canine Knee

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ABSTRACT

Background: The role of the menisci on tibial load transmission and stress distribution has been extensively studied, but few studies have focused on the meniscofemoral joint during physiologic weightbearing. The objective of this study was to determine the contact areas and local contact stresses at the meniscofemoral interface during physiologic range of motion and axial-loading in the canine knee and to determine the influence of a partial or total meniscectomy.

Methods: Both fresh-frozen knees of 3 hound-type canines were tested in a universal testing machine configured for an axial-load of 90-120 N. Measurement of the contact area and the local contact stress were done at three different knee angles (30; 50; 70) and with both menisci intact, after partial meniscectomy, and after total meniscectomy. Pressure distribution was estimated by using pressure sensitive film inserted above the menisci.

Results: After partial meniscectomy, contact areas at 50° of knee flexion decreased approximately 25% on both femoral condyles, and local contact stress increased 30% on the medial femoral condyle but remained unchanged on the lateral. After total meniscectomy, contact areas at 50° of knee flexion decreased approximately 75% on both femoral condyles, and local contact stress increased approximately 60% on the medial compartment and 100% on the lateral compartment.

Conclusions: These data suggest that a conservative partial meniscectomy leaves the meniscus with an inferior weight distribution function; decreasing, but not canceling the protection on the femoral hyaline cartilage. A dramatic decrease of contact area followed by an increase of local contact stress was noted after a total meniscectomy. The clinical value of this study is to emphasize the biomechanical value of surgical procedures addressing the repair of damaged menisci.

Keywords: Meniscus, Load-bearing, Meniscofemoral, Stress.

INTRODUCTION

The role of the meniscus on preservation of contact stresses in the knee joint has been a subject of debate. Following King's[1] and Fairbank's[2] observations, various techniques have been used to demonstrate the extent to which the meniscus bears weight. Several studies utilizing direct measurements[3-5] showed that the meniscus helps transmit and distribute load over the tibial plateau by increasing the area of contact through which this load is transmitted. The effect of a partial or total meniscectomy on the tibial plateau cartilage has been reported as a decrease in contact area and as an increase in local contact stresses[6] thereby leading to degenerative changes. There has been little work on the influence of the menisci on femoral stress distribution, especially at physiologic loads.

The purpose of this *in vitro* study was to estimate and predict the stress distribution and contact areas at the meniscofemoral joint in the canine knee. The authors hypothesized that an intact or partially removed meniscus bears the vast majority of the body weight during physiologic gait, protecting the femoral condyles from excessive concentration of local stresses. In addition, the authors hypothesized that a total meniscectomy could have devastating effects on the cartilage covering the femoral condyles as shown on the tibial plateau cartilage.[3,7-10] The ultimate goal of this study was to predict stress distribution at the meniscofemoral joint in order to test the applicability of using a biologic scaffold to treat traumatic osteochondral defects on the femoral condyles.

MATERIALS AND METHODS

Both fresh-frozen knees of three mature, randomly selected hound-type canines of 16 to 24 kg body weight underwent biomechanical evaluation. Both hind limbs were disarticulated at the hip joint. All of the soft tissues were dissected from the femur and tibia leaving the extensor mechanism, cranial and caudal cruciate ligaments intact. Each joint was wrapped with gauze and wetted with normal saline to prevent the soft tissues from drying. Femur, tibia and fibula were transected 10 cm above the joint line, transfixed with Steinmann pins and mounted

in a cylindrical sleeve with blocks of epoxy resin. Each specimen was secured between the two jigs of a universal testing machine (MTS 810, MTS Systems Corporation, MN). A tension spring was attached to the quadricipital tendon and a 3 N force was applied to simulate the stabilizing function of the extensor mechanism. The test machine was configured for an axial-load of 90-120 N (9-12 kg), applied over a 6-second cycle. Each specimen was tested in the dog's orthostatic position (50°), hyperextension (30°) and flexion (70°). Load-deflection patterns were monitored to assure uniform loading by a computer-based data acquisition system (Labview 501, National Instruments, TX). Throughout the experiment, the tissues were frequently sprayed with saline to prevent drying out.

Measurement of the contact area (CA) and the local contact stresses (LCS) in the joint was performed in three different situations: With both menisci intact, after bilateral partial meniscectomies with removal of half of the posterior horn (approximately 15% of the total area) and after bilateral total meniscectomies. Following the axial-loading test, the pressure distribution was estimated using pressure sensitive film with a sensitivity of 5-25 kgf/cm^2 (Pressurex SuperLow, Sensor Products Inc., NJ) inserted above the menisci through two 8 mm incisions made in the anteromedial and posteromedial joint capsule through the coronary ligament. To keep the film dry while using it in a fully lubricated synovial joint, the two film sheets were sealed between two 0.05 mm thick polyethylene sheets to make up a 'film packet'.[7,11] Knees were loaded, the film was removed, and the resultant pressure patterns on the film were recorded using a densitometer (ImageJ 1.29X, National Institute of Health, MD). The densitometer is precalibrated to convert color intensity to stress in mega pascals (MPa). By measuring the peak intensity on each distribution, the authors receive an estimate of LCS. Weight tracings of the pressure pattern and applying a weight per unit area conversion estimated the contact areas. Statistical analysis was done using the ANOVA test. Statistical significance was set as $p < 0.05$.

RESULTS

Medial meniscus at 50° (Fig. 1): The average CA decreased from 2.1 cm^2 in the intact knee (range, 1.2 to 2.8 cm^2) to 1.6 cm^2 after partial meniscectomy (range, 0.9 to 2.2 cm^2), and to 0.5 cm^2 after total meniscectomy (range, 0.2 to 0.7 cm^2) ($p = 0.002$). The average LCS increased from 1.3 MPa in the intact knee (range, 0.9 to 1.5 MPa) to 1.7 MPa after partial meniscectomy (range, 1.3 to 2.7 MPa), and to 2.1 MPa after total meniscectomy (range, 0.9 to 3.0 MPa) ($p = 0.296$). The average peak LCS increased from 2.2 MPa (range, 1.5 to 3.0 MPa) in the intact knee to 2.7 MPa (range, 1.6 to 3.9 MPa) after partial meniscectomy, and to 2.8 MPa (range, 1.5 to 4.0 MPa) after total meniscectomy ($p = 0.241$).

Medial meniscus at 30° (Fig. 2): The average CA decreased from 1.7 cm^2 in the intact knee (range, 0.8 to 2.4 cm^2) to 1.3 cm^2 after partial meniscectomy (range, 0.7 to 2.0 cm^2) and to 0.4 cm^2 after total meniscectomy (range, 0.2 to 0.7 cm^2) ($p = 0.002$). The average LCS increased from 1.2 MPa in the intact knee (range, 0.6 to 1.4 MPa) to 1.5 MPa after partial meniscectomy (range, 0.7 to 2.1 MPa) and to 2.5 MPa after total meniscectomy (range, 0.9 to 3.4 MPa) ($p = 0.046$). The average peak LCS increased from 2.1 MPa (range, 1.6 to 2.6 MPa) in the intact knee to 2.3 MPa after partial meniscectomy (range, 1.5 to 3.4 MPa) and to 3.1 MPa (range, 1.8 to 4.1 MPa) after total meniscectomy ($p = 0.087$).

Medial meniscus at 70° (Fig. 3): The average CA decreased from 2.4 cm^2 in the intact knee (range, 1.9 to 3.0 cm^2) to 1.7 cm^2 after partial meniscectomy (range, 1.2 to 2.4 cm^2) and to 0.5 cm^2 after total meniscectomy (range, 0.1 to 0.7 cm^2) ($p = 0.001$). The average LCS remained at 1.7 MPa in the intact knee (range, 1.1 to 2.4 MPa) and after partial meniscectomy (range, 1.1 to 2.7 MPa) but increased to 2.3 MPa after total meniscectomy (range, 0.8 to 3.4 MPa) ($p = 0.692$). The average peak LCS remained at 2.8 MPa in the intact knee (range, 1.7 to 4.1 MPa) and after partial meniscectomy (range, 2.3 to 4.1 MPa) but increased to 2.9 MPa (range, 1.4 to 4.0 MPa) after total meniscectomy ($p = 0.884$).

Lateral meniscus at 50° (Fig. 1): The average CA decreased from 3.3 cm^2 in the intact knee (range, 2.2 to 4.3 cm^2) to 2.4 cm^2 after partial meniscectomy (range, 1.9 to 3.0 cm^2) and to 0.7 cm^2 after total meniscectomy (range, 0.5 to 0.8 cm^2) ($p = 0.002$). The average LCS remained at 1.5 MPa in the intact knee (range, 0.9 to 2.1 MPa) and after partial meniscectomy (range, 1.0 to 2.0 MPa), but increased to 2.9 MPa after total meniscectomy (range, 1.9 to 3.8 MPa) ($p = 0.008$). The average peak LCS remained at 2.8 MPa in the intact knee (range, 1.8 to 3.2 MPa) and after partial meniscectomy (range, 2.2 to 3.3 MPa), but increased to 3.8 MPa (range, 3.0 to 4.6 MPa) after total meniscectomy ($p = 0.014$).

Lateral meniscus at 30° (Fig. 2): The average CA decreased from 3.0 cm^2 in the intact knee (range, 2.6 to 3.9 cm^2) to 2.3 cm^2 after partial meniscectomy (range, 1.8 to 3.3 cm^2) and to 0.5 cm^2 after total meniscectomy (range, 0.2 to 0.8 cm^2) ($p < 0.001$). The average LCS remained at 1.3 MPa in the intact knee (range, 0.7 to 2.0 MPa) and after partial meniscectomy (range, 0.8 to 1.7 MPa), but increased to 2.4 MPa after total meniscectomy (range, 0.7 to 3.7 MPa) ($p = 0.473$). The average peak LCS decreased from 2.9 MPa (range, 2.5 to 3.1 MPa) in the intact knee to 2.6 MPa (range, 2.1 to 3.2 MPa) after partial meniscectomy, but increased to 3.1 MPa (range, 1.3 to 4.3 MPa) after total meniscectomy ($p = 0.261$).
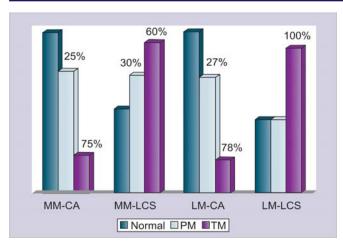
Fig. 1: Variations of contact area (CA) and average local contact stress (LCS) after partial and total meniscectomy at 50° of knee flexion (in canine physiologic standing position). MM – Medial meniscus; CA: p = 0.002; LCS: p = 0.296; LM – Lateral meniscus; CA: p = 0.002; LCS: p = 0.008; Normal – Intact menisci; PM – Partial meniscectomy; TM – Total meniscectomy.
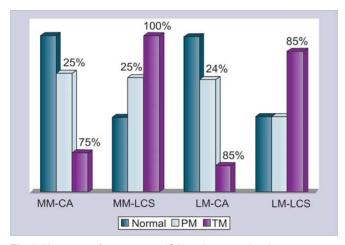

Fig. 2: Variations of contact area (CA) and average local contact stress (LCS) after partial and total meniscectomy at 30° of knee flexion. MM – Medial meniscus; CA: p = 0.002; LCS: p = 0.046; LM – Lateral meniscus; CA: p ≤ 0.001; LCS: p = 0.473; Normal – Normal menisci; PM – Partial meniscectomy; TM – Total meniscectomy.
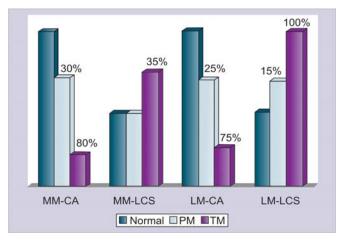

Fig. 3: Variations of contact area (CA) and average local contact stress (LCS) after partial and total meniscectomy at 70° of knee flexion. MM – Medial meniscus; CA: p = 0.001; LCS: p = 0.692; LM – Lateral meniscus; CA: p ≤ 0.001; LCS: p = 0.040; Normal – Normal menisci; PM – Partial meniscectomy; TM – Total meniscectomy.

Lateral meniscus at 70° (Fig. 3): The average CA decreased from 3.2 cm^2 in the intact knee (range, 2.8 to 4.0 cm^2) to 2.4 cm^2 after partial meniscectomy (range, 2.0 to 3.0 cm^2), and to 0.8 cm^2 after total meniscectomy (range, 0.5 to 1.1 cm^2) (p < 0.001). The average LCS increased from 1.4 MPa in the intact knee (range, 0.7 to 1.7 MPa), to 1.6 MPa after partial meniscectomy (range, 1.0 to 2.0 MPa), to 2.9 MPa after total meniscectomy (range, 1.0 to 3.5 MPa) (p = 0.040). The average peak LCS increased from 2.6 MPa (range, 1.4 to 3.8 MPa) in the intact knee to 2.8 MPa (range, 2.1 to 3.6 MPa) after partial meniscectomy and to 3.3 MPa (range, 1.2 to 4.2 MPa) after total meniscectomy (p = 0.105).

DISCUSSION

The authors studied the meniscofemoral load transmission in the canine joint under three different conditions: Intact menisci, partial meniscectomy with removal of approximately 15% of the total area of the menisci and total meniscectomy. The data showed that the values of contact area (CA) and local contact stress (LCS) during physiologic gait differed approximately 25 to 30% when tested in the intact canine knee versus a knee with partial meniscectomy. A dramatic decrease of both CA and increase in LCS was noted after total meniscectomy.

Many investigations have attempted to demonstrate decreased contact area and increased focal stress concentration on the tibial condyles after meniscectomy with various techniques, but few have focused on the meniscofemoral joint. Arthrography,[12,13] joint casting methods,[5,10,14] three-dimensional photoelasticity measurement[15] and pressure sensitive film techniques have been the most used methods.[4,6,7] The focus of the current study was exclusively on the meniscofemoral joint which differs from most previous studies. This study indicates that contact areas and local contact stresses can be consistently measured at the meniscofemoral interface in the canine knee using pressure sensitive film at low axial loads. The film is thin and pliable and can be inserted above the meniscus with sufficient conservation of the anatomy. Therefore, the film can generate estimates of both contact area and stress distributions during instantaneous loading. The major disadvantages of this technique include a limited range of response (5-25 kgf/cm^2), possible overestimation of contact area and stress when a shearing force is applied, and the possibility of artifact when loaded over the small frontal radius of curvature of the femoral condyles.

In the intact knee at low loads (90-120 N), little or no contact occurs on the exposed femoral cartilage. The vast majority of contact occurs at the meniscus itself, and increasing the knee range of motion from 30° to 70° showed progressive posterior shift of the CA with a corresponding retrograde shift of the

location of the LCS. The lateral meniscus was found to carry a large fraction of the load and no significant contact stress on the femoral cartilage was found until total meniscectomy was performed. Brown et al[8] reported similar results in their study on local contact stress on femoral condyles. They found no statistically significant changes in the size of the contact area, the mean contact stress, or in the magnitude of the peak local contact stress during range-of-motion in the human knee from 0 to 30° unless meniscectomy was performed.

Conservative partial meniscectomy leaves the majority of the weight distribution function of the meniscus, which protects the cartilage covering the femoral condyles. The contact area decreased approximately 25% after partial medial or lateral meniscectomy when tested in the canine physiologic standing position at 50° of knee flexion (p = 0.002). The local contact stress increased 30% after partial medial meniscectomy (p = 0.296), but did not change after partial lateral meniscectomy (p = 0.008). After total meniscectomy at 50°, the contact area decreased 75 % both in the lateral and medial femoral condyles (p = 0.002), while the local contact stress increased 60% in the medial compartment (p = 0.296) and 100% in the lateral compartment (p = 0.008).

Our data for CA and LCS fall within the range reported by previous studies that evaluated contact stress on the tibial plateau without varying the knee flexion. After partial meniscectomy, the tibial contact area was found to decrease between 7 and 20%.[6,7] After total meniscectomy, contact area has been reported to decrease between 17 and 75%.[6,7,10,16] Tibial contact stresses have been shown to increase after partial meniscectomy between 67 and 300%,[7,17] and tibial contact stresses have been shown to increase between 15 and 300% after total meniscectomy in human knees.[3,7-10] Lastly, femoral contact stresses have been shown to increase 200% after total meniscectomy in human knees with an applied load of 1000 N.[15] However, the load applied in these studies was more than 20 times greater than in the current study.

There are two major limitations of the current study. First, this study used lower axial loads compared to previous studies with animal and human models. Next, our study carried the risk of creating film artifacts due to the small radius of curvature of the femoral condyles. Regarding the use of low axial loads, two prior studies analyzed the weight distribution on dog limbs during normal gait. Kimura et al[18] reported an average loading of 45% of body weight on a dog's hind limb during normal gait. Budsberg et al[19] reported a value of 20% in a similar study. Several studies[5,8,10] reported that the size of CA in human knees increases rapidly at lower loads (< 500 N), but this rate of increase gradually lessens with increased load. These studies[5,8,10,18,19] suggest to the current authors that the use of a

high axial loads *in vitro* is probably not fundamental in order to achieve comparable results to the *in vivo* situation.

The main clinical value of this study is to emphasize the biomechanical advantage of surgical procedures addressing the repair of damaged menisci. As shown on the tibia,[6,7,17] the femoral condyles may sustain a significant increase in pressure distribution after partial meniscectomy under loads up to 50% of the body weight. Following the results of the current study, the use of traditional or more modern techniques in meniscal repair are highly recommended, despite being time consuming, technically demanding, and showing good, but not excellent results.[20] In addition, if a biologic scaffold is used to treat femoral osteochondral defects in the presence of a partial meniscectomy, an increase of femoral stress concentration by 25 to 30% must be considered; thereby suggesting a more conservative rehabilitation protocol.

REFERENCES

1. King D. The function of the semilunar cartilage. J Bone Joint Surg 1936;18A:1069-76.
2. Fairbank TJ. Knee joint changes after meniscectomy. J Bone Joint Surg 1948;30B:664-70.
3. Ahmed AM, Burke DL. In vitro measurement of static pressure distribution in synovial joints. Tibial surface of the knee. J Biomech Eng 1983;105:216-25.
4. Fukubayashi T, Kurosawa H. The contact area and pressure distribution pattern of the knee. Acta Orthop Scand 1980;51: 871-79.
5. Walker PS, Erkman MJ. The role of the menisci in force-transmission across the knee. Clin Orthop 1975;109:184-92.
6. Ihn JC, Kim SJ, Park IH. In vitro study of contact area and pressure distribution in the human knee after partial and total meniscectomy. Int Orthop 1993;17:214-18.
7. Baratz ME, Fu FH, Mengato R. Meniscal tears. The effect of meniscectomy and of repair on intra-articular contact areas and stress in the human knee: A preliminary report. Am J Sports Med 1986;14(4):270-75.
8. Brown TD, Shaw DT. In vitro contact stress distribution on the femoral condyles. JOR 1984;2:190-99.
9. Krause WR, Pope MH, Johnson RJ, Wilder DJ. Mechanical changes in the knee after meniscectomy. J Bone Joint Surg 1976;58-A:599-604.
10. Kurosawa H, Fukubayashi T, Nakajima H. Load-bearing mode of the knee joint: Physical behavior of the knee with or without menisci. Clin Orthop 1980;149:283-90.
11. Huberti HH, Hayes WC. Patellofemoral contact pressures. J Bone Joint Surg 1984;5:715-24.
12. Kettlekamp DB, Jacobs AW. Tibiofemoral contact area: Determination and implications. J Bone Joint Surg 1972;54-A:349-56.
13. Maquet PG, Van de Berg A, Simonet JC. Femorotibial weightbearing areas: Experimental determination. J Bone Joint Surg 1975;57A:766-71.

14. Walker PS, Hajek JV. The load-bearing area in the knee joint. J Biomech 1972;5:581-92.
15. Radin EL, De Lamotte F, Maquet P. Role of the menisci in the distribution of stress in the knee. Clin Orthop 1984;185:290-94.
16. Anderson DR, Newman AP, Daniels AU. In vitro load transmission in the canine knee: The effect of medial meniscectomy and varus rotation. Knee Surg Traumatol Arthroscopy 1993;1:44-50.
17. Seedhom BB. Transmission of the load in the knee joint with special reference to the role of the menisci. Eng Med Imeche B 1979;207-28.
18. Kimura T, Endo B. Comparison of force of foot between quadrupedal walking of dog and bipedal walking of man. J Faculty Science 1972;4:119-30.
19. Budsberg SC, Verstraete MC, Soutas-Little RW. Force plate analysis of the walking gait in healthy dogs. Am J Vet Res 1987;48:915-18.
20. Farng E, Sherman O. Meniscal repair devices: A clinical and biomechanical literature review. Arthroscopy 2004;20(3): 273-86.