Trochlear Contact Pressures After Anteromedialization of the Tibial Tubercle

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Background: Anteromedialization is recommended for cartilage restoration of patellofemoral defects, with the presumption that it decreases contact pressures across the trochlea. No study has evaluated pressures on the trochlear side of the patellofemoral joint after anteromedialization of the tibial tubercle.

Hypothesis: Anteromedialization of the tibial tubercle decreases contact pressure across the trochlea.

Study Design: Controlled laboratory study.

Methods: Ten cadaveric knees were tested by placing an electroresistive pressure sensor on the femoral side of the patellofemoral joint. A validated model of nonweightbearing resisted extension was simulated by loading the extensor mechanism at 89.1 N and 178.2 N. Knees were tested 3 times per load at 30°, 60°, 90°, and 105°. The center of force and pressure across the patellofemoral articulation were compared before and after a reproducible and consistent anteromedialization.

Results: The mean center of force shifted medially after anteromedialization at 89.1 N and 178.2 N. At 89.1 N, the mean total contact pressure decreased significantly ($P < .05$) at all angles, and at 178.2 N, it decreased significantly at 30°, 60°, and 90° of knee flexion. The mean lateral trochlear contact pressure decreased significantly ($P < .05$) at all flexion angles at both 89.1 N and 178.2 N. The mean central trochlear contact pressure decreased significantly ($P < .05$) at 30° with the 89.1-N and 178.2-N loads but increased significantly ($P < .05$) at 90° with the 89.1-N load. The mean medial trochlear contact pressure increased significantly ($P < .05$) at all flexion angles at 89.1 N and 178.2 N.

Conclusion: Anteromedialization shifts the contact force to the medial trochlea and decreases the mean total contact pressure.

Clinical Relevance: Anteromedialization decreases the mean total contact pressure while shifting contact pressure toward the medial trochlea. This study suggests that anteromedialization is appropriate for unloading the lateral trochlea. However, this procedure appears to have minimal benefit on central chondral defects, and it may actually increase the load in patients with medial defects.

Keywords: patellofemoral contact pressure; anteromedialization; cartilage transplantation; patellofemoral joint

Several clinical studies indicate that patients with patellofemoral knee pain improve after anteromedialization (AMZ) of the tibial tubercle (TT).[1,2,4,7,9,10,15,18,21] Similarly, autologous chondrocyte implantation within the patellofemoral joint has had improved clinical results when performed along with distal realignment.[19] It is presumed that improvement in both pain and function seen after AMZ of the TT is the result of decreased contact pressures within the patellofemoral joint. As a result, AMZ of the TT has been recommended by some clinicians as an adjunct to the autologous chondrocyte implantation, with the presumption that the procedure also benefits from decreasing contact pressure across the patellofemoral joint. Yet, few studies have measured patellofemoral contact pressures after AMZ of the TT,[9,17] and no studies that we are aware of have measured pressure distribution on the trochlear side of the joint after this procedure.

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Our senior investigators have had experience measuring patellofemoral contact pressures using an electroresistive sensor.[11] The purpose of this investigation was to determine the effect of AMZ of the TT on both the magnitude and the distribution of patellofemoral contact pressure across the trochlear surface. Specifically, the study intended to determine the extent that AMZ of the TT redistributes trochlear contact pressures.

We hypothesized that AMZ of the TT would result in decreased patellofemoral contact pressures.

MATERIALS AND METHODS

Technology

An electroresistive sensor using Mylar conductive paint was used in this study (K-Scan #4000, Tekscan Inc, Boston, Mass). This sensor is horseshoe-shaped with a sensor pad 28×33 mm in size on each prong, for a total surface area of 56×33 mm. Each sensor pad has 63 sensels (the electroresistive sensing units within each pad) per square centimeter, with a resolution of approximately 1.25 mm^2. The sensor is 0.1 mm thick. Application of pressure to a sensel results in a change in the resistance of this sensing unit in inverse proportion to the applied pressure. The effective force range of the sensor can be adjusted by changing the sensitivity setting within the software up to a maximum of 2500 lb/in^2. After the sensitivity has been adjusted, calibration allows conversion of resistance into pressure units.

Each sensor was individually calibrated on an Instron material testing system (Instron Model 1321, Canton, Mass). Two calibration points were taken for each sensor, 1 on the low end of the expected force, and 1 on the high end. Each sensor had its own calibration file loaded before each test.

Knee Joints

A total of 10 frozen human cadaveric knee joints from 9 cadavers with a mean age of 47 years (range, 38-57 years; 4 men and 5 women) were tested. We used only specimens that had not had previous surgery and without macroscopic evidence of cartilage defects on the patellar and trochlear surfaces. No bone or soft tissue abnormalities were identified on dissection.

Specimen Preparation and Loading Apparatus

Each specimen was thawed overnight at room temperature before testing and was regularly hydrated throughout the procedure with normal saline. The femur was fixed proximally to the testing station with a clamp. An extended lateral parapatellar arthrotomy was performed on each knee to gain access to the patellofemoral joint. The sensor was first prepared by trimming the excess nonsensing edges of each sensor pad. The sensor edges were then reinforced with cloth tape (3M, St. Paul, Minn). The sensor pads were placed on the trochlear surface; then, the reinforced edges were tacked down with an Easyshot staple gun (Black & Decker, Towson, Md). Special attention was given to ensure that the sensor pads were apposed or slightly overlapping at the center of the trochlear surface while maintaining sensor pad conformity to the surface of the trochlea (Figure 1). The arthrotomy was performed anatomically with a running No. 2 Ethibond suture (Ethicon Inc, Plainsboro, NJ). Care was taken to prevent imbrication of the repair. Two No. 5 Ethibond sutures were then placed in the quadriceps tendon using a Krakow stitch. The suture ends were tied to a rope that ran over a pulley aligned with the shaft of the femur. At the end of the rope, an S-shaped hook was attached for easy loading and unloading of the patellar mechanism.

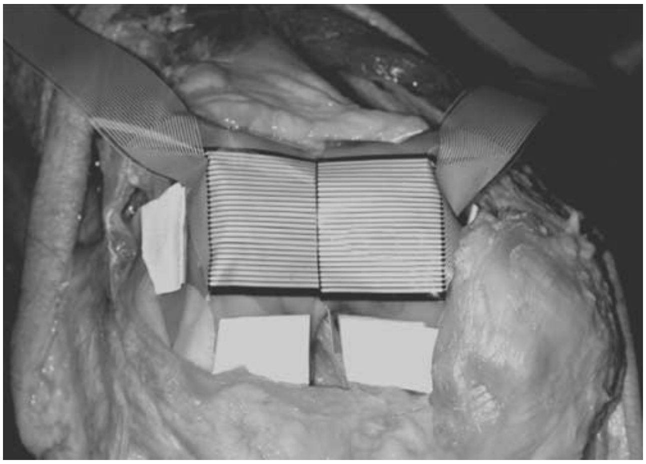

Figure 1. K-Scan sensor pads placed closely approximated at the center of the trochlear surface of the femur.

Applied Forces

A model simulating nonweightbearing resisted knee extension was used, similar to the method described by Skyhar et al.[23] Before testing, each specimen was preconditioned by maximally flexing the knee 5 times from full extension to prevent hysteresis. Each knee was loaded and tested at 89.1 N and 178.2 N, identical to the forces used by Garretson et al[11] and similar to the 100-N force used by Simonian et al[22] and Torzilli et al.[24] The lateral retinacular suture was then removed, leaving a lateral retinacular release to the level of the proximal pole of the patella. Testing was then repeated after AMZ of the TT. The DePuy AMZ Tracker (Warsaw, Ind) was used to make accurate and reproducible oblique TT osteotomies. The guide was positioned and fixed at 30° to the vertical by referencing 2 K-wires drilled directly anteroposterior through the anterior crest of the proximal tibia. After the osteotomy was complete, the 7-cm fragment produced was advanced anteromedially 15 mm (7.5 mm medialization, 13.5 mm anteriorization) by rotating it distally on its periosteal pedicle (Figure 2). The fragment was fixed to the tibia with two 3.5-mm bicortical small fragment screws. The TT was anteriorized 13.5 mm based on the recommendations of Ferguson et al[5] and Fulkerson et al[9] of 0.5 inches and 12 to 15 mm, respectively.

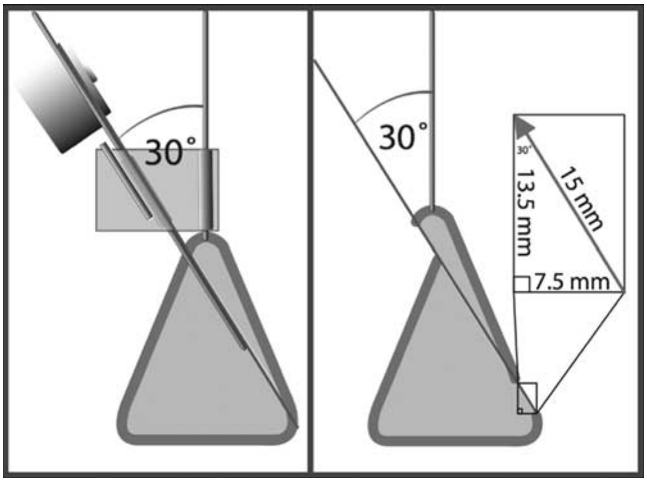

Figure 2. An osteotomy performed at 30° to the vertical K-wires placed straight anteroposterior through the tibial crest; the tubercle then shifted 15 mm anteromedially.

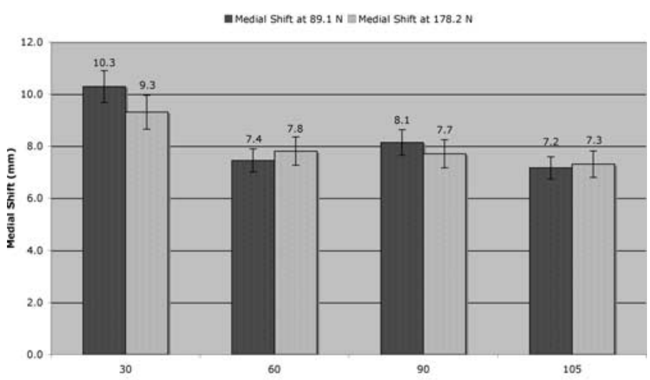

Figure 3. The mean medial shift in the center of force after anteromedialization of the tibial tubercle.

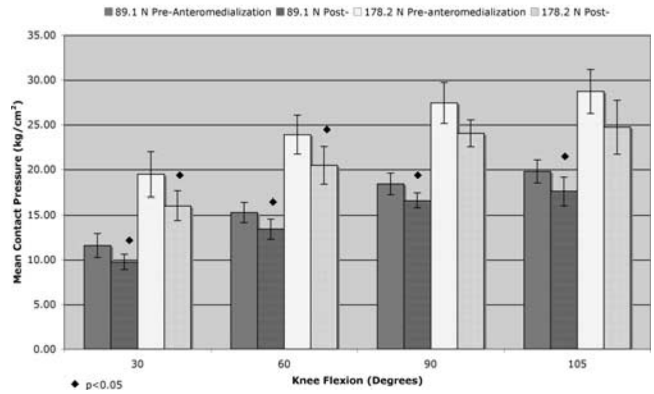

Figure 4. The mean change in patellofemoral total contact pressure after anteromedialization of the tibial tubercle.

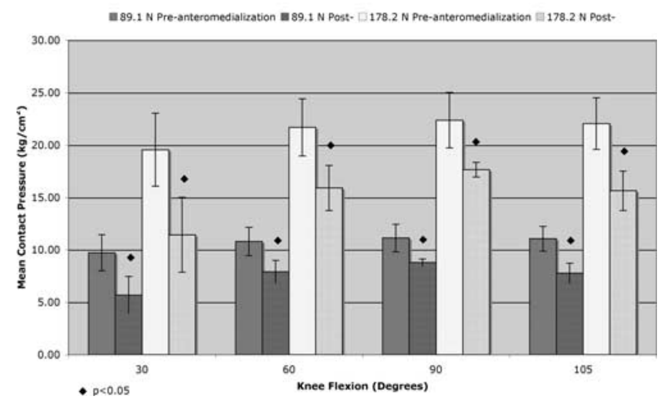

Figure 5. The mean change in pressure for the lateral trochlear surface after anteromedialization of the tibial tubercle.

Experimental Design

The center of force and total contact pressure were measured at 30°, 60°, 90°, and 105° of knee flexion. The knee flexion angles were determined with a goniometer, and all measurements were taken statically. The knee was cycled, and the mean of 3 measurements at each angle were obtained at 89.1 N and 178.2 N before and after AMZ of the TT.

We also divided the entire femoral trochlear surface into lateral, central, and medial regions and then measured changes in pressure distribution before and after AMZ of the TT in each region. Statistical analysis was performed using a paired Student *t* test (significance, $P < .05$). Error bars were calculated using 95% confidence intervals.

RESULTS

At 89.1 N and 178.2 N, there was a net medial shift in the center of force after AMZ of the TT (Figure 3). This shift was consistent with the calculated shift of 7.5 mm medially (Figure 2).

At 89.1 N, mean total trochlear pressure and mean lateral trochlear pressure decreased significantly ($P < .05$) after AMZ of the TT at all angles (Figures 4 and 5). The mean central trochlear pressure decreased significantly ($P < .05$) at 30° and increased significantly ($P < .05$) at 90° (Figure 6). The mean medial trochlear pressure increased significantly ($P < .05$) at all angles (Figure 7).

At 178.2 N, the mean total trochlear pressure decreased significantly ($P < .05$) at 30°, 60°, and 90° of knee flexion (Figure 4). The mean lateral trochlear pressure decreased significantly ($P < .05$) at all degrees of knee flexion (Figure 5). The mean central trochlear pressure decreased significantly at 30° of knee flexion ($P < .05$) but not at 60°, 90°, and 105° (Figure 6). The mean medial trochlear pressure increased significantly ($P < .05$) at 30°, 60°, 90°, and 105° of knee flexion (Figure 7).

DISCUSSION

Several clinical studies indicate that patients with patellofemoral knee pain improve after AMZ of the TT.[1,2,4,7,9,10,15,18,21] Yet, few studies have measured patellofemoral contact pressures after AMZ of the TT,[9,17] and no studies that we are aware of have measured pres-

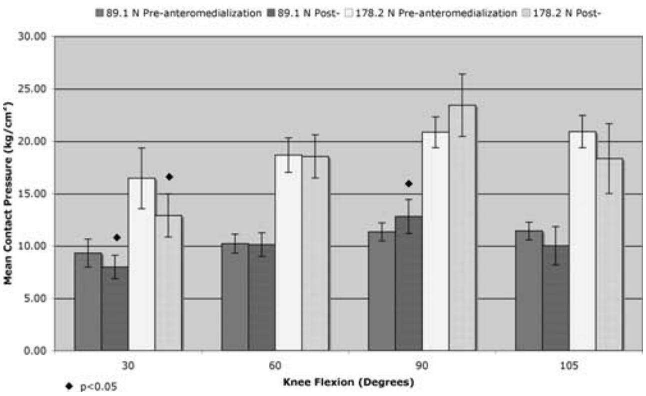

Figure 6. The mean change in pressure for the central trochlear surface after anteromedialization of the tibial tubercle.

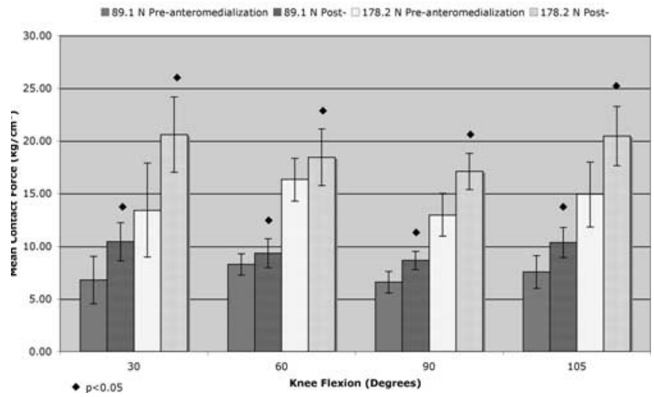

Figure 7. The mean change in pressure for the medial trochlear surface after anteromedialization of the tibial tubercle.

sure distribution on the trochlear side of the joint after this procedure.

Several methods have been used to measure joint contact pressures, including the use of Fujifilm. We chose to investigate the effects of AMZ of the TT using the Tekscan conductive ink pressure sensor (Tekscan Inc). This technology has been previously compared with Fujifilm and was found to be easier to use, more reliable, and more reproducible.[3,13,25] Harris et al[13] reported that contact areas measured with Fujifilm were 11% to 36% lower, and DeMarco and Bachuus[3] found a significant difference in percentage pressure error. Tekscan sensors were 2.5 times more accurate, with a mean error of 4% versus 11% for Fujifilm when the sensors were appropriately calibrated. Unlike Fujifilm, Tekscan sensors also enable repeatable measurements, allowing for multiple test conditions without sensor repositioning. Therefore, Matsuda et al[16] took advantage of this technology and evaluated patellofemoral contact pressures in total knee arthroplasty, Gill et al[12] used it after posterior cruciate ligament reconstruction, and our senior investigator used it to measure trochlear patellofemoral contact pressures at osteochondral donor sites.[11]

The mean total contact pressure decreased after AMZ of the TT at each angle for a given load. This result was predicted by Fulkerson in his first published description of AMZ of the TT.[7] He stated that this beneficial result is provided by anteriorization, thereby relieving some stress in the patellofemoral joint while improving the mechanical alignment and efficiency of the patellofemoral mechanism.[7] Although not immediately obvious, anteriorization of the TT effectively decreases the angle of the applied load across the patellofemoral joint. When this vector is resolved into its components, the force directed perpendicular to the joint surface is decreased, and therefore, the measured mean total contact pressure is also reduced.

Although we did not specifically evaluate trochlear chondral defects, the results of this study are consistent with the clinical results of Pidoriano et al.[20] In a retrospective study by Pidoriano et al, outcomes from AMZ of the TT correlated with the location of patellar articular lesions.[20] In a retrospective review, Pidoriano et al reported the following: (1) patients with lateral patellar chondral defects had improved clinical outcomes compared with those with medial chondral defects and (2) patients with central trochlear lesions almost universally had associated medial patellar defects and uniformly poor results.[20] Our study consistently showed increased patellofemoral contact pressures medially and decreased patellofemoral contact pressures laterally.

The measured mean central trochlear contact pressure results were variable. There was a significant decrease in the mean contact pressure at 30° and a significant increase at 90° of knee flexion. This finding may be attributed to the fact that at lesser degrees of knee flexion, the patella has greater freedom to move medially, and thus, AMZ of the TT has the ability to decrease pressure on both the lateral and central surfaces; whereas at greater degrees of knee flexion, the patella is more firmly engaged within the femoral trochlear groove, and AMZ is less able to relieve stresses centrally. This finding could also be explained by the differences in shape of the patellofemoral surface. In addition, AMZ of the TT may affect central patellofemoral congruency, improving its relationship in some and not in others when the load of the quadriceps is in line with the femur. Finally, although we attempted to closely approximate the sensor pad edges, slight overlap may have had a small effect on the central pressure measurement.

In this study, patellofemoral contact pressures increased with knee flexion up to 90°. This finding is in agreement with findings by Frankel,[6] who stated that with knee flexion, tension across the patella is converted to compression through the articular surface.

Contact pressure decreased above 90° of flexion. Although it has been suggested that patellofemoral contact pressures decrease because of the quadriceps tendon coming into contact with the femoral trochlea surface, thus diminishing the load on the patellofemoral articulation, we believe the decreased pressure seen at 105° may be, in part, attributed to our sensor placement. The sensor pads were not specifically placed into the notch (Figure 1), and as the patella contacted the notch with further flexion, not all contact was measured.

Limitations in this study were related to both the model and the K-Scan. Although these limitations were identified in our previous study by Garretson et al,[11] they warrant further review in this study. The model is hindered by the following points: (1) the entire quadriceps mechanism, rather than its individual components, was loaded; (2) the relative actions of other forces about the knee, particularly the hamstrings, were not accounted for; (3) knee motion occurred by manual manipulation, not through active forces; and (4) the quadriceps angle was not accounted for. The K-Scan is limited by the following areas: (1) its thickness (0.1 mm), (2) its sensitivity to temperature changes, (3) its propensity to crinkle, (4) the potential overlap in the central trochlea, and (5) the establishment of its position of the trochlea. These limitations merit further discussion.

First, we encountered some difficulty when attaching the sensor pads to the trochlear surface. The sensor pads did not readily conform to the articular surface, as they do not stretch over the surface, limiting the type of sensor used. With our previous study, we improved sensor conformity by using a sensor consisting of 2 pads placed on the trochlear surface. In this study, we were able to further improve sensor stability and conformity by using staples instead of sutures to attach the sensor to the femur. Although sensor conformity was improved, a small amount of crinkling of the sensor could not be avoided. This crinkling became problematic because it resulted in dropped data points (not pressure spikes), which increased proportionally to the number of flexion-extension repetitions. As a result, cyclic loading with each knee was limited to 3 cycles per test to prevent a significant number of dropped data points.

Second, interobserver error was eliminated by using the lead investigator both to establish the position of each sensor and to perform the AMZ of the TT. However, sensors were not repositioned for repeat recordings of each knee, and as a result, a small amount of intraobserver error may exist while determining the position of the sensor relative to the trochlear surface.

Third, as pointed out by Skyhar et al,[23] use of nonweightbearing resisted extension does not mimic normal physiologic weightbearing activity. Loads applied in this investigation are more similar to those applied in nonweightbearing exercise. However, because of the complexity of weightbearing motions, we do not believe any cadaveric model would successfully reproduce the complex interaction among all the muscles groups responsible for knee motion. We believe our simplified model enabled us to reproducibly load the quadriceps mechanism and thereby provide insight into the before and after results of this procedure.

Finally, although we determined the effect of AMZ of the TT on patellofemoral contact in normal-appearing knees, our results may not entirely represent those patients for whom the procedure was intended because patients requiring distal realignment commonly are evaluated with articular defects and altered patellofemoral biomechanics, which are not represented in our study. Along those lines, it could be argued that patients with lateral patellofemoral tracking might not have a significant increase in mean medial patellofemoral contact pressure with AMZ of the TT. However, our results seem to be consistent with clinical results by Pidoriano et al[20] and in agreement with Fulkerson,[8] who recommends arthroscopy of the patellofemoral joint before performing AMZ of the TT to help determine the most appropriate approach to realignment, such that normal tracking may be restored without adding load to a lesion. Therefore, we believe the choice of normal-appearing specimens, although not perfect, provided a reasonable and consistent means for evaluating the effect of AMZ of the TT.

Beyond the limitations mentioned above, our study may have been improved in 2 additional ways. First, the use of a navigation device to determine knee flexion angles, such as that used by Hsieh et al,[14] may have provided a more accurate determination of knee flexion angles than the use of a goniometer. Second, evaluating the effect of several osteotomy inclinations may have provided us with additional information regarding the shift of trochlear contact pressures. Although it may be inferred that medial trochlear pressures will increase as one decreases the slope of the TT osteotomy (as a result of the decreased anteriorization and increased medialization), our study did not specifically evaluate this effect.

CONCLUSION

Several procedures are available for treating patellofemoral chondrosis. When selecting a procedure, the surgeon must determine whether the procedure chosen will unload the problematic lesion and the likelihood of increasing the load on a potentially painful articular lesion.[8] This study suggests that AMZ of the TT is appropriate for unloading the lateral trochlea. However, it would appear that this procedure may not benefit central chondral defects and may actually worsen clinical results for medial defects.

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