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Trochlear Contact Pressures After Straight Anteriorization of the Tibial Tuberosity

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Background: Anteromedialization of the tibial tuberosity has been shown to decrease mean total contact pressures of the lateral trochlea and to shift contact pressures to the medial trochlea.

Hypothesis: Modifying the anteromedialization osteotomy to a straight anteriorization osteotomy of the tibial tuberosity can decrease trochlear contact pressures without a resultant medial shift of forces to the medial trochlear contact area.

Study Design: Controlled laboratory study.

Methods: Ten cadavers were tested before and after straight anteriorization tibial tuberosity osteotomy by loading the extensor mechanism with 89.1 and 178.2 N at 0°, 30°, 60°, and 90° of flexion following a validated patellofemoral joint loading protocol. Contact pressures were measured with electroresistive pressure sensors placed directly on the trochlea.

Results: The mean trochlear contact pressures after osteotomy decreased significantly ($P < .05$) for loads of 89.1 and 178.2 N at both 30° (23% and 20%, respectively) and 60° (18.7% and 31.9%, respectively) of knee flexion. The peak contact pressures decreased significantly ($P < .05$) for loads of 89.1 and 178.2 N at 30° (24.3% and 27.0%, respectively) and 60° (31.9% and 24.5%, respectively) and for loads of 89.1 N at 90° (13.4%) of knee flexion.

Conclusion: The authors demonstrated significantly decreased trochlear contact forces after straight anteriorization osteotomy of the tibial tuberosity, without a significant resultant medial shift of the center of force.

Clinical Relevance: Straight anteriorization of the tibial tuberosity may be a useful adjunct for patients with medial articular defects of the patellar or trochlea in whom anteromedialization would be otherwise contraindicated.

Keywords: trochlea; contact pressures; tibial tuberosity; tubercle; osteotomy; anteriorization

Anteromedialization (AMZ) of the tibial tubercle (TT), as described by Fulkerson et al,[13,17] has been shown to decrease total trochlear contact pressures, albeit with a resultant shift of forces to the medial trochlea.[2] Cartilage repair procedures such as autologous chondrocyte implantation have been shown by Peterson et al[29] to have improved results when combined with AMZ of the TT, presumably owing to unloading and protecting the repair.[10,19]

Despite this, there is still a subset of patients with medial patellofemoral cartilage lesions for whom AMZ is not a viable option in isolation or combined with a cartilage repair procedure because of the resultant medial shift of contact forces. Pidoriano et al[30] reported that patients with distal or lateral patellar chondral lesions had significantly better results than did those with medial or proximal lesions. Previous tibial tuberosity anteriorization osteotomies have been described (most well known is the Maquet); however, there have been significant complications such as fracture, nonunion, and skin necrosis, and their use has largely been abandoned.[35] Fulkerson et al

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(unpublished data, 2007) described a straight anteriorization (SA) osteotomy of the TT that is different from the traditional Maquet procedure in that, similar to the AMZ, it does not require bone graft. The benefits of SA osteotomy are yet to be fully elucidated, but potential advantages over the Maquet anteriorization osteotomy are secure bone-to-bone fixation with bicortical screws, no requirement for bone grafting, and less chance of skin complications due to less prominence and more gradual anterior sloping of the osteotomy.

We hypothesized that SA osteotomy of the TT would result in decreased total trochlear contact pressures without the concomitant medial shift of forces as seen in AMZ. Such an osteotomy may have a role in a specific subset of patients with cartilage lesions of the medial trochlea or patella at the time of cartilage repair procedures, to offload and protect the repair, or in patients with global patellofemoral disease. In addition, there are patients without apparent malalignment of the patellofemoral compartment who have central trochlear isolated defects. These patients may benefit in a like manner during cartilage repair techniques if the absolute stress of the patellofemoral compartment is decreased with SA. This study investigates the effects of SA osteotomy on trochlear pressures.

MATERIALS AND METHODS

Ten cadaveric knees were tested before and after SA TT osteotomy by loading the extensor mechanism with 89.1 N and 178.2 N, following a validated model of nonweightbearing resisted knee extension described by Skyhar et al.[37] The mean age of the donors was 61.7 years (range, 46-72 years). All specimens were from donors without known skeletal diseases, and there were no significant signs of advanced articular cartilage degeneration, patellofemoral malalignment, or other bone or soft-tissue disease at the time of preparation.

The 10 frozen human cadaveric knee joints to be used were thawed overnight and regularly hydrated with normal saline throughout the procedure. An extended lateral parapatellar arthrotomy was performed on each specimen, and the electroresistive pressure sensor (Tekscan, South Boston, Mass) was secured in place on the trochlea using staples following the technique of Beck et al.[2] The arthrotomy was closed with suture. Each femur was clamped to the testing station. The quadriceps was loaded by 2 No. 5 Ethibond sutures (Ethicon, Somerville, NJ) through the tendon proximally and connected to a rope, which ran over a pulley in line with the shaft of the femur. Each knee was cycled through a full range of motion and then tested at varying degrees of flexion (0°, 30°, 60°, 90°, and 105°) at 89.1 N and 178.2 N, before and after SA TT osteotomy. The center of force, total contact pressure, and peak contact pressures on the trochlea were measured for each specimen. Statistical analysis was performed using a paired Student t test with significance set at $P < .05$. Error bars were calculated using the standard error of the mean.

OSTEOTOMY TECHNIQUE

Straight Anteriorization TT Osteotomy

The posterior cortex of the tibia and the margins of the TT were the reference points for the saw cuts. At the medial border of the patellar tendon insertion on the TT, a straight anterior-to-posterior saw cut was made in line with the long axis of the tibia. The cut was made to but not through the posterior cortex of the tibia and extended 10 cm distally (Figure 1). The lateral aspect of the proximal tibia was exposed, and the proximal transverse (lateral to medial) cut was made from the proximal aspect of the tuberosity, angling distally at approximately a 45° angle and perpendicular to the long axis of the tibia. A posterior longitudinal lateral-to-medial cut was made in the coronal plane, paralleling the posterior cortex and intersecting with the medial anterior-to-posterior cut. The osteotomy was completed by making the distal cut 10 cm below the proximal aspect of the tubercle. The tubercle was then rotated anteriorly 1 cm, measured at the proximal medial border of the tubercle, keeping the distal margin flush with the anterior surface of the tibia. The osteotomy was stabilized with two 4.5-mm standard cortical screws placed lateral to medial using a standard lag screw technique.

Technology

We used an electroresistive sensor with Mylar conductive paint for this study (K-Scan #4000, Tekscan). The sensor pads were each 28×33 mm in size, for a total of 56×33 mm of surface area coverage on the trochlea. The sensor pads are 0.1 mm thick with 63 sensels/cm^2 (the electroresistive sensing unit) and a resolution of 1.25 mm^2. The sensels calculate pressure by measuring the change in resistance, which is inversely proportional to the applied pressure. The software package used in this study records a virtual "movie" of the displayed pressure distributions on the trochlea over a 10-second duration. From this, total contact area and force can be averaged and displayed (Figure 2). The center of force was calculated as the weighted average, or centroid, of the entire pressure map. The mean forces and pressures were found by creating 2 boxes, 1 on each sensor where the main contact areas were found. The peak force and pressure were calculated for each box, and the highest value was reported for each specimen movie.

Before use, each pressure sensor was preconditioned and calibrated individually on a servo-hydraulic testing machine (Dartec 9690, Dartec Test Systems, Stourbridge, United Kingdom) according to the manufacturer's recommendations. Preconditioning consisted of loading each sensor 3 times to a pressure at least 20% higher than that expected. Subsequently, a 2-point calibration was performed by applying 2 loads within the maximum expected pressure values (20% and 80% of expected values). Calibration values corresponding to each sensor were calculated and loaded into the software before each test.

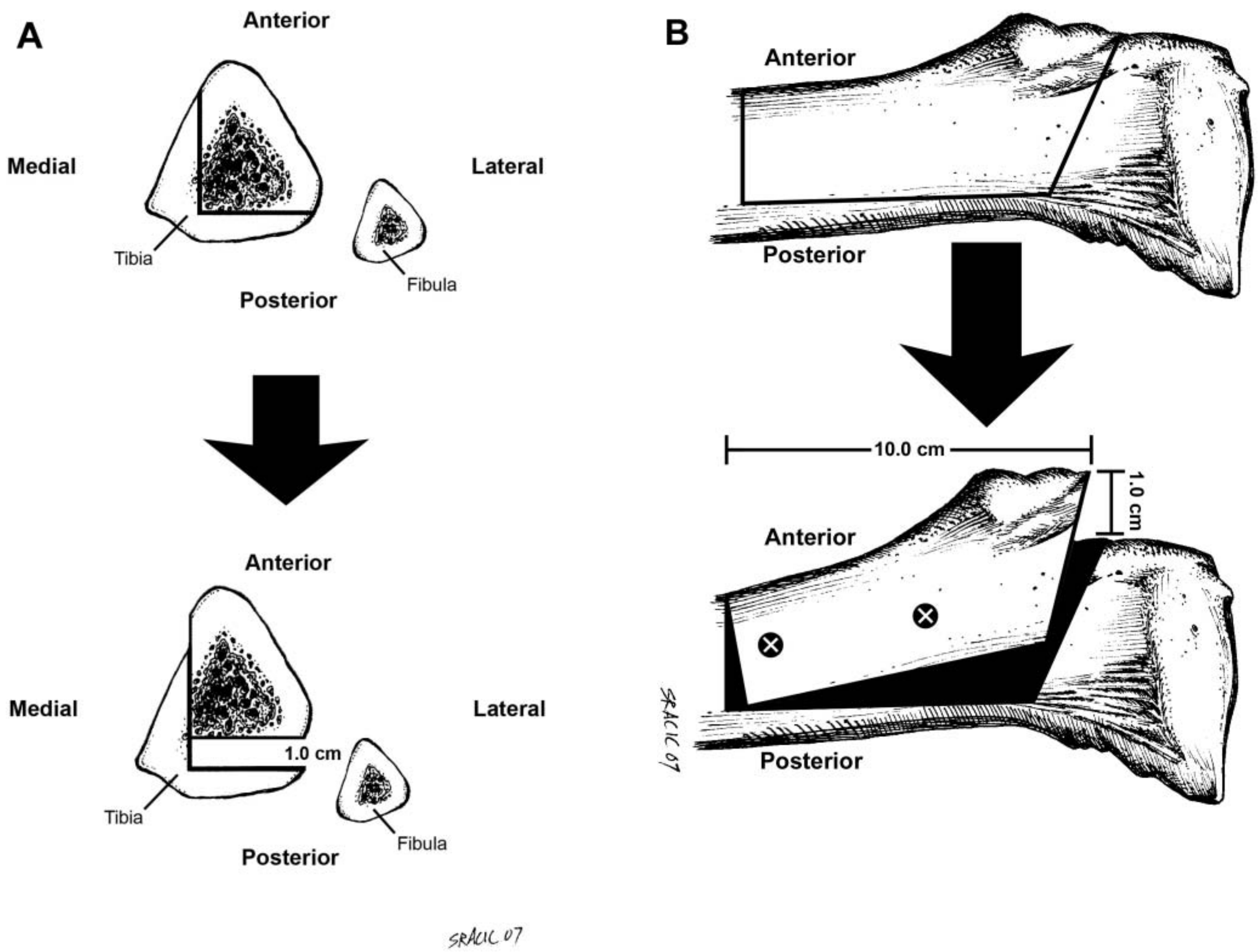

Figure 1. A, schematic axial illustration of straight anteriorization osteotomy. B, schematic sagittal illustration of straight anteriorization osteotomy.

RESULTS

The mean trochlear contact pressures after SA osteotomy decreased significantly ($P < .05$) at 89.1 and 178.2 N at both 30° and 60° of knee flexion (Figure 3). At 30°, the mean decrease in total contact pressure was 23% and 20% at 89.1 and 178.2 N, respectively. At 60° of knee flexion, there was a drop of 18.7% and 31.9% in total contact pressure at 89.1 and 178.2 N, respectively. Although not statistically significant, the mean total contact pressure at 90° decreased 2.1% and 5.6% at 89.1 and 178.2 N, respectively.

The peak contact pressures decreased significantly ($P < .05$) for loads of 89.1 and 178.2 N at 30° (24.3% and 27.0%, respectively) and 60° (31.9% and 24.5%, respectively) and for loads of 89.1 N at 90° (13.4%) of knee flexion (Figure 4). The peak pressure dropped 5.5% at 178.2 N at a knee flexion of 90° but was not statistically significant ($P > .05$). Data from 105° of knee flexion are not included in the analysis as they were unreliable and thought to represent primarily tendon contact.

There was a minimum shift in the center of force both horizontally and vertically after SA osteotomy (Table 1). The center of force shifted distally and laterally at 30° and 90° for both 78.1 and 189.2 N and at 60° for 89.1 N. At 60°, there was a minimal shift proximally at both 89.1 and 189.2 N, but the horizontal shift was laterally at 89.1 N and medially at 189.2 N.

DISCUSSION

Our results demonstrate that SA osteotomy of the TT significantly decreased total contact pressures at 30° and 60° of flexion for 89.1 and 178.2 N and peak contact pressures at 30°, 60°, and 90° of flexion for 89.1 and 30° and 60° for flexion for 178.2 N. There was no clinically significant medial shift in the center of force.

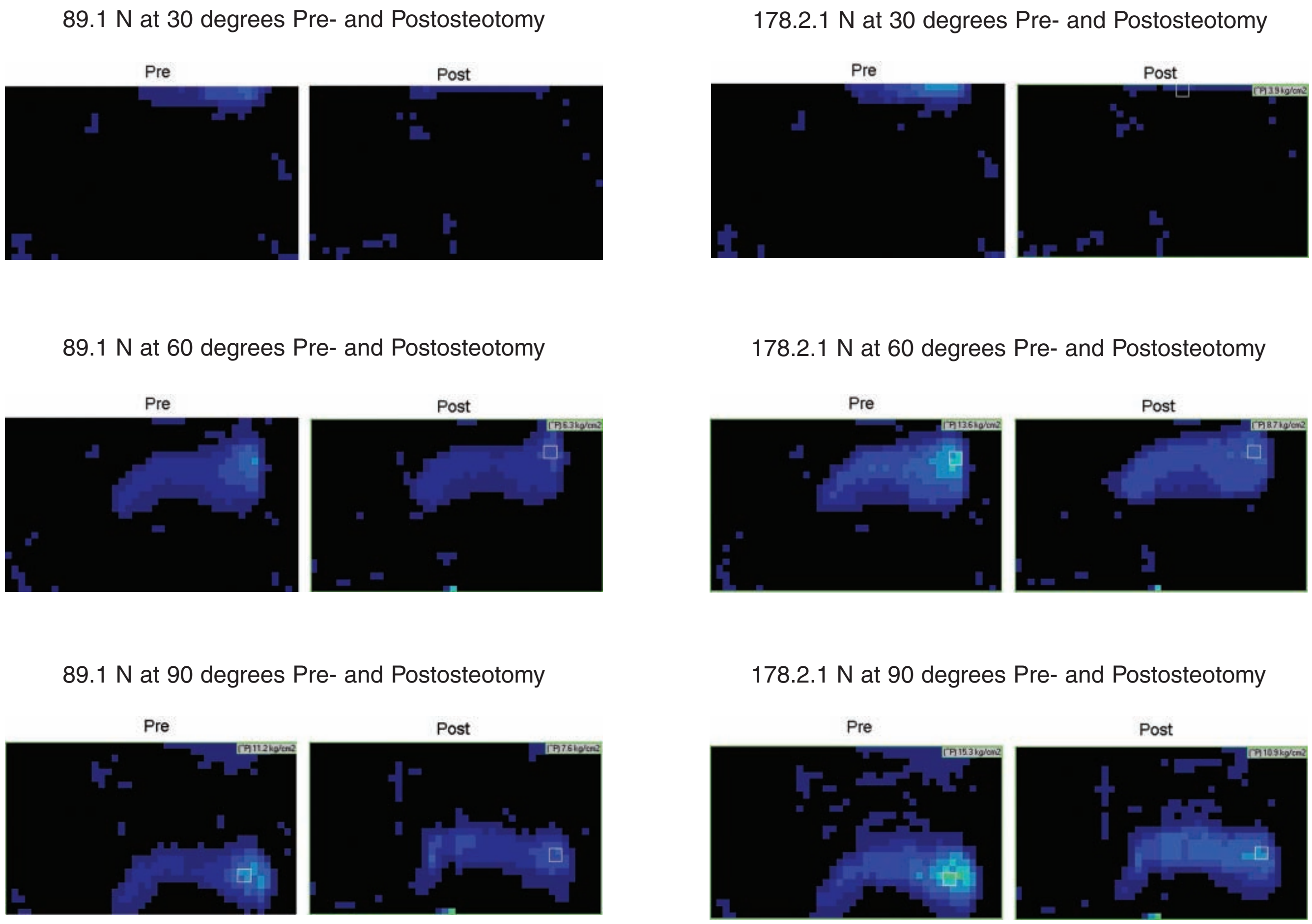

Figure 2. Virtual "movie" of the displayed pressure distributions on the trochlea. Lighter colors represent higher pressures.

Numerous studies have been performed to evaluate the effects of tibial tuberosity anteriorization and medialization on the resultant patellofemoral contact forces.[3,12,20,23,27,33,38] These studies have typically focused on measuring the forces on the patella, rather than the trochlea. Beck et al[2] first evaluated the resultant trochlear pressures after AMZ and described decreased contact forces with a concomitant medial shift, noting the limitation of using "normally aligned" knees. Specifically, in their study, the distance from the TT to trochlear groove did not appear to be abnormally elevated.

To the best of our knowledge, our present study is the first instrumented investigation demonstrating decreased trochlear pressures after SA osteotomy of the TT: a result predicted by the 2-dimensional force calculations of Maquet.[25] These results are particularly useful when planning cartilage repair procedures on the trochlea, as they may offer an offloading alternative to AMZ for patients with medial trochlear lesions.

Typical clinical indications for AMZ are for patients with symptomatic arthrosis of the lateral or distal aspects of the patella with clinical and radiographic malalignment, such as tilt and/or subluxation, who have failed nonoperative treatment. Pidoriano et al[30] noted optimal results with type 1 lesions (distal lateral patellar chondrosis and intact trochlea) and poor results with types 3 and 4 (panpatellar and trochlear involvement) after AMZ. Ramappa et al[33] compared medialization and AMZ for correcting patellar maltracking and found them to be equivalent. Anteromedialization has also been recommended for those patients undergoing simultaneous cartilage repair procedures as an adjunct to unload and protect the patellofemoral joint.[9,10,19] Anteromedialization shifts forces proximally and medially; however, both anteriorization and AMZ techniques can produce highly variable results because the biomechanics of the contact forces in the patellofemoral joint are multifactorial, as shown by Johnson et al[21] and Cohen et al.[5]

Standard AMZ techniques produce a 7-cm-long tuberosity pedicle, which is elevated a constant number of millimeters (typically 10-15 mm), and the amount of medialization (to optimize the TT–trochlear groove) is preoperatively calculated and then affected by varying the slope. The actual amount of displacement in each plane can be varied depending on the surgeon's preference and goals of the osteotomy. If more anteriorization is desired, the osteotomy can be cut in a more sagittal fashion. Similarly, if more medialization is desired, the osteotomy may be cut flatter (ie, medial-lateral or in the coronal plane). In a cadaveric study using pressure-sensitive film

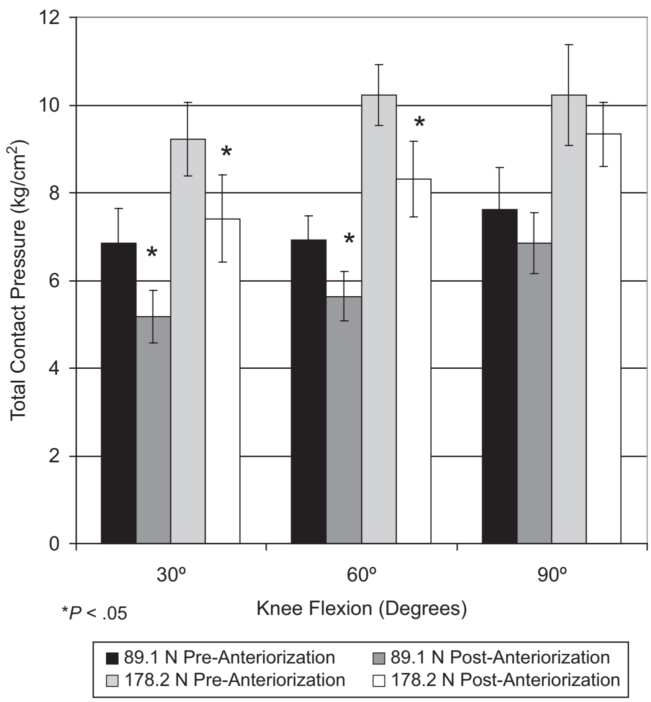

Figure 3. Mean change in total trochlear contact pressure after straight anteriorization of the tibial tuberosity.

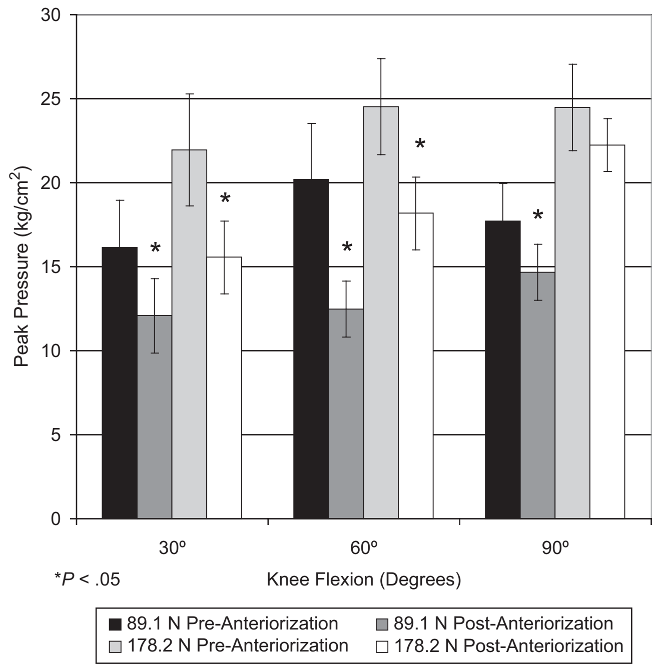

Figure 4. Mean change in peak trochlear contact pressure after anteriorization of the tibial tuberosity.

(Fuji Photofilm, New York, NY), Fulkerson et al[17] demonstrated a 65% reduction in lateral patellar facet pressure after AMZ and recommended 12 to 15 mm of anteriorization to maximize the decrease in contact forces.

The AMZ can be modified to maximize the anteriorization of the tibial tuberosity by increasing the slope of the oblique osteotomy; however, the amount of anteriorization is limited by the intermuscular septum and triangular shape of the tibia, which limits this slope to approximately 60°. Schepsis et al[34] described an anteriorization osteotomy using a 10-cm tubercle shingle hinged distally and anteriorized with an autologous bicortical iliac crest bone graft. This technique elevated the TT 12 to 15 mm. Fulkerson[16] described a modification to the AMZ whereby an offset bone graft is used in conjunction with a maximally oblique osteotomy to maintain anteriorization, eliminating medialization.

The AMZ was designed as an alternative to the Maquet procedure, which is essentially a straight anterior tibial tuberosity elevation (medialization as desired was discussed in the original technique, but the name Maquet today is synonymous with SA) that was associated with complications such as wound problems, nonunions, and fractures.[31] Maquet[26] first described the benefits of anteriorization of the TT in 1963. His described technique elevated the TT 2 cm, which (by 2-dimensional vector analysis) decreased overall resultant patellofemoral contact forces by 50% by decreasing patellofemoral joint reaction forces. It is now generally accepted that the amount of anterior elevation should not exceed 12 to 15 mm, as greater amounts of elevation lead to increased proximal patellar loading and higher rates of complications such as skin compromise.[35] In addition, the Maquet procedure requires bone grafting, an additional morbidity that is eliminated with the AMZ.[13,17]

Radin and Pan[32] evaluated the long-term results of patients who had undergone the Maquet procedure with respect to the length of the TT shingle used. Anteriorization techniques essentially rotate the patella along the sagittal plane, decreasing pressures distally but potentially increasing them proximally, especially at elevations of greater than 15 mm. They determined that shorter shingle lengths led to increased "tipping" of the patella with elevated pressures proximally, whereas longer shingle lengths minimized this tipping effect. Pan et al[28] described the degree of patellar rotation as being related to the length of the tubercle pedicle.

Several authors have evaluated the effects of various anteriorization elevations on contact pressure in the patellofemoral joint. Ferguson et al[11] studied the patellofemoral contact stress after anterior displacement of the TT. Using miniature piezoelectric contact stress transducers, they found that most of the relief of pressure was obtained by anteriorizing the TT 0.5 in (1.27 cm) and that increasing the amount of anteriorization beyond that resulted in only marginal decreases in patellofemoral stress. Fernandez et al,[12] using similar technology, showed that a 1-cm elevation was most efficient and that higher elevations, although decreasing overall pressures, did result in zones of higher peak pressures proximally. Benvenuti et al[3] designed a computer simulation of various anterior elevations and medializations on cadaveric models. Cohen et al[4] performed virtual surgeries using the MRIs of patients who were scheduled for AMZ using finite element analysis and

TABLE 1
Mean Shift (mm) in the Center of Force After Straight Anteriorization Osteotomy[a]

	89.1 N		178.2 N	
Flexion, deg	Medial-Lateral	Proximal-Distal	Medial-Lateral	Proximal-Distal
30	2.37	–1.02	1.92	–0.95
60	0.6	0.34	–0.85	0.95
90	2.92	–0.66	0.9	–0.92

[a]Negative numbers indicate distal or medial shift.

found highly variable changes in patellofemoral stress. Fulkerson et al[17] demonstrated that distal and lateral lesions of the patella benefited from AMZ. In addition, several other authors have demonstrated good results with this technique.[17,23,30] Nakamura et al[27] demonstrated in a cadaveric model that a 1-cm elevation optimized the decrease in resultant deduced patellofemoral forces. Their technique was limited, however, because forces were calculated indirectly using kinesiological techniques, rather than directly at the patella or trochlear contact areas.

Despite the abundance of published reports demonstrating improvement after realignment or offloading procedures such as the Maquet or AMZ, the precise mechanism for the symptomatic improvement is unclear.[15] Direct palpation of advanced patella chondromalacia has been shown to be insensate.[8] The theory of tissue homeostasis has been proposed to explain the origin of patellofemoral pain.[7] This theory incorporates many of the principles described by other authors, including increased intraosseous pressure,[36] denervation after surgical procedures,[40] and the role of the peripatellar synovium,[14,22] to explain the source of patellofemoral pain.

The technique used in this investigation is a modification of the SA osteotomy of the tibial tuberosity proposed by Fulkerson et al (unpublished data, 2007), which eliminates the need for bone grafting. Although this technique is technically challenging and is not recommended for general use at this time, there is a subset of patients who may benefit from its use. The technical specifications of the osteotomy were specifically designed to optimize potential decreases in contact pressure while minimizing the potential for complications. Based on the previously outlined anteriorization studies, it was thought that an anteriorization of 1 cm would provide optimal mechanical advantage, and when combined with a 10-cm-long tibial shingle, it would minimize potential side effects such as proximal patellar loading from patellar tipping and skin complications. Because the present study measured trochlear contact pressures, as opposed to the vast majority of previous investigations that recorded patellar pressures, we cannot comment on whether our SA osteotomy technique resulted in patellar tipping or proximal patellar loading. However, there was no clinically significant proximal or distal shift in the center of force after SA osteotomy, suggesting that such patellar tipping did not occur to any significant extent. Further investigation of the patellar contact pressures after SA osteotomy could possibly demonstrate this effect more clearly. In addition, as the literature has primarily focused on patellar contact pressures, a comparison study of trochlear contact pressures after the Maquet anteriorization osteotomy could offer further insight into the potential differences between the 2 anteriorization osteotomy techniques.

There were several limitations to our study, specifically regarding the cadaveric model and the pressure sensors used. There are a variety of pressure sensor systems available for use. Tekscan sensors have been shown to be more accurate than is pressure-sensitive film,[1] are reusable, and allow for preosteotomy and postosteotomy testing at varying loads and angles without the need to change sensors. Use of the Tekscan sensors allows comparison with other studies measuring trochlear pressures.[2,18] The sensors themselves have specific limitations such as their ability to lay completely flat on the complex trochlear contour. They have a propensity to crinkle and are fragile as they are quite thin (0.1 mm). The benefit of using a thin sensor is that there is a low likelihood of confounding the results due to the presence of material between the articular surfaces of the patellofemoral joint. In addition, because of variations in the cadaveric sizes, some specimens had areas of the trochlear that were not fully covered by the sensors, potentially missing areas of altered contact pressures. This can be seen in Figure 2 as areas of increased contact pressure near the edges of the map. To minimize this potential error, the sensors were placed uniformly starting at the superior aspect of the trochlea, centered medial to lateral.

Although the pressure sensors provided flexibility for performing the investigation with repeat measurements at varying angles and extensor loads, there is considerable variability between our results and those of previous authors. Specifically, although our experimental design was similar to that of Beck et al[2] and our findings similar in terms of showing a decrease in contact pressures after osteotomy, our absolute values for pressure were not comparable. Possible explanations for these variations are differences in specimens such as femoral-tibial angles, Q angles, and tibial size, as well as subtle variations in calibration techniques. Our preosteotomy values were comparable with those published by Garretson et al[18]; therefore, we chose to focus on the change in contact pressure after osteotomy rather than absolute values for the resultant pressures.

The cadaveric model has limitations specific to the loading of the quadriceps tendon only, and knee flexion position was held manually with the aid of an extension block rather than actively through contraction of the hamstring muscle units. As such, this represented an open kinetic chain model. Although this experimental technique has been previously validated,[2] it is unclear what difference would have resulted from use of a closed kinetic chain model such as that used by Kuroda et al,[24] although in the clinical setting, closed kinetic chain exercises have been shown to have some advantage over open kinetic chain exercises for patients with patellofemoral pain.[39]

In addition, there was considerable variability in specimen size and mechanical alignment, highlighting the need for refinement of the experimental model. The minimal shifts shown in the center of force were not thought to be clinically significant. Cohen et al[5] reported up to 4.4-mm medial shift of patellofemoral forces after AMZ but found no statistical difference in the center of force after Maquet anteriorization, corresponding to our findings.

CONCLUSION

We demonstrated significantly decreased trochlear contact forces after SA osteotomy of the TT, without a resultant medial shift of the center of force. Further biomechanical testing of SA osteotomy of the TT, similar to that done previously for AMZ,[6] is needed to determine strength characteristics of the osteotomy technique before recommending this procedure for routine clinical use. The SA osteotomy of the TT may be a better alternative than AMZ for patients with chondral lesions of the medial patellofemoral contact areas or for those with normal alignment undergoing patellar and/or trochlear cartilage repair procedures.

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