Contact Pressure at Osteochondral Donor Sites in the Patellofemoral Joint

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Background: The lowest contact pressure point is presumed to be the best site to harvest an osteochondral plug and minimize morbidity.

Hypothesis: Patellofemoral contact pressures are not uniform and are lowest along the medial patellofemoral articulation.

Study Design: Controlled laboratory study.

Methods: Seven cadaveric knees were tested with an electroresistive, dynamic pressure sensor placed onto the femoral side of the patellofemoral joint. The extensor mechanism was loaded with 89.1 N and 178.2 N, and the knee was manually cycled 3 times (0°-105°) per load. Mean trochlear pressures were calculated.

Results: Mean contact pressures were greatest in the central trochlea (5.80 kgf/cm^2), followed by the lateral (2.56 kgf/cm^2) and medial trochlea (1.60 kgf/cm^2) at 89.1 N ($P < .05$). At 178.2 N, pressures increased to 9.47, 5.81, and 2.75 kgf/cm^2, respectively ($P < .05$). Lateral trochlear pressures decreased moving distally from 1.25 to 0.50 kgf/cm^2 at 89.1 N and 4.57 to 1.29 kgf/cm^2 at 178.2 N.

Conclusions: Contact pressures are lowest along the medial trochlea and decrease distally along the lateral trochlea.

Clinical Relevance: Osteochondral plugs from the medial femoral trochlea may be desirable if trochlear size permits. If harvesting from the lateral femoral trochlea, consider harvesting distally near the sulcus terminalis.

Keywords: osteochondral transplantation; patellofemoral contact pressure; donor morbidity

Osteochondral autograft transplantation techniques have become an accepted treatment option for some symptomatic isolated cartilage defects in the knee. Currently, osteochondral autograft plugs are most often harvested from the lateral femoral trochlea or femoral notch and transferred into the defect in the weightbearing cartilage surface. Hangody et al[11] described donor sites on the medial, superior, and lateral aspects of the femur at the patellofemoral joint but did not indicate the biomechanical advantages of one site over another.

Theoretically, to minimize donor site morbidity, osteochondral plugs should be harvested from sites with the lowest contact pressures. Brown et al[4] demonstrated increased contact stress concentration at the rim of osteochondral defects ranging in size from 1 to 7 mm in a weightbearing area of the canine femoral condyle. Increased rim stress concentration will lead to degenerative changes, as shown by Jackson et al.[15] In a goat model, they showed that 6-mm osteochondral defects "undergo progressive changes resulting in resorption of the osseous walls of the defect, the formation of a large cavitary lesion, and the collapse of the surrounding articular cartilage and subchondral bone."[15(p53)] At best, osteochondral donor sites heal with fibrocartilage rather than hyaline cartilage. Techniques vary with regard to donor plug size, which ranges from 2.7 to 10 mm. The mosaicplasty technique advocates the use of many small plugs, whereas the osteochondral autograft technique (also called OATS) uses fewer, larger plugs. Success with both techniques has been documented at early follow-up.[5,10,22] Regardless of the plug size, rim stress around osteochondral defects may lead to concentration and degeneration in addition to morbidity associated with patellofemoral pain. In an effort to

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decrease the propensity for donor site degeneration and postoperative patellofemoral symptoms, the graft should be harvested from sites with the lowest contact pressure.

A variety of methods have been used to measure joint contact pressures, including joint sectioning, dyes, cement casts, computer models, and pressure-sensitive film.[1,9,13,21] Although there is significant literature regarding patellofemoral contact pressure, most of it involves the retropatellar surface rather than the femoral side of the joint. Simonian et al[18] evaluated contact pressures on the lateral trochlea and in the femoral notch using a bioabsorbable tack to transfix pressure-sensitive film. They reported a uniform pressure distribution of between 22.4 and 28.0 kgf/cm^2. Ahmad et al also recently published a study in which they used a stereophotogrammetric technique to determine contact pressure and radius of curvature at donor sites.[2] They found 3 areas of non–load bearing: the most lateral and medial trochlear areas and the most inferior aspect of the intercondylar notch. Of the donor sites tested, only the most distal-medial donor site showed statistically decreased patellofemoral contact pressures.

In our study, an improved method of contact pressure measurement was used. This involved a mylar conductive paint sensor (K-Scan, Tekscan Inc, Boston, Mass), which is thinner than pressure-sensitive film (0.1 mm vs 0.3 mm) and allows for dynamic and repeated pressure measurement through a computer interface. This technology has been previously compared to Fuji film and was found to be easier to use, more reliable, and more reproducible.[6,12] Harris et al reported that contact areas measured with Fuji film were 11% to 36% lower than those measured by the Tekscan sensors.[12] Furthermore, DeMarco et al found a significant difference in percent pressure error: Tekscan sensors were 2.5 times more accurate, with an average error of 4% versus 11% for Fuji film, when the sensors were appropriately calibrated.[6] In addition to the increased accuracy, the Tekscan sensors have other significant advantages over Fuji film, including real-time (instantly repeatable measurements that allow for multiple test conditions without sensor repositioning). Matsuda et al[16] took advantage of this technology and evaluated patellofemoral contact pressures in total knee arthroplasty. Their model varied quadriceps load as a function of knee flexion angle and found peak contact pressure that increased from about 5.1 kgf/cm^2 at 0° to 51.0 kgf/cm^2 at 105°. However, no evaluation of the location or distribution of pressures was made.

Our study hypothesis is that contact pressures in the patellofemoral joint are not equal. The purpose of this study was to accurately define the distribution of patellofemoral contact pressures, using contemporary technology to determine the optimal donor site from which to harvest an osteochondral autograft.

MATERIALS AND METHODS

Technology

An electroresistive sensor using mylar conductive paint was used in this study (K-Scan #4000, Tekscan Inc). The

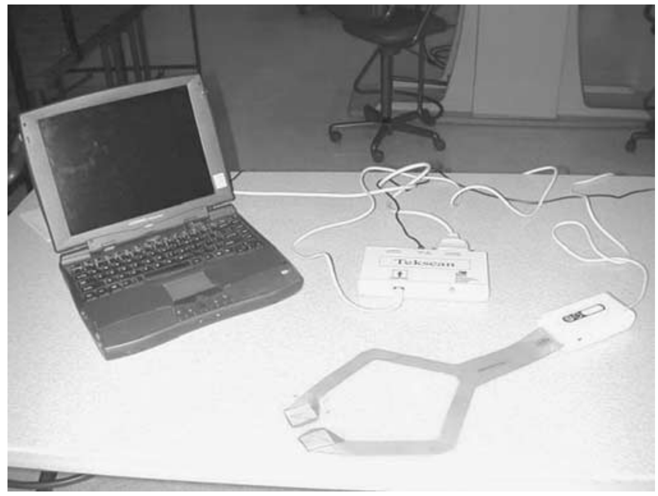


Figure 1. Horseshoe-shaped sensor pad.

Model 4000 sensor is horseshoe-shaped with a sensor pad 28 × 33 mm in size on each prong, for a total surface of 56 × 33 mm (Figure 1). 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 psi. After adjusting the sensitivity, calibration allows conversion of resistance into pressure units. The computer interface allows display of pressure distribution on the sensor pad in real time so that dynamic and repeated measurement of pressure in the patellofemoral joint during knee range of motion can be recorded in a "movie." The display is color coded, giving a visual representation of the pressure distribution.

The software allows for sophisticated data analysis. After a movie is recorded, the maximum pressure placed on each sensel during the entire movie can be displayed. Alternatively, the movie can be analyzed on a frame-by-frame basis, giving dynamic information. For each frame, the total contact area and force are easily displayed. Repeat measures are easily obtained by additional cycling events.

Each sensor was individually calibrated on an Instron materials testing system (Model 1321, Instron, 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. When a sensor was used, its specific calibration file was loaded into the software interface.

Specimen Preparation

Seven fresh cadaveric knee specimens, including the distal half of the femur and the proximal half of the tibia and fibula, were tested. The mean age of the donors was 67

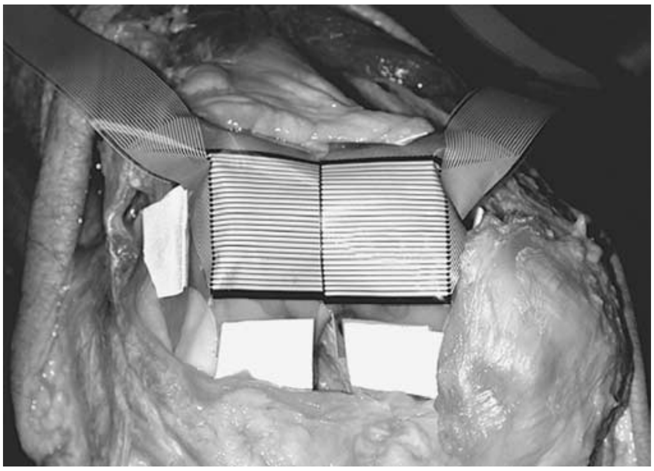


Figure 2. The pad sewn into place covering the medial, central, and lateral trochlea.

Figure 3. Testing apparatus with weight applied to the extensor mechanism.

years (range, 47-82 years). The specimens originated from donors without known skeletal diseases. The specimens had no signs of articular cartilage degeneration, bone disease, or soft tissue disease at the time of dissection.

Specimens were firmly fixed to the testing station by a clamp on the femoral shaft. An extended lateral parapatellar arthrotomy was performed in each knee to gain access to the patellofemoral joint. The sensor was sutured onto the femur using a No. 3-0 Vicryl suture (Ethicon Inc, Somerville, NJ) at the juxta-articular margin so that 1 pad covered the medial trochlea and 1 pad covered the lateral trochlea; the pads were apposed in the trochlea or overlapped slightly (Figure 2). The lead investigator then recorded a movie while outlining the edge of the trochlear surface with a pencil for each knee. The recorded movie for each knee was used in subsequent analysis to establish the position of each sensor relative to the trochlear surface.

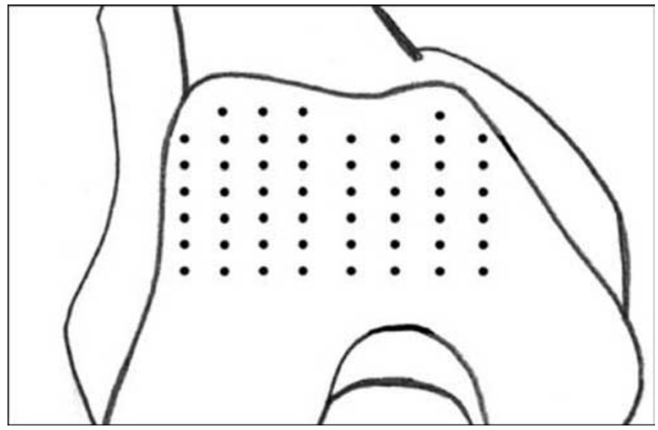


Figure 4. Schematic mapping of pressure points.

The arthrotomy was repaired with a No. 0 Ethibond suture (Ethicon Inc) in a running fashion, leaving the soft tissue envelope intact over the knee. Care was taken to prevent imbrication of the repair. Two Krackow stitches with No. 5 Ethibond sutures (Ethicon Inc) were then placed in the quadriceps tendon and connected to a fish scale. The scale was connected to a rope, which ran over a pulley and which could be loaded as desired (Figure 3). A model that simulated nonweightbearing resisted extension of the knee was used, similar to the method of Skyhar et al.[19] Each knee was loaded with a constant 89.1-N load on the quadriceps tendon, similar to the 100-N force used by Simonian et al[18] and Torzilli et al.[20] The force was aligned with the shaft of the femur.

Each knee was manually cycled 3 times through a functional range of motion from 0° to 105°. The 89.1-N load through the quadriceps tendon was kept constant throughout the 3 cycles. The 3 cycles were performed at a rate of 1 cycle every 15 seconds. While the cycles were performed, a movie of the pressure changes on the sensor was recorded. At the end of the loading cycle, the load was increased to 178.2 N, and the 3 cycles were repeated and another movie was recorded. Therefore, 2 movies for each specimen were obtained, for a total of 16 movies.

RESULTS

A pressure map of the anterior aspect of the distal femur, consisting of 52 pressure points, was created (Figure 4). The map included the medial, lateral, and central trochlea to a point 3 cm distal to the proximal origin of the trochlea. The data points filled 8 columns and 7 rows, in which the first row is proximal and the first column is lateral. This left a total of 7 specimens for inclusion in the results. For each movie, the position on the sensor corresponding to each pressure point was determined, and the maximum pressure encountered was recorded. Thus, the maximum pressure encountered at any point on the anterior femur was known for each specimen at both loading conditions.

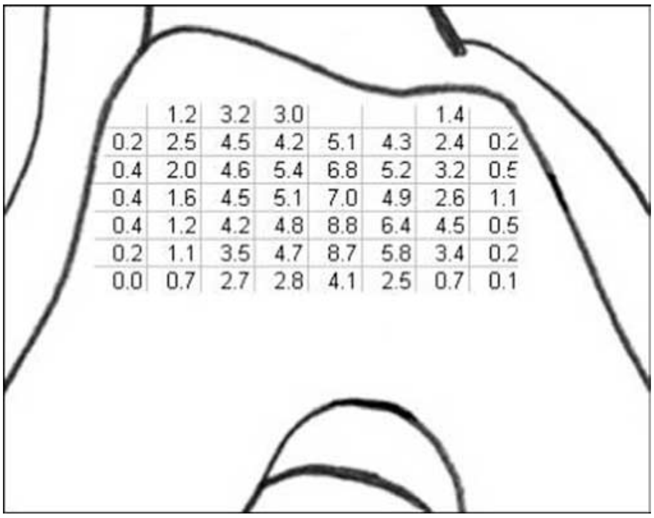


Figure 5. Pressure distribution with 89.1-N load.

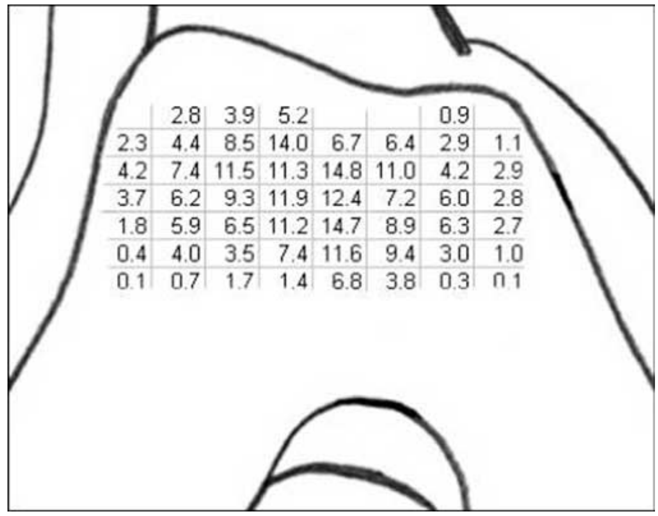


Figure 6. Pressure distribution with 178.2-N load.

TABLE 1
Pressure Versus Flexion Angle, 89.1-N Load

Flexion, degrees	Pressure, kgf/cm^2	Row	Column	Contact Area, mm^2	Force, N
0	4.9	4.7	8.4	111.0	20.5
30	10.3	8.0	12.5	205.2	58.1
60	9.7	13.6	10.2	268.6	65.1
90	10.7	19.3	11.1	309.6	68.4
105	10.9	20.8	11.0	336.7	66.7
90	8.4	19.5	10.2	250.8	42.4
60	7.9	14.0	11.0	218.0	42.9
30	8.0	10.4	12.5	189.0	38.4
0	4.0	4.9	8.3	103.9	17.1

TABLE 2
Pressure Versus Flexion Angle, 178.2-N Load

Flexion, degrees	Pressure, kgf/cm^2	Row	Column	Contact Area, mm^2	Force, N
0	6.4	8.1	11.1	138.4	28.3
30	19.7	8.1	10.9	187.8	77.7
60	19.5	12.8	11.5	258.1	111.1
90	19.0	16.4	11.0	333.0	119.3
105	19.7	18.5	9.8	376.2	118.0
90	18.0	16.8	11.3	308.3	101.5
60	18.9	13.3	10.7	237.5	88.7
30	16.6	9.1	10.6	173.2	60.8
0	6.1	8.4	10.7	121.9	27.1

The maximum pressures at each point were averaged among the 7 specimens (Figures 5 and 6).

Data analysis based on the angle of knee flexion was performed. For each loading cycle, the sensel encountering the highest pressure at 0°, 30°, 60°, 90°, and 105° of flexion was determined as the knee was flexed and extended. The values for the 3 motion cycles were averaged for each specimen for both loading conditions. The values for each of the 7 specimens were then averaged for both loading conditions (Tables 1 and 2). In these tables, the rows and columns indicated are taken from the sensor itself, on which each sensel is designated by a row and column. Because each sensel covers slightly less than 1 mm^2, each column is roughly 1 mm in width and each row roughly 1 mm in height. The column numbers increase going from lateral to medial and the rows from proximal to distal. These tables demonstrate that the maximum contact pressure moves medially and distally with knee flexion, and the contact force and contact area both increase with knee flexion up to 90°, then decrease with further flexion.

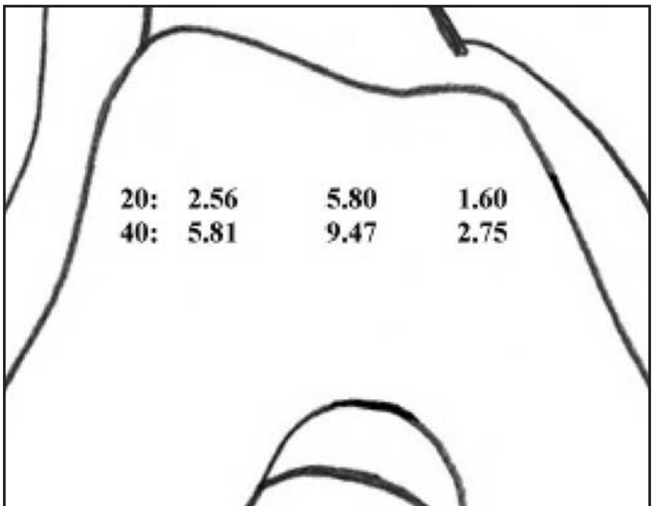
For each specimen, the individual sensel encountering the highest pressure during the 3 loading cycles was determined. The pressure was recorded, as well as the position of the sensel on the femoral map and the angle of knee flexion at which the pressure occurred. A grid in which rows were 1 mm in height and columns 1 mm in width was used to determine position. In addition, the software calculated the center of force (Table 3).

A ratio of the widths of the medial, central, and lateral trochlea was determined by measuring each specimen. The average width of the lateral trochlea was 2 times greater than the average width of the central and medial trochlea, which resulted in the lateral trochlea receiving 4 columns and the medial and central trochlea receiving only 2 columns. In Figures 5 and 6, columns 1 through 4 represent the lateral trochlea, columns 7 and 8 represent the medial trochlea, and columns 5 and 6 represent the central trochlea. With the 89.1-N quadriceps load, the mean of the lateral trochlear pressures was 2.56 kgf/cm^2, the mean of the medial trochlear pressures was 1.60 kgf/cm^2, and the mean of the central trochlear pressures was 5.80 kgf/cm^2.

TABLE 3
Peak Pressures at 89.1 N and 178.2 N[a]

	89.1 N	178.2 N
Pressure, kgf/cm^2	17.4	31.1
Row	13.3	12.9
Column	13.6	11.1
Angle, degrees	68.3	58.1
COF row	12.1	11.4
COF column	24.7	27.1

[a]COF, center of force.



89.1 N:

	Lateral	Central	Medial
Mean ± SD	2.56 ± 1.81[a,b]	5.80 ± 1.86[a,b,c]	1.60 ± 1.46[a,c]
Range	0.039-5.43	2.49-8.81	0.167-4.47

[a]Significant for each location (lateral, central, and medial) ($P < .05$).
[b]Significant difference between lateral and central ($P < .05$).
[c]Significant difference between medial and central ($P < .05$).

178.2 N:

	Lateral	Central	Medial
Mean ± SD	5.81 ± 3.94[a,b]	9.47 ± 3.47[a,b]	2.75 ± 1.93[a,b]
Range	0.12-14.03	3.84-14.8	0.28-6.32

[a]Significant for each location ($P < .05$).
[b]Significant difference between each location ($P < .05$).

Figure 7. Mean pressures by the load conditions 89.1 N (20 lb) and 178.2 N (40 lb).

The differences among these pressures differed significantly according to a single-factor analysis of variance (F = 20.37, $P < .05$). Additional post hoc analyses indicated that the lateral maximum pressures differed significantly from central pressures ($t = 2.07$, $P < .05$) but not from lateral mean pressures ($t = 2.03$, $P > .05$). Central maximum pressures also differed significantly from medial maximum pressures ($t = 2.03$, $P < .05$). With the 178.2-N load, the single-factor analysis of variance revealed that location again significantly affected the maximum pressures observed (F = 12.37, $P < .05$). In this case, each mean pressure differed significantly from each of the others indicated according to post hoc analysis (lateral vs central, $t = 2.03$, $P < .05$; lateral vs medial, $t = 2.03$, $P < .05$; central vs medial, $t = 2.08$, $P < .05$) (Figure 7). There was no significant difference between the pressures on the far lateral femur (column 1) and the far medial femur (column 8) at both loads.

TABLE 4
Summary of Pressures

	Mean Pressures, kgf/cm^2	
	89.1 N	178.2 N
Lateral trochlea	2.56	5.81
Medial trochlea	1.6	2.75
Central trochlea	5.8	9.47
Group 1	1.25	4.57
Group 2	0.92	4.41
Group 3	0.5	1.29
Column 1	0.27	2.09
Column 8	0.43	1.74

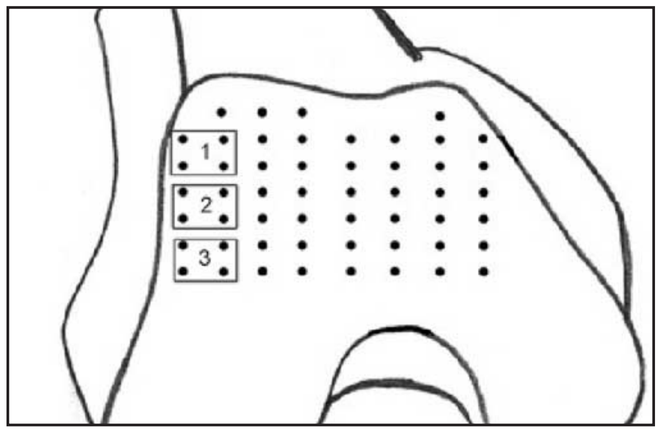


Figure 8. Grouping of pressure points.

The lateral trochlear pressure points were grouped to cover an area representative of a 10-mm plug (a large plug), as shown in Figure 8. The average pressures for groups 1, 2, and 3 with the 89.1-N load were 1.25, 0.92, and 0.5 kgf/cm^2, respectively. For the 178.2-N load, the pressures were 4.57, 4.41, and 1.29 kgf/cm^2, respectively. The pressure for group 3 was lower than that for groups 1 and 2 at both loads, and these differences were statistically sig-

TABLE 5
Summary of the Literature by Technique

Study	Testing Method	Sensor	Pressure, kgf/cm^2
Eilerman et al[7]	647- and 1923-N quadriceps load	Pressure-sensitive film	8.5-12.4
Ahmed et al[3]	734- and 1468-N quadriceps load	Pressure-sensitive film	0-35.8
Matsuda et al[16]	Varying quadriceps load	Mylar conductive paint	5.1-51.0
Simonian et al[18]	100-N quadriceps load	Pressure-sensitive film	22.4-28.0
Ferguson et al[8]		Mathematical model	30.6
Matthews et al[17]	421- to 3420-N quadriceps load	Mathematical model	13.05-128.5
Heegaard et al[13]	40-N quadriceps load	Mathematical model	5.1

nificant ($P < .05$) (Table 4). Medial trochlear pressure points were not grouped in a similar fashion because we felt this area was too small for a large 10-mm plug.

DISCUSSION

Several studies have evaluated contact pressures of the retropatellar surface, with significant variations in reported pressures (Table 5). Ahmed et al[3] studied 24 cadaveric retropatellar contact pressures with 734-N and 1468-N quadriceps loads. They found marked specimen-to-specimen variations. In general, at 0° to 10° of flexion, the contact area was ovoid in distribution, located on the median patellar ridge with no contact in the trochlea. As flexion increased to the 20° to 60° range, pressure was distributed equally in 10 of 24 specimens or was dominant on the medial or lateral patellar facet in 14 of 24 specimens. Contact pressure rose from 50 to 400 N between 0° and 60°, remained constant, and then decreased after 90°. Contact pressures were 0-3.44 MPa (0-35.1 kgf/cm^2). Eilerman et al[7] also measured retropatellar contact area and pressure using 2 quadriceps loads, 647 N and 1923 N. They found no significant difference in the spatial distribution of the pressure with change in angle or load, although pressure increased with higher loads. Mean high pressures increased from 8.5 to 12.4 kgf/cm^2 with change in load from 647 to 1923 N. Huberti and Hayes[14] analyzed 12 specimens using pressure-sensitive film. They found contact pressures evenly distributed between the medial and lateral facets at various knee angles.

Other authors have used mathematical modeling in their analyses. Ferguson et al[8] found a contact pressure of 0.3 MPa (3 kgf/cm^2) using a quadriceps force consistent with light movement. Matthews et al[17] calculated patellofemoral forces from 421 to 3420 N for various activities, with pressures ranging from 1.28 to 12.6 MPa. Heegaard et al[13] modeled patellofemoral biomechanics and found higher lateral facet pressure with the knee in full flexion and extension; pressures averaged 0.4 MPa medially and 0.5 MPa laterally with a 40-N quadriceps load.

In the current investigation, mean lateral trochlear pressure was significantly higher than the mean medial trochlear pressure. Evaluation of the pressure map, however, reveals no significant difference in the mean contact pressure on the far medial and far lateral femur at either of the quadriceps loads. The generally lower pressure on the medial trochlea compared to the lateral trochlea suggests that based on biomechanical considerations, this may be an acceptable alternative site to harvest an osteochondral graft. However, large grafts may not be suitable for the medial trochlea because of its small size. Pressures in general decreased as the contact area moved distally. The grouping of pressure points on the lateral trochlea showed that pressure was significantly lower 2 cm distal on the lateral trochlea, suggesting that large grafts obtained from the lateral trochlea should be harvested at a point just proximal to the sulcus terminalis. The medial trochlea was not analyzed in similar fashion because of its small size. In this study, the average width of the femoral articular surface at the proximal aspect of the trochlea was 40.8 mm (15.3 mm medial and 25.5 mm lateral). Therefore, a 10-mm plug would leave only one third of the medial trochlear width remaining, an amount we considered excessively destructive for clinical purposes, independent of the relatively low pressures at that location.

The finding of nonuniform pressures in this study contrasts with the findings of Simonian et al,[18] Huberti and Hayes,[14] and Eilerman et al,[7] who all found uniform contact pressures. However, the studies of Ahmad et al,[2] Ahmed et al,[3] and Heegaard et al[13] found nonuniform pressures. There are differences between the findings in this study and those of Simonian et al, despite similar methodologies. These may be explained by the different technology used to measure pressures. Placing Fuji film onto a hard surface, such as the Suretac which Simonian et al[18] used, may artificially elevate the pressure and cause it to appear uniform.

The dynamic evaluation used in this study showed that the contact area was well covered by the sensor for this range of motion. Furthermore, the contact force decreased at greater than 90° of flexion, as predicted by normal knee biomechanics and the contact of the quadriceps tendon against the distal femur in high degrees of flexion. Although notch pressures were not measured in this study, the decrease in pressure as the contact area moved distally might suggest that notch pressures are lower, as shown by Ahmad et al.[2] Flexion beyond 105° is not required for most activities of daily living and results in contact of the quadriceps tendon with the femoral trochlea. Eilerman et al[7] used a quadriceps muscle force of 647 N to represent walking and 1923 N for stair climbing. However, Simonion et al[18] used a 100-N quadriceps load for the measurement of patellofemoral pressure. The values obtained in this study validate our approach. Relative force distribution is the most important information obtained, and this distribution was consistent with increasing load. Higher load on the quadriceps tendon resulted in a corresponding increase in contact pressure.

Limitations in this study were related to both the model and the K-Scan. The model was hindered by the fact that (1) the entire quadriceps mechanism was loaded rather than its individual components; (2) the relative action of other forces about the knee, particularly the hamstrings, was not accounted for; and (3) knee motion occurred by manual manipulation, not through active forces. The K-Scan was limited by (1) its thickness (0.1 mm), (2) its sensitivity to temperature changes, (3) its propensity to crinkle, (4) overlap in the central trochlea, and (5) establishing its position of the trochlea. The latter 3 points warrant further discussion.

We encountered some difficulty when tacking down the sensor pads to the trochlear surface. The sensor pads did not readily conform to the articular surface because they do not stretch over the surface. This limited the type of sensor used. We initially used a single sensor pad that was large enough to cover the entire surface of the trochlea; however, we were unable to conform the sensor to the concave surface of the central trochlea, resulting in gapping over this area and crinkling during testing, which led to pressure spikes and excessive sensor motion. Therefore, we used a sensor with 2 pads that enabled us to improve the conformity of the sensor in the central trochlea. The pads in the central trochlea were closely approximated or slightly overlapped to ensure that we recorded pressures in this region. A limitation in this technique is that recording error had to be corrected with each sampling. Finally, we eliminated interobserver error by using a single investigator to establish the position of each sensor. Sensors were not repositioned by this investigator 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.

CONCLUSIONS

It has previously been recommended that osteochondral autografts be harvested from the lateral trochlea or the femoral intercondylar notch, but these recommendations were not supported by biomechanical or basic science data. Our data demonstrate that the pressure on the medial trochlea is less than on the lateral trochlea. These results indicate that proximal lateral donor sites may be suboptimal and that medial donor sites may be the best option. However, because the medial trochlea is narrower than the lateral trochlea, we conclude that the medial trochlear donor site may be appropriate only for smaller donor grafts. Evaluating larger contact areas (10 mm^2) on the lateral trochlea (a relatively large donor site area) reveals that contact pressures decrease as one moves distally along the lateral trochlea. The lowest contact pressure was measured just proximal to the sulcus terminalis.

Based on these data and the limitations of the medial trochlea, we recommend that grafts 5 mm or smaller be taken from the medial trochlea starting just proximal to the sulcus terminalis. Larger grafts should be taken from the lateral trochlea, also starting just proximal to the sulcus terminalis. Because we did not test the femoral intercondylar notch, we cannot make recommendations regarding that location.

It is currently unknown whether these osteochondral donor sites will lead to degenerative changes, as the study by Jackson et al suggested.[15] Our study hypothesis was that contact pressures in the patellofemoral joint are not equal. Knowledge of accurate patellofemoral articulation pressures may help identify osteochondral donor sites with the lowest potential for morbidity. We believe that these sites have been identified by our study, and we hope that additional studies may help refine the technique of osteochondral autografting in an effort to minimize the morbidity associated with these procedures.

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