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The Effect of Tibial Tuberosity Realignment Procedures on the Patellofemoral Pressure Distribution

Archana Saranathan, MS^{1,2}, Marcus S. Kirkpatrick, MD¹, Saandeep Mani, MS^{1,2}, Laura G. Smith, BS^{1,2}, Andrew J. Cosgarea, MD³, Juay Seng Tan, PhD², and John J. Elias, PhD¹

¹Department of Orthopaedic Surgery Akron General Medical Center Akron, OH

²Department of Biomedical Engineering University of Akron Akron, OH

³Department of Orthopaedic Surgery Johns Hopkins University Baltimore, MD

Abstract

Purpose—The study was performed to characterize the influence of tibial tuberosity realignment on the pressure applied to cartilage on the patella in the intact condition and with lesions on the lateral and medial facets.

Methods—Ten knees were loaded in vitro through the quadriceps (586 N) and hamstrings (200 N) at 40°, 60° and 80° of flexion while measuring patellofemoral contact pressures with a pressure sensor. The tibial tuberosity was positioned 5 mm lateral of the normal position to represent lateral malalignment, 5 mm medial of the normal position to represent tuberosity medialization, and 10 mm anterior of the medial position to represent tuberosity anteromedialization. The knees were tested with intact cartilage, with a 12 mm diameter lesion created within the lateral patellar cartilage, and with the lateral lesion repaired with silicone combined with a medial lesion. A repeated measures ANOVA and post-hoc tests were used to identify significant ($p < 0.05$) differences in the maximum lateral and medial pressure between the tuberosity positions.

Results—Tuberosity medialization and anteromedialization significantly decreased the maximum lateral pressure by approximately 15% at 60° and 80° for intact cartilage and cartilage with a lateral lesion. Tuberosity medialization significantly increased the maximum medial pressure for intact cartilage at 80°, but the maximum medial pressure did not exceed the maximum lateral pressure for any testing condition.

Conclusions—The results indicate that medializing the tibial tuberosity by 10 mm reduces the pressure applied to lateral patellar cartilage for intact cartilage and cartilage with lateral lesions, but does not overload medial cartilage.

Keywords

malalignment; patellofemoral; tuberosity realignment; lesions; pressure; kinematics

INTRODUCTION

Patellofemoral disorders are frequently attributed to lateral malalignment [41]. A laterally malaligned patella is shifted and/or tilted more than normal with respect to the trochlear groove [15]. Several anatomical conditions can contribute to lateral malalignment, including a lateralized tibial tuberosity [3] and a weak vastus medialis obliquus (VMO) [27]. Lateral

malalignment can contribute to overloading the cartilage on the lateral facet of the patella [9, 38] and degradation of the overloaded cartilage [18, 41]. Lateral dislocation can also cause an area of cartilage degeneration, or a lesion, to develop on the medial facet of the patella, due to contact between the medial facet and the lateral condyle of the femur [14, 33]. Cartilage lesions increase the pressure applied to the surrounding cartilage [9, 22], which can overload the subchondral bone and activate the nociceptive fibers in the bone, causing pain [14].

Tibial tuberosity medialization and anteromedialization are two common surgical options for improving patellofemoral alignment [17, 41]. Medialization is primarily performed to reduce the lateral orientation of the patellar tendon for patients with a history of dislocation and minimal cartilage degeneration [16]. Anteromedialization is typically reserved for patients with pain or instability accompanied by high grade partial thickness (> 50%) or full thickness (exposed bone) lesions on the lateral or distal patella [17, 37]. The anteriorization component of anteromedialization is performed to decrease the posterior orientation of the patellar tendon and increase the moment arm about the center of rotation of the knee, both decreasing patellofemoral compression [17, 29]. Caution is advised when considering medialization or anteromedialization for patients with lateral malalignment and a medial lesion, due to concerns about shifting pressure toward the lesion [17, 29, 37], limiting surgical options for these patients.

In vitro studies have indicated that both medialization and anteromedialization of the tibial tuberosity improve alignment [38] and decrease the pressure applied to lateral patellofemoral cartilage [4, 38]. However, these in vitro studies have not addressed the belief that these procedures reduce the pressure surrounding a lesion on the lateral facet, but increase the pressure surrounding a lesion on the medial facet [17, 29, 37]. The current study was performed to characterize the influence of tuberosity medialization and anteromedialization on the patellofemoral pressure distribution for patellas with lateral and medial cartilage lesions. The hypothesis was that tibial tuberosity medialization and anteromedialization decrease pressure adjacent to a lateral lesion, but increase pressure surrounding a medial lesion.

MATERIALS AND METHODS

In vitro experimental design

Ten cadaveric knees from ten separate donors were tested in vitro. The median age was 64 years (range: 47 to 85 years), and four of the knees were from female donors. Concurrent studies were performed with the same group of knees [10, 28]. Each knee was stored at -20 °C prior to dissection. Soft tissues surrounding the joint were removed, except for the tendon attachments for the quadriceps muscle group, the semimembranosus, and the biceps femoris. The combination of the vastus intermedius/vastus medialis longus/rectus femoris (VI/VML/RF) was separated from the VMO and the vastus lateralis (VL). The ligaments of the knee were not disturbed during dissection. Knees with grade 3 or 4 lesions [36] within the patellofemoral cartilage were excluded, with less than half of the knees examined used for testing.

Each knee was tested with forces applied through the quadriceps and hamstrings while flexed to 40°, 60° and 80° [10, 28] (Fig. 1). The femur was positioned horizontally on a previously evaluated testing frame [10, 28]. A tibial rod was passed through a slotted fixture secured to a plate that controlled the flexion angle. While flexion was constrained, the other tibiofemoral degrees of freedom were unconstrained other than the relatively low friction between the plastic rod and fixture. The knees were kept moist with 0.9% saline solution.

The tibial tuberosity was positioned to represent pre-operative lateral malalignment, as well as surgical medialization and anteromedialization [28]. The order of the tuberosity positions was varied between the series of tests. The tuberosity was osteotomized from the tibia along a medial-lateral plane with an oscillating saw (Multi-Max, Dremel, Denver, CO) using a step-cut. The osteotomized tuberosity was reattached to the tibia with aluminum screws and nuts. To represent the pre-operative, laterally malaligned knee, the tuberosity was shifted laterally. The average ($\pm$ standard deviation) tibial tuberosity-trochlear groove (TT-TG) distance was 19 ± 1 mm, which is approximately 5 mm greater than the average value in asymptomatic knees [1, 42]. To represent medialization, the tuberosity was shifted medially by 10 mm from the pre-operative position. To represent anteromedialization, the tuberosity was anteriorized by 10 mm from the medialized position by placing a 10 mm thick plastic component behind the tuberosity. The lateral retinaculum was sectioned to represent the lateral release that typically accompanies tibial tuberosity medialization and anteromedialization [17, 37]. The lateral release was considered to have minimal influence on the pre-operative condition, as a previous in vitro study showed no significant influence on patellar medial translation and an increase in medial tilt of approximately 1° from 40° to 80° of flexion, with the change having no significant influence on the maximum pressure [34]. A decrease in the pre-operative lateral pressure due to a lateral release would decrease the influence of tuberosity realignment on the pressure distribution.

The quadriceps and hamstrings were loaded through a weight-and-pulley system. Loading cables were secured to straps sutured into the tendons. The cable representing the VI/VML/RF was oriented along the axis of the femur. The VMO cable was aligned at an angle of approximately 45° medial to the axis of the femur in the coronal plane, and the VL cable was aligned at an angle of approximately 20° lateral to the same axis [11, 26], with the anatomical orientation in the sagittal plane also represented. The loading cables for the semimembranosus and the biceps femoris were oriented parallel to the femur. Electromyographic-derived contributions of each quadriceps muscle to the extension moment for patients with pain and asymptomatic subjects [27, 45] were input into a computational model [7] to determine a distribution of forces that represented subjects with patellofemoral pain and an elevated lateral pressure [9]. The loading cables representing the VI/VML/RF, the VL and the VMO were loaded to 432 N, 127 N and 27 N, respectively [9, 10, 28]. The semimembranosus and the biceps femoris were both loaded to 100 N [10, 28].

Each knee was initially tested with the cartilage intact, followed by testing with a lateral and then a medial lesion on the patella. The patella was everted to create full-thickness lesions with a coring device (Arthrex, Naples, FL) and a scalpel. The lateral and medial lesions were centered on the appropriate facet, at a point midway between the patellar ridge and the lateral or medial edge of the articular surface and midway between the proximal and distal edges of the articular surface [9]. To limit the medial lesion to the medial facet, a diameter of 12 mm was used for each lesion, producing an area 30%-40% smaller than lesions typically encountered in vivo [22, 32]. For tests performed with a medial lesion, the lateral lesion was filled with silicone (Aquarium Sealant, All-Glass Aquarium Co., Franklin, WI) and allowed to cure for 90 minutes to reduce pressure concentrations surrounding the lateral lesion [9]. Only the pressure applied to the medial facet was analyzed when the lateral lesion was filled with silicone.

Kinematic measurements

The position and orientation of the femur and patella were tracked throughout testing using sensors from a pulsed DC magnetic tracking system (trakSTAR, Ascension Technology, Burlington, VT) secured to each bone. Tracking data was only analyzed for the intact cartilage, since the lesions were created to determine the influence on the pressure distribution rather than kinematics. The sampling rate (200 Hz) and the configuration of the

testing frame were optimized based on previous studies to limit the influence of metal components within the magnetic field on the recorded position of each sensor to less than 0.5 mm [10, 24, 30]. A digitizer consisting of a sensor and probe recorded the position of previously described anatomical landmarks to establish the femoral and patellar reference axes [10, 31, 40]. The transepicondylar axis (x-axis) was determined by digitizing the most medial and lateral points on the femoral epicondyles, with the knee center positioned midway between the two points. The long axis of the femoral shaft was established by digitizing two points along the posterior femur. The mutual perpendicular to the two axes determined the anterior-posterior axis (y-axis), and the proximal-distal axis (z-axis) was formed from the cross-product of the x and y-axes. The reference axes for the patella were similarly identified, using one axis connecting the most medial and lateral points on the patella and a second axis from the midpoint of the medial-lateral axis to the most distal point on the patella. The positions and orientations of the femoral and patellar reference axes were quantified throughout testing based on the motion of the sensors fixed to the bones.

Patellofemoral kinematics were quantified based on the translations and rotations of the patellar reference axes with respect to the femoral axes. Patellar rotation about the medial-lateral axis (flexion), rotation about the anterior-posterior axis resulting in lateral translation of the distal pole of the patella (lateral rotation), rotation about the superior-inferior axis in the lateral direction (lateral tilt), and lateral translation (shift), were quantified from the reference axes using the floating axis coordinate system [10, 21]. The standard deviations about the mean for repeated measurements with the same loading conditions were on the order of 0.3° and 0.2 mm for patellar rotations and translations, respectively [10].

Pressure measurements

Patellofemoral contact forces were measured using thin film sensors (I-Scan 5051, Tekscan, Boston, MA) inserted into the patellofemoral joint, with access provided by the lateral release. The 0.1 mm thick sensors include 44 rows and columns of force-sensing elements, or sensels, every 1.27 mm. The sensors were coated with surgical jelly for calibration and the in vitro measurements to minimize shear forces. Each sensor was calibrated on a material testing machine while sandwiched between two steel plates and two sheets of neoprene rubber [9, 10] by relating at least five levels of applied force to sensor output with a polynomial curve [5]. Pressures were quantified by dividing the applied force by the area of each sensel. Within the patellofemoral joint, the reproducibility for repeated measurements of the maximum pressure has been reported to be approximately 0.1 MPa [25, 43, 44].

For each test, the sensor was positioned to cover the patellofemoral contact area. The VMO and VL were loaded to secure the sensor within the joint, and the pressure pattern was recorded while palpating the accessible portion of the patellar ridge to identify the position of the ridge on the sensor. The forces applied by the VI/VML/RF and hamstrings were added for each test. The sensor output was recorded at 10 Hz for 10 seconds, with the data averaged to create a single pressure profile. Each pressure profile was output to a spreadsheet and analyzed to determine the lateral force ratio and the maximum lateral and medial pressure. The lateral force ratio is the ratio of the contact force applied to cartilage lateral of the patellar ridge to the total contact force. To clearly distinguish between the maximum medial and lateral pressure, these measurements excluded a 5 mm wide band characterized as the patellar ridge.

Statistical analysis

Comparisons between the three tuberosity positions were performed at each flexion angle for all cartilage conditions. The maximum lateral pressure and the lateral force ratio were

analyzed for the intact cartilage and cartilage with a lateral lesion. The maximum medial pressure was analyzed for the intact cartilage and cartilage with a medial lesion. Because two knees sustained fractures following testing for the lateral lesion, one through the osteotomized tuberosity and the other at a corner of the step cut, only 8 knees were included in the analysis of the maximum medial pressure with a medial lesion. A repeated measures ANOVA was performed at each flexion angle, for each cartilage condition, to determine if any of the output varied significantly ($p < 0.05$) between the tuberosity positions. A post-hoc repeated measures Student-Newman-Keuls test was used to identify individual differences between the three conditions. Based on previous data, the targeted pressure difference related to tuberosity realignment was 0.5 MPa [4, 39]. A power analysis for paired comparisons indicated 10 specimens would be sufficient to identify a significant difference with a power of 0.94 if the standard deviation of the mean difference between tuberosity positions was 0.4 MPa [13]. With 8 specimens the power decreases to 0.86.

RESULTS

Medialization of the tibial tuberosity decreased the lateral shift, while anteromedialization decreased both the lateral shift and patellar flexion. The average lateral shift was significantly larger for the pre-operative condition than for the other two conditions at 40° and 80° ($p < 0.04$), with a difference of at least 1.0 mm for each significant change (Table 1). The average patellar flexion was 3.0° to 5.0° smaller with the tuberosity in the anteromedial position than for the other two positions, with the difference significant for each flexion angle ($p < 0.05$). No other significant kinematic differences were identified (Table 2).

With the cartilage intact, medialization and anteromedialization of the tibial tuberosity reduced the force and pressure applied to the lateral cartilage. Tuberosity medialization and anteromedialization decreased the average lateral force ratio (Fig. 2) by 5% to 14% compared to the pre-operative condition, with a significant difference ($p < 0.05$) for each condition except for anteromedialization at 40° (Table 3). Medialization and anteromedialization significantly ($p < 0.02$) decreased the maximum lateral pressure (Fig. 3) by 15% to 20% at 60° and 80° compared to the pre-operative condition. Medialization significantly ($p < 0.04$) increased the maximum medial pressure (Fig. 4) by 35% at 80° of flexion for intact cartilage, but the increase did not elevate the maximum medial pressure to the level of the maximum lateral pressure.

With a lateral lesion in place, tuberosity medialization and anteromedialization reduced the pressure applied to the lateral cartilage (Fig. 5), but realignment had little influence on the pressure applied to cartilage with a medial lesion. With a lateral lesion in place, medialization and anteromedialization significantly ($p < 0.05$) decreased the maximum lateral pressure by 15% to 23% at 60° and 80° compared to the pre-operative condition (Fig. 3). With a medial lesion in place, tuberosity realignment did not significantly influence the maximum medial pressure (Fig. 4, Table 3).

DISCUSSION

The most important finding of the current study was that tibial tuberosity medialization decreases the lateral shift of the patella and the force and pressure applied to lateral cartilage for malaligned knees. Previous in vitro studies have indicated that tuberosity medialization decreases the lateral shift [38] and tilt [35, 38] of the patella. The relatively large tilt moment produced by loading the VL, which was not loaded in the previous studies, could have contributed to medialization not influencing tilt for the current study. Even without influencing the tilt, tuberosity medialization shifted compression off the lateral facet of the

patella and decreased the maximum lateral pressure at 60° and 80° of flexion. A previous study that combined data from 0° to 90° of flexion indicated that medializing the tuberosity decreases the force applied to lateral cartilage and the maximum pressure [38]. Another study indicated that medializing the tuberosity has minimal influence on the maximum pressure at 45° [23], similar to the current study, indicating that tuberosity medialization is least effective at decreasing pressure near 40°. Medializing the tuberosity did not consistently increase the maximum medial pressure. With the tuberosity medialized, on average, one-third or less of the joint compression was applied to the medial facet of the patella. Medialization significantly increased the maximum medial pressure for only intact cartilage at 80°, with the maximum medial pressure still less than the maximum lateral pressure for this condition.

The anteriorization component of anteromedialization had less influence on the data than medialization. To maintain a uniform loading condition for all tests, the patellar tendon was reoriented without decreasing the quadriceps force, so the study did not account for the increased moment arm of the patellar tendon about the center of rotation of the knee. Therefore, anteromedialization could still provide a greater pressure reduction than medialization in vivo. One previous in vitro study showed a decrease in the peak patellofemoral pressure due to tuberosity anteriorization, without decreasing the quadriceps force [39]. On the contrary, another showed minimal decrease in the maximum pressure when anteriorizing the tuberosity from a medialized position, even though the simulated knee squat should have represented the quadriceps force decrease due to the increased moment arm [38].

Variations in pressure with lateral and medial lesions present were similar to those noted for intact cartilage. A lateral lesion tended to elevate the maximum lateral pressure, in agreement with a previous study [9]. Therefore, the decrease in the maximum lateral pressure due to medialization tended to be larger when a lateral lesion was present. The pressure decrease could reduce activation of nociceptive fibers in the subchondral bone and decrease pain [14]. Medialization did not significantly increase the maximum medial pressure with a medial lesion in place. Variability related to the medial lesion and silicone filling the lateral lesion likely contributed to the inconsistent increase in the maximum medial pressure. The analysis with medial lesions included two less knees than the analysis for intact cartilage. Because the difference in the maximum medial pressure between the tuberosity positions was less than half the targeted difference from the power analysis, a significant difference would not have been established with 10 knees. The average maximum medial pressure with a medial lesion did not reach the lowest maximum lateral pressure value for intact cartilage at any flexion angle.

The experimental set-up characterized patellofemoral kinematics and the pressure distribution at three separate flexion angles. Quadriceps and hamstrings forces were applied in a manner that represented a weakened VMO with a physiologically realistic extension moment [27, 45] and hamstrings co-contraction [10, 28]. For each test, the pressure sensor was optimally positioned to record the area of contact, and the position of the patellar ridge on the sensor was manually identified. Data was averaged over 10 seconds to reduce variations in the output of the sensor with time. Flexion angles less than 40° were not tested to avoid patellar instability that could be caused by the simulated lateral malalignment, VMO weakness and large quadriceps forces. From 40° to 80°, the shift in pressure allowed assessment of the influence of tuberosity realignment on the pressure distribution as the contact area moved from distal to a lesion to proximal to a lesion (Fig. 5).

Limitations related to in vitro representation of symptomatic knees should be noted. To control the size and location of lesions, knees with existing patellofemoral lesions were not

tested. The specimens with intact cartilage were generally well aligned, so malalignment was represented by increasing the TT-TG distance [10, 23, 28]. Trochlear and patellar dysplasia that can accompany malalignment [2, 15, 20] was not represented. To clearly separate the lesions, only lateral and medial lesions were represented [9], although proximal and diffuse lesions are also common [12, 19] and cause more pain following anteromedialization [37]. The lesions included an abrupt change from intact cartilage to no cartilage, which is not typical in vivo and could have elevated the surrounding pressure concentration, although this change was at least partially offset by creating lesions smaller than those encountered in vivo [12, 19, 22, 32]. Placing a pressure sensor within the patellofemoral joint also creates sources of experimental error, due to wrapping the sensor around the patella [43], shear loads [38], and differences in compliance between cartilage and the rubber used to calibrate the sensors [8, 43]. Each limitation influences the accuracy of the pressure magnitudes, although the inaccuracies are expected to be similar within a knee for each position of the tuberosity. Therefore, the trends from repeated testing of the knees are believed to be more accurate than the absolute pressure values. The trends indicate that medializing the tibial tuberosity improves alignment and reduces the pressure applied to lateral cartilage in a malaligned knee, contributing to improved function. The limited influence of medialization on the maximum medial pressure indicates that the risk of overcorrection is relatively low.

CONCLUSION

The original hypothesis was partially supported by the data. As expected, medialization and anteromedialization of the tibial tuberosity decreased pressure adjacent to a lateral lesion on the patella. The realignment procedures also decreased the maximum lateral pressure when the cartilage was intact. Medialization and anteromedialization of the tuberosity did not increase the pressure surrounding a medial lesion as much as expected. The results indicate that, within this in vitro model of a maligned patellofemoral joint, medializing the tuberosity by 10 mm effectively decreases the pressure applied to lateral cartilage with a lesion, without overloading medial cartilage, although the limitations of in vitro simulation must be considered when translating the results to clinical practice.

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Figure 1.

A schematic diagram of the testing frame, including representations of the reference axes for the femur and patella. The cables applying the forces representing the quadriceps and hamstrings muscles were secured to straps sutured into the tendons. The total force applied by the quadriceps was 586 N, with 200 N applied through the hamstrings. The osteotomized tibial tuberosity was placed in three positions to represent the pre-operative, medialized and anteromedialized conditions.

Figure 2.

Average ($\pm$ standard deviation) lateral force ratio for the knees with intact cartilage and with a lateral lesion. Significant differences between the tuberosity positions at each flexion angle are marked with letters (a > b at $p < 0.05$).

Figure 3.

Average ($\pm$ standard deviation) maximum lateral pressure for the knees with intact cartilage and with a lateral lesion. Significant differences between the tuberosity positions at each flexion angle are marked with letters (a > b at $p < 0.05$).

Figure 4. Average ($\pm$ standard deviation) maximum medial pressure for the knees with intact cartilage and with a medial lesion with silicone filling the lateral lesion. Significant differences between the tuberosity positions at each flexion angle are marked with letters (a > b at $p < 0.05$).

Figure 5.

Patellofemoral pressure distributions for the pre-operative and medial tibial tuberosity positions at 40° and 80° of flexion for two knees with a lateral cartilage lesion. The position of the patellar ridge and the lesion are indicated. Medializing the tuberosity shifted force and pressure from the lateral facet to the medial facet of the patella.

Table 1

Average patellofemoral kinematics data for each flexion angle and tibial tuberosity position [10].

	Lateral Shift (mm)			Flexion (°)			Lateral Rotation (°)			Lateral Tilt (°)		
	Pre	Med	Ant	Pre	Med	Ant	Pre	Med	Ant	Pre	Med	Ant
40°	2.8	1.8	1.4	0.5	31.1	32.0	27.0	0.6	8.4	6.9	7.1	0.8
60°	5.2	4.8	4.3	0.5	46.1	45.2	41.1	2.4	8.9	7.6	8.3	1.1
80°	7.8	6.7	6.4	0.4	61.2	60.4	57.4	1.1	8.8	7.2	7.7	0.8

Pre: Pre-operative tuberosity, Med: Medialized tuberosity, Ant: Anteromedialized tuberosity

SED: Standard error of the mean difference between the largest and smallest values

Bold font: Significantly ($p < 0.05$) different from other two tibial tuberosity positions

Table 2

Significance levels for all kinematics comparisons

	Flexion Angle, p		
	40°	60°	80°
Lateral Shift			
Pre-operative > Medial	< 0.04	> 0.1 (n.s.)	< 0.03
Pre-operative > Anteromedial	< 0.02	> 0.1 (n.s.)	< 0.01
Flexion			
Pre-operative > Anteromedial	< 0.01	< 0.04	< 0.01
Medial > Anteromedial	< 0.01	< 0.05	< 0.01
Lateral Tilt			
No differences	> 0.3 (n.s.)	> 0.5 (n.s.)	> 0.7 (n.s.)
Lateral Rotation			
No differences	> 0.1 (n.s.)	> 0.4 (n.s.)	> 0.1 (n.s.)

Bold font: significant difference, n.s.: non-significant

Table 3

Significance levels for all force and pressure comparisons

	Flexion Angle, p		
	40°	60°	80°
Lateral Force Ratio: Intact Cartilage			
Pre-operative > Medial	< 0.01	< 0.01	< 0.01
Pre-operative > Anteromedial	> 0.05 (n.s.)	< 0.05	< 0.02
Lateral Force Ratio: Lateral Lesion			
Pre-operative > Medial	< 0.02	> 0.07 (n.s.)	< 0.01
Pre-operative > Anteromedial	< 0.05	> 0.07 (n.s.)	< 0.04
Max Lateral Pressure: Intact Cartilage			
Pre-operative > Medial	> 0.4 (n.s.)	< 0.02	< 0.01
Pre-operative > Anteromedial	> 0.4 (n.s.)	< 0.02	< 0.01
Max Lateral Pressure: Lateral Lesion			
Pre-operative > Medial	> 0.2 (n.s.)	< 0.03	< 0.05
Pre-operative > Anteromedial	> 0.2 (n.s.)	< 0.01	< 0.04
Max Medial Pressure: Intact Cartilage			
Medial > Pre-operative	> 0.2 (n.s.)	> 0.3 (n.s.)	< 0.04
Anteromedial > Pre-operative	> 0.2 (n.s.)	> 0.3 (n.s.)	> 0.06 (n.s.)
Max Medial Pressure: Medial Lesion			
No Differences	> 0.7 (n.s.)	> 0.3 (n.s.)	> 0.8 (n.s.)

Bold font: significant difference, n.s.: non-significant