ORIGINAL ARTICLE

Biomechanical Evaluation of a High Tibial Osteotomy with a Meniscal Transplant

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ABSTRACT

This study determines the biomechanical advantage and the optimal configuration of a high tibial osteotomy (HTO) and meniscus transplantation performed concurrently. Six cadaver knees were placed in a spatial frame, and an HTO was completed. Loading points between a mechanical 6 degrees of varus and 8 degrees of valgus were loaded to 800 N for medial meniscal intact, meniscectomized, and transplanted states. Posterior slope was also increased by 3 degrees in these specimens. Contact data was recorded. Peak pressures significantly increased in the meniscectomized state in every degree of varus/valgus ($p < 0.05$). For both peak and total medial compartment pressures, there was a significant drop ($p < 0.001$) between neutral and 3 degrees of valgus. Lateral compartment pressures linearly increased from varus to valgus orientation. There was no significant change in the pressure profile of the knee with a 3-degree increase in posterior slope. This biomechanical study confirms the hypothesis that an HTO improves the peak pressures in the medial compartment at all degrees of varus/valgus alignment in the setting of meniscal transplantation. Furthermore, the largest decrease in medial pressures was between neutral and 3 degrees of valgus, suggesting that perhaps neutral aligned knees could benefit from an HTO.

KEYWORDS: Meniscus, transplant, tibial, osteotomy, high

Meniscectomy is commonly performed in contemporary orthopedics. It effectively addresses an irreparable and painful symptomatic meniscal lesion. However, meniscal deficiency also significantly decreases the tibial contact area and increases the tibial contact stresses. Paletta et al[1] showed that a total lateral meniscectomy can increase tibial contact pressure by 235% to 335%. The changes that occur as a result of this increased contact pressure were eloquently described by Fairbank[2] and have been shown to accelerate significantly the progression to articular cartilage and subchondral damage.[3] Thus, meniscal transplantation has experienced increased clinical applicability in recent years. It is an evolving technology that has shown clinical and physiologic efficacy in various studies.[4–20]

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One aspect of meniscal transplantation that requires further clarification is the role for a concomitant high tibial osteotomy (HTO). It has been proposed that patients with uncorrected varus malalignment do not achieve optimal outcomes with cartilage restorative procedures,[21,22] and a high tibial valgus osteotomy can improve long-term results. Thus, an HTO performed with a medial meniscus transplant has the potential to both unload the compartment and potentially improve the outcome of a transplant in a varus knee.[23,24] Furthermore, isolated realignment procedures have been shown to be an effective treatment for unicompartmental arthritis.[25–28]

As such, there is a limited amount of evidence available that would directly or indirectly support meniscal transplantation with a realignment procedure, and there is no literature that addresses the direct biomechanical influence of a transplanted meniscus in the setting of a medial opening wedge HTO. In addition, even in a well-performed HTO, posterior tibial slope may be altered, thus changing the mechanical function of the knee and potentially providing different meniscal transplant loading characteristics. The purpose of this study is to clarify the biomechanical effects of a realignment procedure in a meniscal transplant. It is hypothesized that there will be a synergistic decrease in medial compartment pressures with the combination of a meniscus transplant and an HTO in a simulated varus-aligned knee.

MATERIALS AND METHODS

Specimens

Six fresh-frozen cadaver knees were available for testing where the mean donor age was 57 years (range, 52 to 65 years). There were five male and one female donors. Anteroposterior radiographs were taken to determine anatomic alignment and to rule out any significant osseous pathology. The average pretesting anatomic alignment was 4 degrees of valgus (range, 2 to 7 degrees) as measured by computer software (MagicWeb; Visage Imaging Inc., San Diego, CA) from the radiographs. Once alignment was determined, the knees were grossly dissected down to the joint capsule. The capsule, medial collateral ligament, lateral ligament complex, anterior cruciate, and posterior cruciate ligaments were retained. The patella, quadriceps tendon, and patellar tendon were removed to facilitate exposure. An anterior arthrotomy was used to access the joint.

Sample Preparation

The femur of the dissected knee was placed in a polyvinyl chloride (PVC) potting cylinder and secured with dental acrylic (Lang Dental, Wheeling, IL). The tibia was then placed in a Taylor Spatial Frame (Smith & Nephew, Memphis, TN) and secured with two Shanz pins in the anteroposterior (A-P) plane and two half pins inserted medial and lateral at ~1 cm below the joint line. The distal aspect of the Taylor Spatial Frame was mounted to the tibia with half pins (Fig. 1).

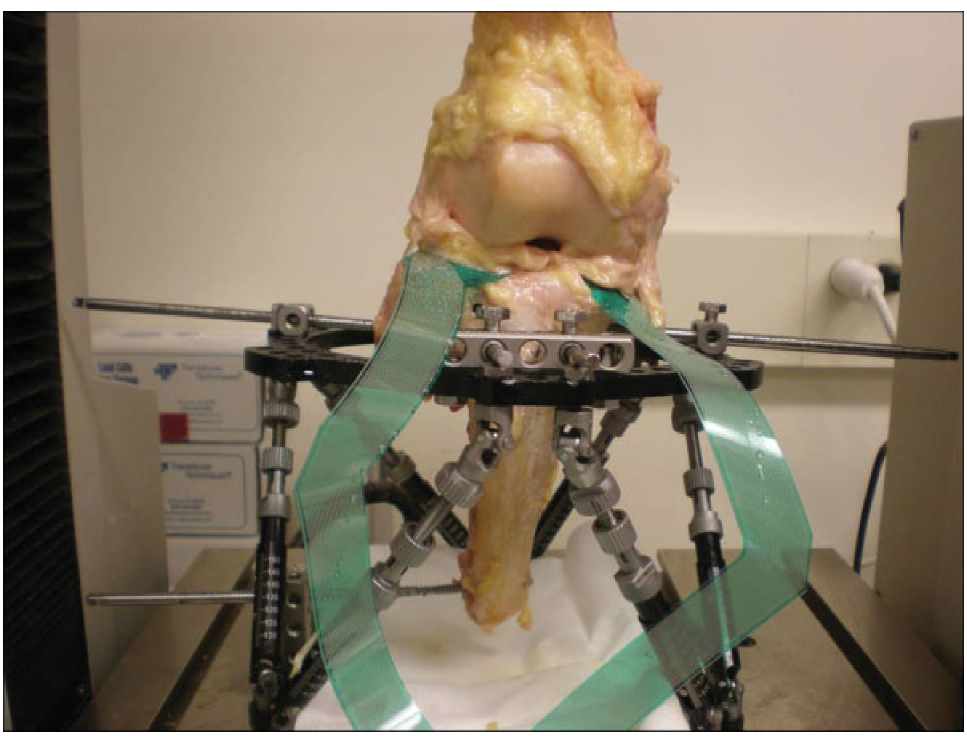


Figure 1 Testing setup. Tibia in Taylor Spatial Frame with femur in MTS machine and Tekscan sensors placed submeniscally. Real-time pressure measurements were collected in the medial and lateral compartments.

An osteotomy was then completed using a Stryker (Mahwah, NJ) oscillating saw (blade 18 mm wide × 0.89 mm thick) and a 1-inch thin osteotome. The osteotomy was initiated at 2 cm below the joint line on the medial side and exited through the lateral cortex at ~1.5 cm below the joint line. The removal of two struts on the Taylor Spatial Frame allowed adequate access to complete the osteotomy.

Once the tibia and the femur were secured in the testing apparatus and the osteotomy had been completed, the knee was mounted on a materials testing system (MTS Insight 5; MTS, Eden Prairie, MN) with the femur attached superiorly to the actuator, and the Taylor Spatial Frame was left free to rotate distally. The knee was placed in extension and Tekscan sensors (K-Scan model 4000; Tekscan, Boston, MA) were placed submeniscally in the medial and lateral compartments (Fig. 1) via insertion through the anterior arthrotomy. The sensors were secured with hemostat clips to the posterior capsule to ensure no sensor translation between sequential trials. Tekscan sensors are thin, flexible electronic pressure transducers specifically designed for the knee that allow the measurement of pressures from 0.1 to 172 MPa with an accuracy of 0.1 MPa. They are 0.1 mm thick and comprise two measuring fields, each with an area of 33 × 22 mm and a spatial resolution of 0.1 mm.

Testing Conditions

The initial "neutral" position was found by allowing the knee to attain its resting position, which was defined as mechanical neutral alignment (correlating with ~6 degrees of anatomic valgus alignment). This position was then confirmed with photoanalysis through the determination of anatomic alignment with imaging software (ImageJ 1.41N; National Institutes of Health, Bethesda, MD). This anatomic alignment was then cross-referenced with the radiographic information obtained at the initiation of the study. Furthermore, the specimen was conditioned by loading it 10 times at 800 N. The neutral position was then tested by loading the knee to 800 N in full extension under the assumption that 60% of the force should be transmitted through the medial compartment and 40% located in the lateral compartment. This is consistent with previously published values for knee pressure distribution between the medial and lateral compartments.

To facilitate comprehension of the following protocol, a brief description of the Taylor Spatial Frame construct is warranted. The frame consists of proximal and distal rings that span the site of the osteotomy and are connected by six adjustable struts. Each strut has a scale that defines a number value for each position. Once the initial position is locked in, the number value for all six struts are entered into a Web-based proprietary software program (www.spatialframe.com). Each desired sagittal plane correction is then input into the software, and the required values for each strut are determined by the program.

Initially, the neutral position (or 0 degrees of mechanical alignment) was locked into place by securing the Taylor Spatial Frame, and the value on each strut was recorded. The knee was then loaded twice to 800 N in the "neutral" position at a rate of 10 N/s with the final load held for 5 seconds. This loading protocol was then repeated with the knee sequentially positioned according to the testing conditions listed below. Each position was determined by entering the desired sagittal plane angulation into the Taylor Spatial Frame software and adjusting the struts to the prescribed values. These conditions were repeated for an intact, deficient, and transplanted meniscal state. Of note, due to the volume of potential data points, the increase in posterior slope of 3 degrees was limited to the neutral, 3-degree valgus, and 6-degree valgus positions secondary to the fact that these are the most clinically relevant models for correction.

For testing conditions, the order of testing was randomly varied between trials and specimen:

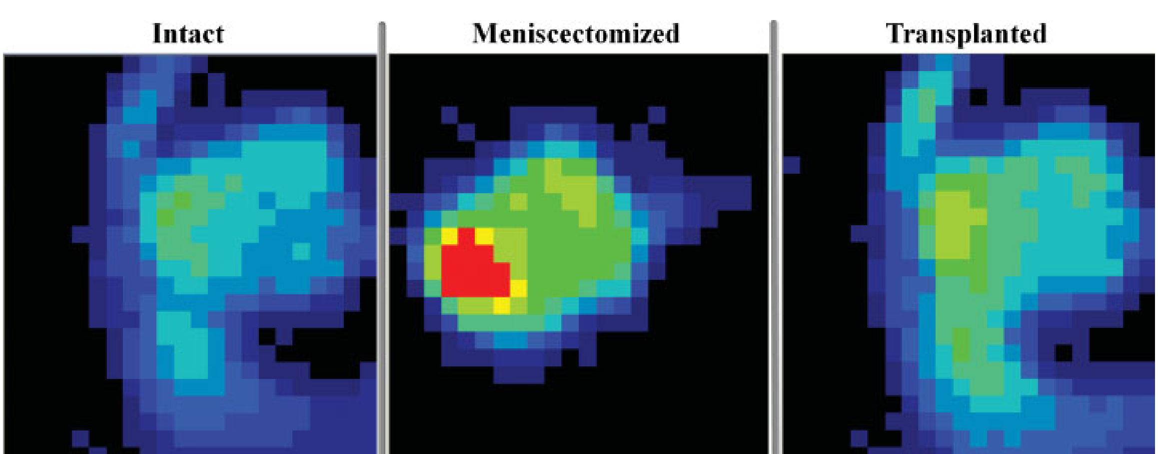


Figure 2 Medial compartment peak pressure maps at neutral (specimen no. 4, 63-year-old female).

Figure 3 Meniscus removed with attached bone block (specimen no. 5, 65-year-old male).

1. 6 degrees mechanical varus
2. 3 degrees mechanical varus
3. 0 degrees "neutral"
4. 0 degrees "neutral" + 3 degrees posterior slope
5. 3 degrees mechanical valgus
6. 3 degrees mechanical valgus + 3 degrees posterior slope
7. 6 degrees mechanical valgus
8. 6 degrees mechanical valgus + 3 degrees posterior slope
9. 8 degrees mechanical valgus

Once all the testing conditions were completed, the data were analyzed using the Tekscan software package on a Windows-based PC. Pressure maps (Fig. 2) were analyzed for peak and total pressures with the average of each pair of values recorded.

Meniscectomy and Meniscus Transplant

In the meniscal-deficient meniscectomized state, the medial meniscus was completely removed by detaching all capsular attachments and creating a tibial bone block that included the anterior and posterior horns. A Stryker (Mahwah, NJ) sagittal saw was used to initiate the creation of the bone block, which was then completed using a thin osteotome through the posterior cortex. The medial meniscus was then extracted as a unit attached to the bone block (Fig. 3). The loading conditions were repeated in the same order as for the intact state, and the knee was prepared for the meniscal transplant.

The meniscal transplant was performed by using the bone trough/slot technique.[29] The meniscus that was previously removed from the same knee was reinserted with its bone block into the slot created with its removal. A 5-mm metal interference screw (Smith & Nephew) was inserted below the articular surface to secure the bone block and meniscus for testing. Statistical analysis consisted of two-way ANOVA testing using GraphPad Software (GraphPad Software Inc., La Jolla, CA) with Tukey post hoc testing for individual differences. Statistical significance was determined at $p < 0.05$. Post hoc power analysis (STATISCA; StatSoft Inc., Tulsa, OK) for both one-way and two-way ANOVAs for the nine conditions in three treatment groups with six samples per group resulted in a power of 83%.

RESULTS

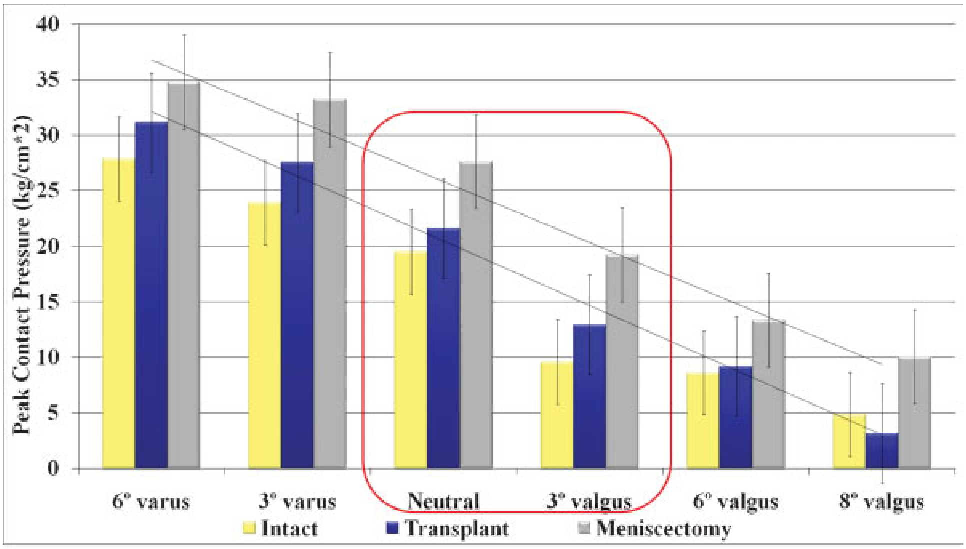
There was a significant increase in medial compartment peak pressures between the intact and transplanted versus the meniscal-deficient state at all angulations (Table 1, Fig. 2). There were no significant differences between the intact and transplanted state. Furthermore, there were no significant differences in lateral compartment pressures between the intact, transplanted, and meniscal-deficient state for any given alignment. The 3-degree increase in posterior slope did not significantly change the peak or total pressure in the medial compartment. No change was seen in the location or coordinates of the peak contact pressure with a 3-degree increase in posterior slope.

Comparison across the different alignment angles demonstrated that for the intact, meniscectomy, and transplant states there were no significant stepwise differences in medial compartment peak pressures for the changes from 6 degrees to 3 degrees varus, 3 degrees

Table 1 Mean Medial Compartment Peak Contact Pressures (kg/cm^2*)

Condition	Intact (Mean ± SEM)	Transplant (Mean ± SEM)	Deficient (Mean ± SEM)	*p* Values (ANOVA)*
6 degrees varus	27.85 ± 1.67	31.13 ± 1.56	34.79 ± 1.98	< 0.05
3 degrees varus	23.90 ± 1.72	27.54 ± 1.86	33.23 ± 1.71	< 0.01
Neutral	19.49 ± 1.02	21.58 ± 2.00	27.62 ± 0.86	< 0.01
3 degrees valgus	9.59 ± 2.15	12.92 ± 2.10	19.26 ± 1.94	< 0.01
6 degrees valgus	8.62 ± 2.89	9.18 ± 3.67	13.34 ± 3.91	< 0.05
8 degrees valgus	4.88 ± 3.23	3.14 ± 2.12	10.07 ± 4.65	< 0.05
Neutral + slope	16.63 ± 1.08	18.31 ± 1.86	25.93 ± 2.21	< 0.01
3 degrees valgus + slope	13.71 ± 1.65	12.19 ± 2.22	21.60 ± 2.39	< 0.01
6 degrees valgus + slope	7.93 ± 4.05	7.35 ± 3.18	13.39 ± 4.64	< 0.05

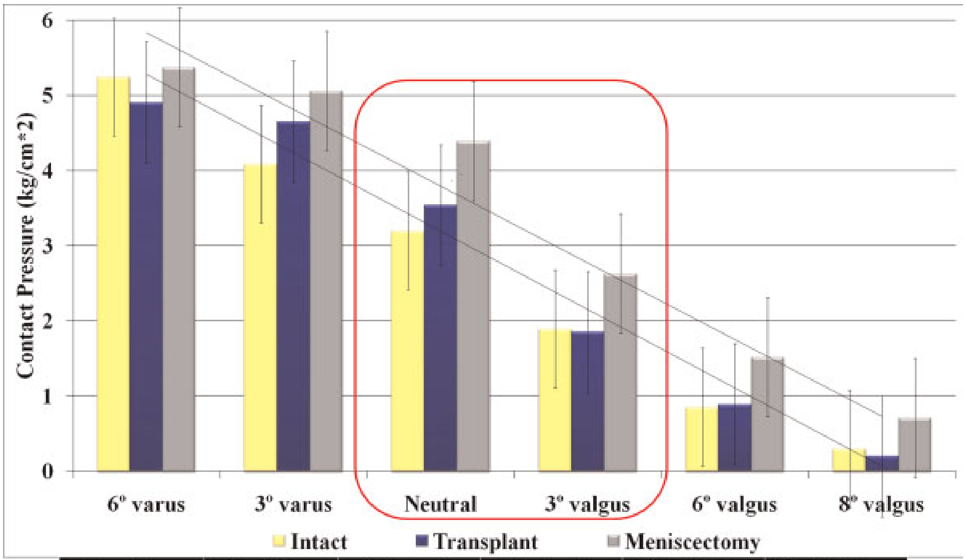
*Significance: $p < 0.05$
SEM, standard error of the mean.



Condition	6° to 3° Varus	3° Varus to Neutral	Neutral to 3° Valgus	3° to 6° Valgus	6° to 8° Valgus
Intact	p > 0.05	p > 0.05	p < 0.05	p > 0.05	p > 0.05
Meniscectomy	p > 0.05	p > 0.05	p < 0.05	p > 0.05	p > 0.05
Transplant	p > 0.05	p > 0.05	p < 0.05	p > 0.05	p > 0.05

Figure 4 Medial compartment peak pressures: significant decrease from neutral to 3 degrees of valgus.

varus to neutral, 3 degrees to 6 degrees valgus, or 6 degrees to 8 degrees valgus. However, there was a significant difference ($p < 0.05$) from neutral to 3 degrees of valgus (Fig. 4). With regard to medial compartment total pressures, there was again a significant drop in total pressures from neutral to 3 degrees of valgus as displayed in Fig. 5. In addition to this large change, there were also significant decreases for the intact 6 degrees to 3 degrees varus and 3 degrees varus to neutral; meniscectomized 3 degrees to 6 degrees of valgus; as well as the transplanted 3 degrees varus to neutral and 3 degrees to 6 degrees of valgus.



Condition	6° to 3° Varus	3° Varus to Neutral	Neutral to 3° Valgus	3° to 6° Valgus	6° to 8° Valgus
Intact	p < 0.05	p < 0.05	p < 0.001	p > 0.05	p > 0.05
Meniscectomy	p > 0.05	p > 0.05	p < 0.001	p < 0.05	p > 0.05
Transplant	p > 0.05	p < 0.05	p < 0.001	p < 0.05	p > 0.05

Figure 5 Medial compartment total contact pressures: significant decrease from neutral to 3 degrees of valgus.

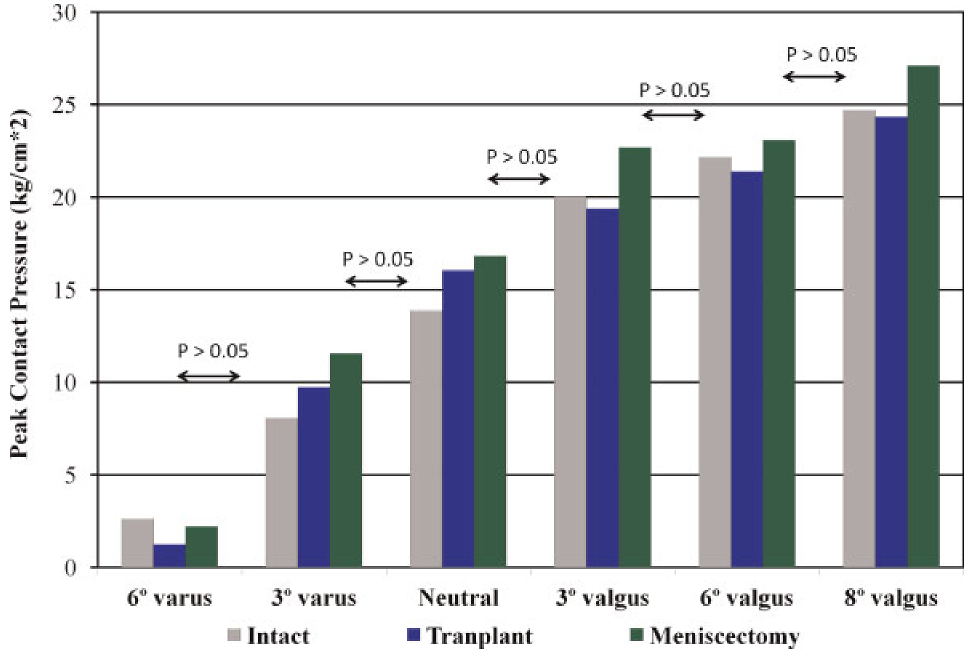
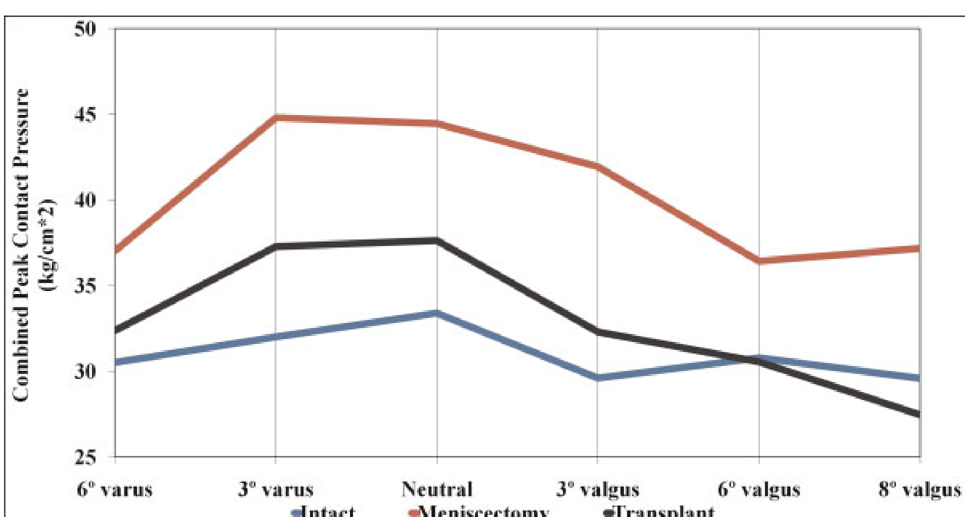


Figure 6 Lateral compartment peak pressures (ANOVA, $p < 0.001$).

Lateral compartment peak pressures were also measured and displayed a linear increase as the knee was placed into more valgus (Fig. 6). The ANOVA analysis revealed that the overall trend was significant; however, there were no significant stepwise changes. Therefore, the large change in contact pressures between neutral and 3 degrees valgus on the medial side were not replicated on the lateral side. The medial and lateral peak pressure data were then combined to further analyze the interaction between the two compartments (Fig. 7). This relationship did not reach significance. However, the trend of the data suggests a plateau for peak contact pressure improvement was reached at 3 degrees of valgus for the intact and transplanted states (Fig. 7). This similar plateau is present at 6 degrees of valgus for the meniscectomized knee.

DISCUSSION

This study confirms the theory that a valgus-producing HTO improves the medial compartment environment in



Condition	6º Varus	3º Varus	Neutral	3º Valgus	6º Valgus	8º Valgus
Intact	30.53 ±3.95^	32.02 ±2.74	33.40 ±1.19	29.61 ±1.99	30.79 ±2.74	29.59 ±3.58
Meniscectomy	37.03 ±5.08^	44.80 ±3.37	44.45 ±1.77	41.94 ±1.50	36.43 ±2.67	37.19 ±3.70
Transplant	32.38 ±4.55^	37.28 ±3.07	37.63 ±1.33	32.31 ±1.67	30.56 ±2.84	27.48 ±3.51

Figure 7 Combined medial and lateral peak pressures (kg/cm^2*).

the context of a meniscal transplant. Peak and total contact pressures were significantly decreased with an HTO at almost all angulations. Furthermore, there was a significant decrease in medial pressures from neutral to 3 degrees of mechanical valgus with no corresponding significant increase in lateral peak pressures. Lastly, no variations in contact dynamics after the 3-degree increase in posterior slope were observed. These results suggest three main tenets: an HTO improves the medial compartment contact profile in the setting of meniscal transplantation; a knee in neutral alignment may benefit from valgus realignment; and an increase of 3 degrees in posterior slope does not significantly affect the contact pressures in the knee. However, further clinical research is needed to corroborate these biomechanical findings.

In isolation, both meniscal transplantation and valgus-producing osteotomies have been explored clinically and biomechanically. Wirth et al[30] first reported the technique for meniscal transplantation, which led to Milachowski et al performing meniscus transplants in humans in 1989.[31]

Coventry[32] described a tibial osteotomy to treat symptomatic unicompartmental arthrosis, and in a critical analysis of his initial patients he found a significant decrease in survivorship for patients corrected to less than 8 degrees of anatomic valgus.[26] Eventually, the use of realignment osteotomies found relevance in conjunction with articular preserving procedures, such as meniscus transplantation. The corrected alignment not only provided pain relief but also protected the transplanted meniscus/cartilage from overload and reinjury. However, there remains much debate surrounding the technical aspects of the operations and any potentially advantageous concomitant procedures.[9,13,15,33]

Van Arkel and de Boer[34] suggested that malalignment plays a role in meniscal transplant failure, and de Boer and Koudstaal[35] maintained that malalignment was the cause of failure in select patients at midterm follow-up. Verdonk et al[15] reviewed 27 medial meniscal transplants; the patients that also underwent HTO had significantly greater improvements in pain and functional scores compared with those that had isolated transplants. In their survivorship analysis, they found that the 10-year survival rates were 83.3% for the group with a combined transplant and osteotomy versus 74.2% for the medial transplant–only group. It is unknown, however, whether the clinical improvement can be attributed to the meniscal transplant, the osteotomy, or both. Cameron and Saha[36] acknowledged the difficulty in determining which part of the procedure was most important in providing clinical improvement in their study on 34 knees that received a meniscal allograft in combination with an osteotomy. Good or excellent results were found in 29 (85%) of these patients.

With regard to changes in slope, El-Azab et al[37] and Marti et al[38] in retrospective reviews found that tibial slope was increased ~3 degrees with opening wedge osteotomies. Agneskirchner et al[39] then showed in a biomechanical model that altering tibial slope does affect the location and contact pressure of the involved knee. However, this fact was challenged in a study by Rodner et al[40] that found no difference for ligament-intact knees and an increase in posterior contact pressure for ligament-deficient knees with increasing tibial slope. The results from our study support the conclusion that in a ligament-intact knee, the 3-degree increase in posterior slope with an HTO does not significantly change the contact pressures or location in the medial compartment.

The current study does represent a validated biomechanical model (Mina et al[41]) in the evaluation of an HTO with a reparative procedure. However, as with many biomechanical studies, the effects seen in a controlled cadaver specimen must be translated with care to the clinical setting where many more dynamic influences exist. Furthermore, the current testing protocol used knees in a static extension position. Although this does provide relevant data, the authors acknowledge that the knee is variably influenced by the meniscus along the arc of motion. Follow-up studies will attempt to quantify the effect of a meniscal transplantation and osteotomy throughout the range of motion.

In the current study, contact pressures were compared in intact, deficient, and meniscal transplanted knees with changes in coronal and sagittal tibial plane angulations. A synergy was demonstrated between a medial meniscal transplantation and a valgus-producing osteotomy. At every condition from 6 degrees of varus to 8 degrees of valgus, there was a significant decrease in peak contact pressures with the addition of a meniscal transplant and no change with a 3-degree increase in posterior slope. A significant drop was also observed in peak and total contact pressures for the medial compartment between neutral and 3 degrees of mechanical valgus (Fig. 4 and Fig. 5). This finding suggests that there may be a significant benefit to knees, with regard to contact pressures, in the change from neutral to 3 degrees of valgus. When the lateral compartment data was combined with the medial results, there was a continued trend toward decreased pressures from neutral to 3 degrees of valgus for the intact and transplanted states. A similar level was reached at 6 degrees of valgus for meniscectomized knees. Overall, the current study supports the fact that an HTO in conjunction with meniscal transplant has the potential to further improve contact pressures and potentially reciprocally protect the transplanted tissue. Additionally, the reported results demonstrate a substantial benefit in the pressure profiles for the varus knee realigned into valgus and suggest that there may even be a significant benefit for neutral knees with a correction to 3 degrees of mechanical valgus.

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