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Effect of Meniscus Replacement Fixation Technique on Restoration of Knee Contact Mechanics and Stability

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Abstract: The menisci are important biomechanical components of the knee. We developed and validated a finite element model of meniscal replacement to assess the effect of surgical fixation technique on contact behavior and knee stability. The geometry of femoral and tibial articular cartilage and menisci was segmented from magnetic resonance images of a normal cadaver knee using MIMICS (Materialise, Leuven, Belgium). A finite element mesh was generated using HyperWorks (Altair Inc, Santa Ana, CA). A finite element solver (Abaqus v6.9, Simulia, Providence, RI) was used to compute contact area and stresses under axial loading and to assess stability (reaction force generated during anteroposterior translation of the femur). The natural and surgical attachments of the meniscal horns and peripheral rim were simulated using springs.

After total meniscectomy, femoral contact area decreased by 26% with a concomitant increase in average contact stresses (36%) and peak contact stresses (33%). Replacing the meniscus without suturing the horns did little to restore femoral contact area. Suturing the horns increased contact area and reduced peak contact stresses. Increasing suture stiffness correlated with increased meniscal contact stresses as a greater proportion of tibiofemoral load was transferred to the meniscus. A small incremental benefit was seen of simulated bone plug fixation over the suture construct with the highest stiffness (50N/mm). Suturing the rim did little to change contact conditions. The nominal anteroposterior stiffness reduced by 3.1 N/mm after meniscectomy. In contrast to contact area and stress, stiffness of the horn fixation sutures had a smaller effect on anteroposterior stability. On the other hand suturing the rim of the meniscus affected anteroposterior stability to a much larger degree.

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This model emphasizes the importance of the meniscus in knee biomechanics. Appropriate meniscal replacement fixation techniques are likely to be critical to the clinical success of meniscal replacement. While contact conditions are mainly sensitive to meniscus horn fixation, the stability of the knee under anteroposterior shear loads appeared to be more sensitive to meniscal rim fixation. This model may also be useful in predicting the effect of biomaterial mechanical properties and meniscal replacement shape on knee contact conditions.

Keywords: Finite element analysis, surgery, biomechanics, meniscus, knee, cartilage

1 Introduction

The menisci are important biomechanical components of the knee. Loss of the meniscus substantially increases contact stresses and is associated with early onset osteoarthritis [5]. Injuries to the menisci commonly occur during traumatic activities in younger individuals or after degeneration in older individuals. The general therapeutic approach has shifted from total meniscectomy in the mid 1900s to partial meniscectomy (with an increasing emphasis on meniscus tissue conservation) and meniscal repair [9]. Even partial meniscectomy has been associated with early onset osteoarthritis and various meniscus replacements are being actively evaluated [4].

The meniscus shares the loads in the knee and increases tibiofemoral articular conformity thus distributing contact stresses in the knee. Studies of contact area and stresses after total or partial meniscectomy have reported substantial reduction in contact area associated with an increase in contact stresses. The magnitudes of increased stresses are greater that those considered physiological and have been shown to result in cell death and matrix degeneration [3]. Hence, the therapeutic goal of meniscal replacement would be restoration of load sharing and contact conditions in the knee.

Therapeutic replacement could restore load-bearing and contact conditions but is subject to several critical issues. An ideal meniscal replacement should replicate the size and shape of the missing structure, possess biomechanical properties comparable to native meniscal tissue, allow for feasibility of implantation, as well as satisfy requirements of biocompatibility and long-term durability. A meniscal allograft is an attractive option since it possesses the necessary biomechanical properties and is relatively biocompatible (within the constraints of allogeneic tolerance). However, mismatch between the shape of the allograft and the recipient knee anatomy is an area of concern and can preclude restoration of normal contact mechanics [11]. While current allograft standards involve a size-matching algorithm based on plain radiographic measurements, other parameters that determine shape (such as thickness of tissue, width of meniscal footprint, and curvature in the axial direction) can affect contact conditions [8]. Artificial meniscal replacements can be manufactured in custom shapes and sizes but may not have the appropriate biomechanical properties. Both allograft and artificial replacements can be affected by surgical technique issues such as site of attachment and biomechanics of the attachment technique.

Allograft meniscal attachment techniques are broadly classified into two categories [2,13]. The first involves suturing the anterior and posterior horns to the tibial bone using drill holes. The second involves grafting the meniscus with bone plugs or a bone bridge that contains the original attachment of the horns to the bone. Additional sutures may be placed to secure the rim of the meniscus in place. The effect of using sutures or bone plugs on contact conditions has been studied in cadaver experiments [1,2,11]. The conclusion was that suture fixation of the horns did not fully restore contact conditions to normal levels. However, only one type of suture material was used for horn fixation and the issue of suture stiffness was not considered. Further, only contact area and pressure were measured and the effect of meniscal replacement on knee stability was not studied.

The knee is a complex joint that is subjected to multiaxial loading and kinematic conditions. This study used the finite element method to simulate dynamic contact conditions of the knee. The objective was to evaluate the effect of the surgical technique of meniscus replacement on contact conditions and knee stability.

2 Methods

2.1 Model geometry

The surface geometry of femoral and tibial cartilage and the menisci was segmented manually and reconstructed from a three-dimensional spoiled gradient-recalled magnetic resonance image of a normal knee using a commercially available program (MIMICS, Materialise, Leuven, Belgium). A hexahedral mesh was generated from the surface geometry in Hypermesh (Altair Inc, Santa Ana, CA). The subchondral bone was modeled using rigid surfaces. For this study only the medial compartment (medial femoral condyle, medial meniscus, and medial tibial plateau) was constructed (Fig. 1A).

2.2 Material properties

The femoral cartilage and the tibial cartilage were meshed with linear elastic isotropic elements with a stiffness of 15 MPa. The medial meniscus was meshed as a transversely isotropic elastic material with a stiffness of 20 MPa in the radial and vertical directions, a stiffness of 150 MPa in the circumferential direction, in-plane Poisson ratio of 0.2, out-of-plane Poisson ratio of 0.3, and shear modulus of 58 MPa [7]. The

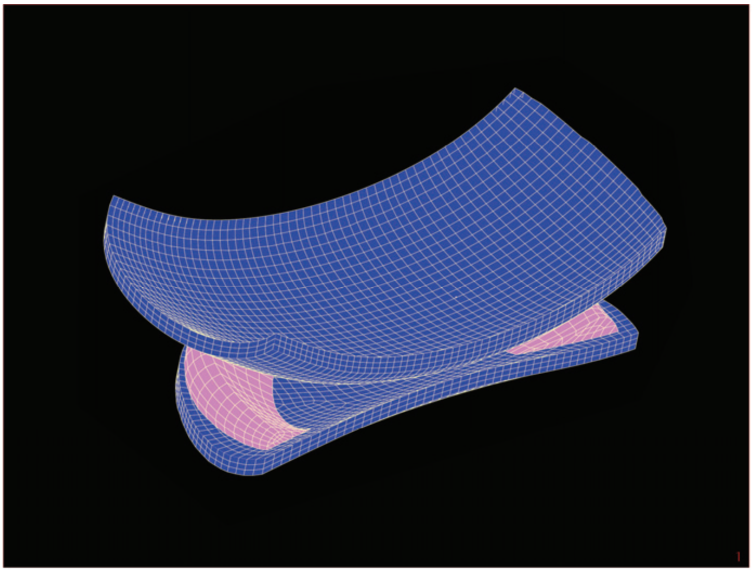

Figure 1A: Finite element mesh of meniscus and tibial and femoral articular cartilage of the medial compartment of the knee.

transversely isotropic model simulated the increased stiffness due to the circumferential organization of the collagen fibers. The attachments of the meniscal horns were simulated using linear springs with no stiffness in compression (Fig. 1B). For bone plug anchorage, the tensile stiffness of the springs was adjusted to match the elastic stiffness of the meniscus in the circumferential direction (150 MPa). The stiffness of the attachment of the meniscal rim (Fig. 1D) was chosen to represent the reported elastic modulus of 5.6 MPa [14].

2.3 Surgical attachment

The tensile stiffness of the horn attachment springs (Fig. 1C) was modulated to simulate three conditions: no attachment, suture constructs (with mean stiffness ranging from 1–50 N/mm), and bone plug anchorage (spring stiffness corresponding to 150 MPa). The range of suture stiffness chosen was based on the reported stiffness of commercially available suture materials. The stiffness of No. 2 Ethibond (Ethicon, Somerville, NJ) is reported as 13 N/mm, No. 5 Ethibond is reported as up to 25 N/mm, and No. 5 FiberWire (Arthrex Inc, Naples, FL) is reported as 62N/mm [6,10].

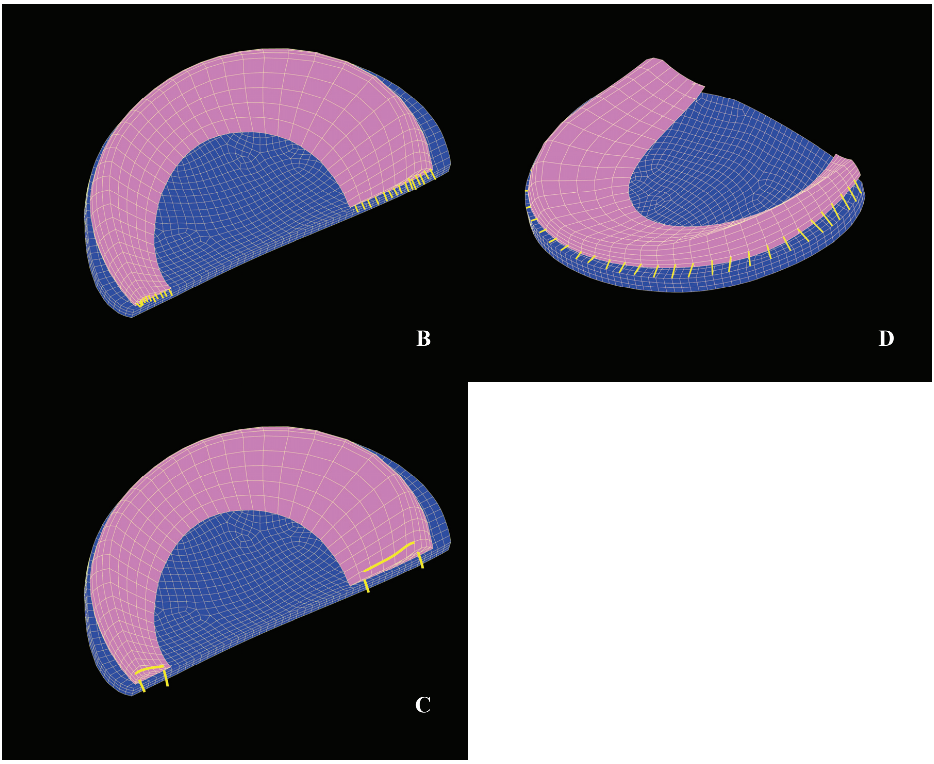

Figure : 1B: The ligamentous attachments of the anterior and posterior horns were modeled with springs that had no stiffness in compression but generated tensile stiffness that simulated 150 MPa of tensile modulus. 1C: Suture fixation of the horns was modeled using springs with stiffness ranging from 1 N/mm to 50 N/mm to cover the range of commercially available suture materials. 1D: Suture fixation of the rim of the meniscus was modeled using springs to represent the menisco-tibial ligament (with tensile modulus of 5.6 MPa) or sutures with appropriate tensile stiffness.

2.4 Finite element analysis

Contact area, contact stress, and meniscal horn displacement were computed during the applied axial load using a commercial finite element analysis software (Fig. 1, Abaqus v 6.9, Simulia, Providence, RI). Axial load representing bodyweight (600N) acting on the entire knee was applied on the femur with the knee in full extension. Frictionless contact was simulated at the meniscofemoral, meniscotibial, and tibiofemoral articulation. No friction was specified because of the low coefficient of friction (0.001) present in normal knee joints. For comparison with a previously reported cadaver study of stability of the knee [12], we computed femoral reaction force while translating the femur ±5 mm in the anteroposterior direction under an axial load of 160N.

3 Results

3.1 Meniscectomy

In the intact condition, femoral contact area was 289mm^2 and peak stresses reached 2.93 MPa, (average, 1.04 MPa, Fig. 2). After total meniscectomy, femoral contact area decreased by 26% with a concomitant increase in average contact stresses (36%) and peak contact stresses (33%).

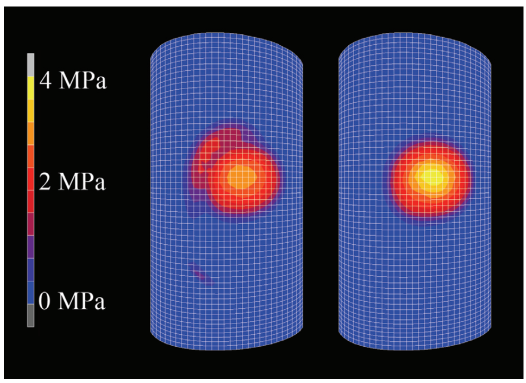

Figure 2: **Left:** Knee loading with the meniscus intact generated peak contact stress and contact area within the range reported for experimental studies. **Right:** Meniscectomy substantially reduced contact area and increased peak contact stress.

3.2 Contact Analysis

Replacing the meniscus without suturing the horns did little to restore femoral contact area, because the horns separated easily under load (>4mm displacement) and circumferential stiffness was insufficient to maintain meniscofemoral contact. Suturing the horns increased contact area and reduced peak contact stresses (Fig. 3). Sutures of low stiffness (1 N/mm) allowed the horns to displace up to 2.5mm. Sutures of the highest stiffness (50 N/mm) reduced displacement to sub-millimeter levels. Increasing suture stiffness correlated with increased meniscal contact stresses (Fig. 4) as a greater proportion of tibiofemoral load was transferred to the meniscus. A small incremental benefit was found of simulated bone plug fixation over the suture construct with the highest stiffness (50N/mm). Removal of the coronary ligament at the rim of the meniscus did not affect contact area or peak stresses. Similarly, suturing the rim did little to change contact conditions.

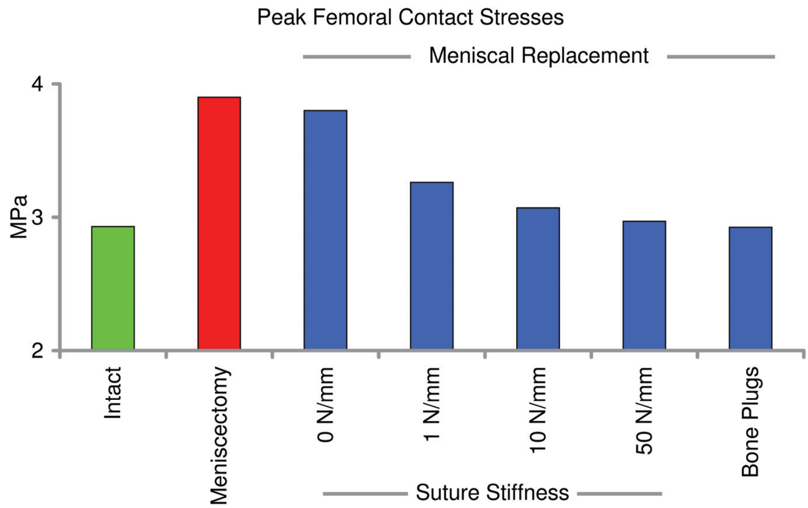

Figure 3: Suturing the horns increased contact area and reduced peak contact stresses. Increasing suture stiffness (up to 50 N/mm) correlated with decreased femoral contact stresses. A small incremental benefit was seen of simulated bone plug fixation over the suture construct with the highest stiffness (50 N/mm).

3.3 Stability

The meniscus also stabilizes the knee in the anteroposterior direction. The nominal anteroposterior stiffness reduced by 3.1 N/mm after meniscectomy similar to that reported in the cadaver study [12], thus validating our model (Fig. 5). In contrast to contact area and stress, stiffness of the horn fixation sutures had a smaller effect on anteroposterior stability (Fig. 6). On the other hand, suturing the rim of the meniscus affected anteroposterior stability to a much larger degree.

4 Discussion & Conclusion

We developed and validated a finite element model of meniscal replacement. The objective of this study was to determine the effect of various meniscus fixation techniques on contact behavior and knee stability. This model yields several insights

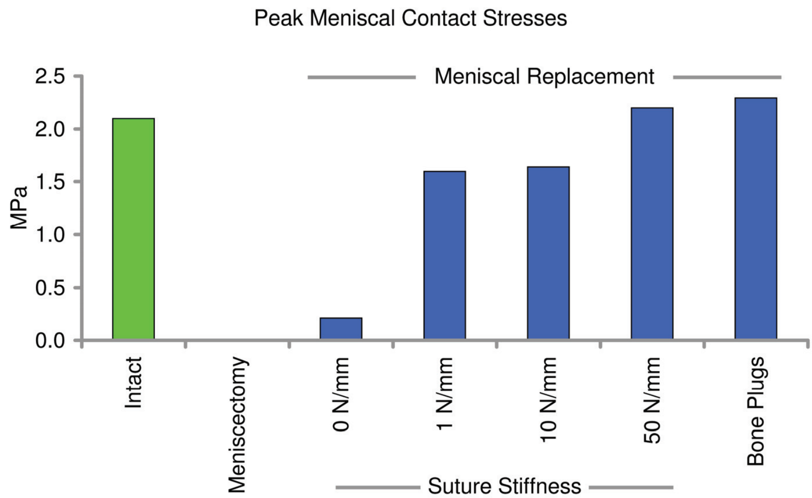

Figure 4: Increasing suture stiffness correlated with increased meniscal contact stresses as greater tibiofemoral load was transferred to the meniscus.

into the complex role of the meniscus in knee biomechanics and provides quantitative outcome measures that may be related to the clinical success of meniscal replacement.

Meniscectomy reduced femoral contact area and increased contact stresses within the range experimentally reported and served to validate our model [1]. Our results indicate that the method of horn fixation is critical to restoring normal conditions. Replacing the meniscus without attaching the horns generated contact stresses very similar to that of meniscectomy. The meniscus is wedge-shaped along a radial cross-section. As a result, axial loading tends to extrude the meniscus radially; thereby generating hoop stresses that are primarily resisted by the horn attachments. Cadaver studies have reported similar findings in which menisci with detached horns were extruded during axial loading and did not reduce femorotibial contact stresses [2,11].

The biomechanics of meniscal replacement have been studied in cadavers. Allograft meniscal replacement in a cadaver study increased contact area compared to the meniscectomy state but did not fully restore contact area to the intact state [11]. This result was likely due to mismatch in meniscal size especially in meniscal height and radial depth. A cadaver study of autograft lateral meniscus replacement (the same meniscus was surgically excised and then replaced) reported restoration of normal contact measures (maximum pressure, average pressure, and area) when

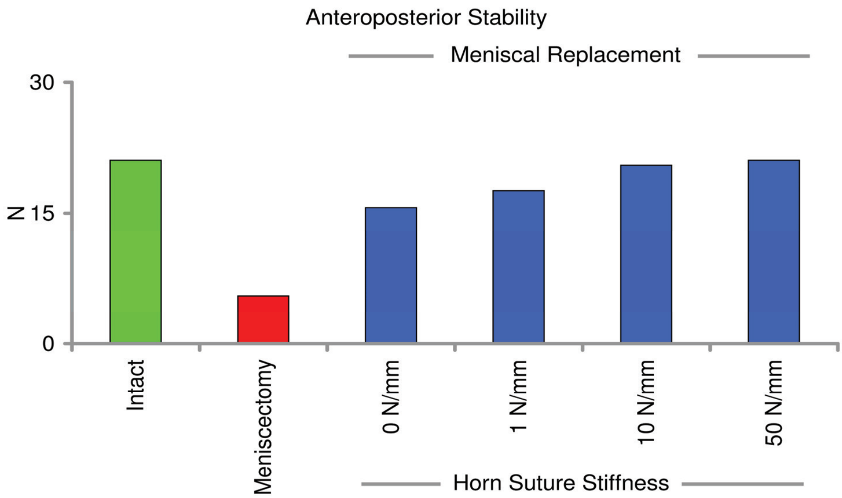

Figure 5: Suturing the horns of the meniscus had a modest effect on the force resisting anteroposterior translation of the femur.

the meniscus was replaced with the horns attached to bone plugs [2]. Another cadaver study, which used autograft medial meniscal replacement, reported restoration of contact conditions to normal when the meniscal horns were surgically repaired with horns attached to bone plugs [1]. However, contact conditions were not fully restored when the horns were surgically repaired with No. 2 Ethibond suture fixation. Collectively, these reports validate our finite element model since the reported stiffness of No. 2 Ethibond suture is 13 N/mm [10], and in our simulation, suture stiffness of less than 50 N/mm did not restore contact pressure and area to normal. On the other hand, suturing the horns with sutures of higher tensile stiffness (50 N/mm) approximated the contact conditions generated while using bone plugs for fixation. This stiffness is comparable to that of No. 5 FiberWire (polyethylene covered with braided polyester).

The addition of sutures to the peripheral rim of a meniscal graft did not appear to substantially affect contact conditions. Again these results are consistent with those reported in an experimental study [1]. This result suggests that the dominant mechanism for resistance to meniscal deformation under axial compressive load is through the attachment of the horns. Suturing the peripheral rim of the meniscus does not appear to have a significant effect on the extrusion of the meniscus during

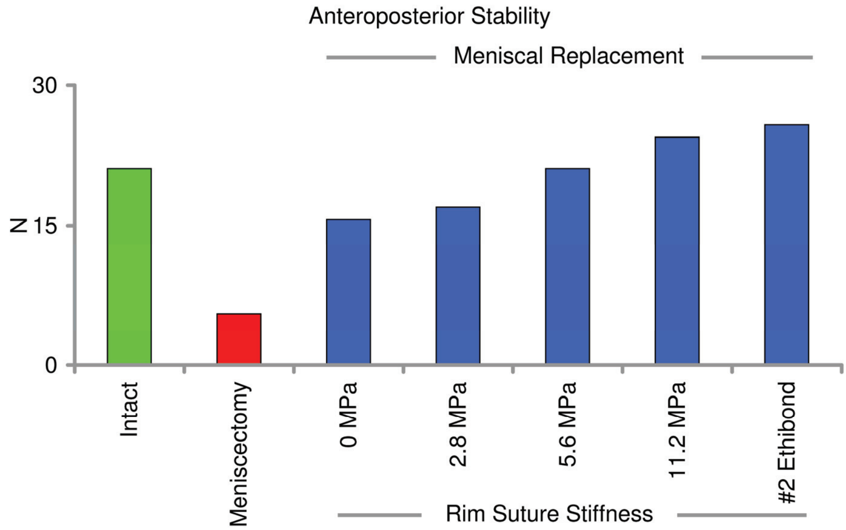

Figure 6: Suturing the rim of the meniscus increased the force resisting anteroposterior translation of the femur in direct correlation with the tensile stiffness of the sutures.

axial loading.

The meniscus provides dual biomechanical functions. The first is to improve the joint congruity to increase contact area and distribute contact stress. The second is to provide stability in the anteroposterior direction. The anterior cruciate ligament is considered the primary stabilizer of the knee to anterior tibial translation. However, the meniscus can also provide substantial stability, sometimes making up for an anterior cruciate ligament deficiency under low to moderate loads [12]. Meniscectomy dramatically reduced the force required to translate the femur in the anteroposterior direction consistent with a previous report [12]. The peripheral rim attachment stabilized the meniscus against displacement during anteroposterior shear loads while the stiffness of suture repair of the horn attachments had a smaller effect. This was in direct contrast to the results of the contact analysis, again highlighting the complex role of the meniscus.

Since only one knee geometry was studied, these specific results may not apply to all knees. However, the trends are likely to be broadly applicable. Only the medial compartment was simulated in our study. The lateral compartment has a substantially different geometry and may result in different contact conditions. However, a cadaver study on lateral meniscus replacement reported results similar to ours regarding the effect of preserving horn attachments [2]. Our simulation resembles a meniscal autograft in that the replacement meniscus was identical to the original meniscus. In patients, the shape of the meniscal replacement (either allograft or artificial) is almost never the same and therefore replacing the meniscus even with optimal surgical technique may not completely restore normal contact conditions [11].

In summary, we developed and validated a finite element model of meniscal replacement. This model emphasizes the importance of the meniscus in knee biomechanics. Appropriate meniscal replacement fixation techniques are likely to be critical to the clinical success of meniscal replacement. While contact conditions are mainly sensitive to meniscus horn fixation, the stability of the knee under anteroposterior shear loads appeared to be more sensitive to meniscal rim fixation. This model may also be useful in predicting the effect of biomaterial mechanical properties and meniscal replacement shape on knee contact conditions.

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