Alterations in Regional Loading Patterns on Articular Cartilage Following Meniscectomy and Meniscal Transplantation

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Introduction: Meniscal allograft transplantation (MAT) is intended to restore pre-injury mechanics to knees with deficient menisci in an attempt to prevent or delay progression of articular cartilage damage. However, cadaveric studies have demonstrated that MAT does not completely restore mechanics to that of the uninjured knee (contact area and peak contact stress), [1,2] but exactly how the subtle change in joint mechanics affects the long-term health of articular cartilage remains unknown. An underlying, but as yet unproven premise is that articular cartilage cannot adapt to changes in loading that occur with joint injury. [3] To explore this concept in more detail and how it relates to MAT requires an analysis of the regional dynamic loading patterns that articular cartilage experiences during activities of daily living for the intact, meniscectomized, and MAT knees. The objective of this study was to quantify the regional dynamic loading patterns on tibial articular cartilage before and after meniscectomy and meniscal transplantation during simulated gait. It was hypothesized that: (i) there will be pronounced knee-independent, but regionally dependent changes in cartilage loading patterns after meniscectomy, and (ii) meniscal transplantation will fully restore the commonly occurring loading patterns to that of the intact joint.

Methods: Seven fresh frozen human cadaveric knees were mounted to a modified Stanmore load-controlled Knee Simulator after stripping the surrounding soft tissue (Fig. 1A) and subjected to synchronous multidirectional forces and femoral flexion/extension mimicking walking (Fig. 1B).[2, 4] Contact stresses on the tibial articular surface were recorded at 100 Hz using a thin electronic sensor (4010N, Tekscan Inc.), Fig. 1C, which was inserted under both menisci and fixed to the tibial plateau. Contact forces applied to each individual sensing element (sensel) across the tibial plateau throughout simulated gait were recorded for three conditions: 1) intact, 2) meniscectomy, where the medial meniscus was resected with bone plugs en-bloc, and 3) meniscal transplantation, where the bone plugs of the medial meniscus were reduced back to their respective insertions (Fig. 2). [2] In order to minimize the factor of graft size, geometry and material properties, a ‘remove-replace’ method was performed where the native medial meniscus was excised out of the knee in its entirety, and then fixed back in place using attachment techniques similar to that used clinically.

Within each condition, the common loading patterns were determined using a Normalized Cross Correlation (NCC) based algorithm following a published protocol.[5] Briefly, the process consists of two steps: For Step 1, the loading profile at each sensel across the tibial plateau of each knee was compared using NCC - a metric of similarity between two profiles (0≤NCC ≤1, 0-no match, 1-identical), and only those with NCC greater than a pre-selected threshold (0.93) were selected. The average loading profiles of sensels with NCC greater than the threshold were calculated as the knee specific regional loading...
pattern. For Step 2, the common loading patterns between knees were identified by combining profiles shared by a majority (≥75%) of the knees. A custom written program (MATLAB, MathWorks Inc.) was used for data analysis. After these two steps, a distribution map of the common loading profiles (Fig. 3) was created for the intact, meniscectomized and meniscal transplanted conditions. The tibial cartilage of the medial and lateral tibial plateau was divided into five regions (a = anterior, p = posterior, e = external, i = internal, c = central, M = medial, L = lateral, T = tibial cartilage).

For statistical analysis, the peak loads of each pattern were compared between intact, meniscectomized, and MAT conditions using the Kruskal-Wallis test. The significance level was set at P < .05.

**Results:** For the intact knees three knee-independent, but region-dependent loading patterns were found (Fig. 3a). The first pattern (pattern-1) was located in pMT (posterior medial tibial) region which consisted of a single peak at 14% of the gait cycle with an average magnitude of 1.30 ± 0.75 MPa. The second pattern (pattern-2) was found in cLT and pLT regions and consisted of two peaks which occurred at 14% and 45% of the gait cycle; the magnitudes of the first and second peaks were 2.2 ± 0.71 MPa and 2.55 ± 0.85 MPa, respectively. The third pattern (pattern-3) was found in cMT region, consisting of two peaks with the second peak (3.69 ± 0.92 MPa) significantly higher (P < .01) than the first peak (2.05 ± 0.57 MPa).

Following medial meniscectomy, the area of the articular cartilage in which pattern-1 occurred was greatly reduced (Fig. 3b) and the magnitude of the peak increased to 2.85 ± 1.11 MPa (P < .01). Pattern-3 in cMT region was absent completely. On the lateral plateau, pattern-2 shifted anteriorly and laterally to eLT region while the magnitudes remained unchanged.

Following meniscal replacement, the area over which pattern-1 occurred was restored (P > .05) (Fig. 3c). The magnitude of the single peak was reduced to 1.02 ± 0.71 MPa, which was slightly lower than that of the intact condition. No further change was found in the location or profile magnitude of pattern-2 compared to the meniscectomy condition; however, a new commonly occurring loading pattern (pattern-4) was found in pLT region of the lateral tibial plateau. Pattern-4 profile has skewed double peaks - with the second peak (2.71 ± 1.0 MPa) significantly higher than the first (0.83 ± 0.31 MPa) (P < .01).

**Discussion:** Following medial meniscectomy, all three common regional loading profiles which were identified in the intact knees were altered, leading us to accept our first hypothesis. Upon meniscal transplantation, only the profile located at the pMT region was restored, leading us to reject our second hypothesis. The largely increased peak load (pattern-1) at the pMT region and the disrupted loading profile (pattern-3) at the cMT region associated with meniscectomy may contribute to the previously found patients' local articular cartilage loss following meniscal tear over 2-year period.[6-7] The residual changes of regional loading patterns following meniscal transplantation may provide a potential explanation for the clinical finding of moderate rate of cartilage degeneration following MAT.[8] The knee-independent, but regionally dependent loading profiles will ultimately be applied to cartilage explants or bioreactors so that the connection between the subtle change in contact mechanics and the biological response of articular cartilage can be more definitively made.

**Significance:** There are site-dependent changes in regional loading patterns on both the medial and lateral tibial articular cartilage following medial meniscectomy. Meniscus transplantation provides restoration of the loading pattern at posterior aspect of the medial plateau but not at any other site.
The load profiles identified in this study can be input to bioreactors to study the effect of the altered loading patterns on the biological response of chondrocytes.

**Figure 1:** Experiment setup. (A) The femur and tibia were potted into fixatures with PMMA bone cement. The forces and torque were applied on the tibia, and the flexion and extension was applied on the femur, while the varus/valgus rotation and superior/inferior translation were not controlled. (B) The knee simulator applies flexion/extension rotation, anterior/posterior force, axial force and internal/external torque to mimic the dynamic multidirectional loads during gait. (C) The contact stresses on the tibial plateaus were collected in real-time using a Tekscan sensor.

**Figure 2:** Schematic diagrams of three conditions tested: (A) intact, (B) medial meniscectomy, (C) medial meniscal transplantation using a “remove and replace” autograft with bone-plug fixation.
Figure 3: Common loading patterns on the tibial plateaus for different conditions. (A) Three common patterns (1, 2, 3) are found on the tibial plateaus of the intact knees. (B) Two patterns (1, 2) are found for the medial meniscectomized condition. (C) Three patterns (1, 2 and 4) are found for the meniscal transplanted condition. (a = anterior, p = posterior, e = external, i = internal, c = central, M = medial, L = lateral, T = tibial cartilage).