A Novel Quantitative Approach for Biomechanical Performance Evaluation of a Meniscal Implant

INTRODUCTION:
One of the functions of the meniscus is to distribute contact forces over the articular surfaces by increasing joint contact areas [1]. It is widely accepted that total/partial loss of the meniscus increases the risk of joint degeneration. A short-term method for evaluating whether degenerative arthritis can be prevented would be to determine if peak pressure and contact area coverage of the tibial plateau (TP) articular surface in the knee are restored at the time of implantation. Although several published works already utilized TP contact pressure measurements as an indicator for biomechanical performance of allograft menisci [2,3], there is a paucity of a quantitative method for evaluation of these parameters in situ with a single effective parameter. In the present study, we developed such a method and employed it on sheep and human cadaveric knees.

METHODS:
Description of the quantitative method
Contact pressures under the intact meniscus were measured in normal human (or sheep) cadaveric knees under compression. Knees were positioned on specially designed jigs for mechanical compression testing (Fig. 1a), then all degrees of freedom were fixed, and the MCL bone plug was released to allow for the insertion of the contact pressure sensor (Tekscan Inc.). With the medial meniscus intact, knees were subjected to a 1200N load at a flexion angle of 0° (300N and 45° flexion in sheep). Next, a complete meniscectomy was then performed and the protocol was repeated with the meniscal implant. An example of the attained pressure maps is shown in Fig. 1b.

The pressure distribution maps attained from these tests (menisci and implants) were analyzed and compared on a regional basis rather than as a whole. A comparison of local characteristics is advantageous in expressing small changes in performance and in emphasizing regions of interest. Furthermore, since area alone does not withhold information on the shape, quantization of the area better approximates the shape of contact area. Thus, based on the natural meniscus shape, the pressure map was divided to 9 regions (Fig. 1b). Three measures were used for the evaluation of performance, based on a ±30% (modifiable) property ratio similarity range, portrayed by the binary function ’Bin’:

Binary function:

\[ Bin[x] = \begin{cases} 1, & \text{if } 0.7 < x < 1.3 \\ 0, & \text{otherwise} \end{cases} \]  

(1)

Utilization of Area (UA):

\[ UA = 6.6 \cdot Bin \left[ \frac{A_{00}C(I)}{A_{00}C(M)} \right] \]  

(2)

where \( A_{00}C \) represents the Total Contact Area detected by the sensor in \( mm^2 \) for the implant \((I)\) and natural meniscus \((M)\).

Contact Area (CA):

\[ CA = \sum w_n \cdot Bin \left[ \frac{A_n}{A_n^I} \right] \]  

(3)

where \( A_n \) and \( A_n^I \) represent the Contact Area detected by the sensor \( mm^2 \) in region \( n \) for the implant and natural meniscus, respectively. \( w_n \) represents the weight factor of region \( n \) (Table 1).

Peak Contact Pressure (PCP):

\[ PCP = \sum w_n \cdot Bin \left[ \frac{PP_n}{PP_n^I} \right] \]  

(4)

where \( PP_n \) and \( PP_n^I \) represent the Peak Pressure measured in region \( n \) of the pressure map of the implant and natural meniscus, respectively. \( P_n^I \) and \( P_n^A \) represent the average pressure measured in region \( n \) of the pressure map for the implant and natural meniscus respectively. \( q_n \) represents the weight factor of region \( n \) (Table 1).

Two more essential measures for successful performance were observation of Implant Movement or Dislocation (IM) and Implant Impingement on the Cruciate Ligaments (CP). If any of these occurred, the parameter was zeroed, otherwise receiving a value of one. The total implant score (relative to the natural meniscus) was therefore defined as the sum of tests with the exception of any violation of normal loading, through implant dislocation or cruciate pressure for which the score is zeroed:

\[ SCORE = (UA + CA + PCP) \cdot IM \cdot CP \]  

(5)

The total score for the natural meniscus is always 100, as all of the parameters are normalized by the value attained for natural meniscus.