REPAIRED ARTICULAR SURFACES IN CONTACT WITH NORMAL CARTILAGE: INFLUENCE OF THE SUPERFICIAL TANGENTIAL ZONE

Owen, J R and Wayne, J S
Orthopaedic Research Laboratory, Departments of Orthopaedic Surgery and Biomedical Engineering, Virginia Commonwealth University, Richmond, VA
Senior author jwayne@vcu.edu

INTRODUCTION:
Engineering tissue to repair articular surface defects remains a challenge. Normal zonal characteristics of articular cartilage throughout its thickness, particularly the superficial tangential zone (STZ), and normal material properties have not been reproduced in vitro in scaffolds nor in vivo in repairing defects. Without sufficient quality, such transplanted scaffolds in vivo may be doomed mechanically from the outset. The importance of the STZ in normal function [1-3] and deficient behavior of repair tissue [4-5] is well documented in the literature. Studies have modeled higher tensile properties in the STZ via transverse isotropy [6-9] or tension-compression nonlinearity [10] to better predict experimental results. This finite element study further examined the role of an STZ with strain-dependent permeability on the behavior of normal and repaired articular surfaces under contact loading by incorporating normal cartilage layer.

METHODS:
Using ABAQUS® (version 6.7, SIMULIA, Providence, RI) finite element analysis software, a 2D axi-symmetric model (4325 quadrilateral pore fluid/stress elements, 13,423 nodes) was developed to represent contact loading between two incongruent articular cartilage layers (1.5mm thick; top layer outer surface 20.5mm radius; bottom layer inner surface 26.5mm). The STZ occupied 20% of the thickness while the middle/deep zone was 80%. A central region (3mm arc on the surface) was created for simulation of a repair cartilage plug in the bottom layer. Mesh was refined in areas expected to have large gradients. Material properties comparable to those found in the literature [9,14] were assigned to the regions as dictated by the scenarios (Table 1). A 5N load was applied to the top layer via a rigid bone region, which transferred load to the bottom layer through contact between the two center regions of the articular surfaces, and held constant for 30 sec to evaluate short-term creep. Nonlinear geometry was incorporated to accommodate finite deformation. Fluid flow occurred across the contact regions to maintain continuity of pore fluid pressure at the surface interface, while fluid was allowed to freely drain from the articular surfaces outside of the contact area. Three scenarios were investigated:

NORM: Properties of STZ and middle/deep zones of both layers as bilinear isotropic to simulate normal tension/compression nonlinear behavior (Table 1).

REP: As in NORM, except repair isotropic cartilage modeled throughout thickness in the central region of the bottom layer.

REPwSTZ: As in REP, except the central STZ of the bottom layer modeled with normal properties to simulate covering the underlying repair tissue with a normal STZ.

Strain dependent permeability was modeled in the normal STZ only, using the exponential relationship \( k = k_0 \exp(M \varepsilon) \), where \( k_0 \) = initial permeability, \( M \) = material constant, \( \varepsilon \) = volumetric strain. An M of 5 was chosen to represent the mid-range of values normally found [15].

RESULTS:
The STZ covering developed higher stresses thereby shielding underlying repair regions (Figure 1a) and resulting in flow patterns for REPwSTZ approaching the model for normal cartilage (Figure 1b). The STZ in REPwSTZ reduced full thickness compression, as compared to REP, by 15% (Figure 2). In the center of the repair region immediately beneath the STZ, von Mises stress in REPwSTZ as compared to REP, decreased 21%, axial logarithmic strain (LE22) decreased 8%, and pore fluid pressure increased 13%. Contact area increased from 74.9mm² for REP to 80.3mm² for REPwSTZ, but then began returning to NORM for REPwSTZ AT 78.5mm².

DISCUSSION:
This analysis modeled contact between incongruent cartilage layers, more closely approximating behavior of articular cartilage in vivo by incorporating nonlinear features and accounting for fluid flow between layers. This study predicts that, compared to an isotropic repair (REP), a STZ with normal nonlinear tension/compression properties and strain-dependent permeability in place over a repair (REPwSTZ) will develop higher pore pressures, reduced von Mises stress, and reduced logarithmic strain in the underlying repair, and reduced full thickness compression of the repaired cartilage layer. Previous studies [1-3] emphasizing the importance of the STZ in normal cartilage support these findings. Also, these findings are congruent with earlier simpler models investigating the effect of the STZ [11,12,13]. This study continues to suggest that transplanted material with a quality STZ may provide an improved mechanical environment for appropriate mechanotransduction signals in the entire repairing region, even for repair tissue with inferior mechanical properties. A viable STZ may be critical in achieving the long-term survival of repairing cartilage.

REFERENCES:

Table 1: Material properties for respective regions.

<table>
<thead>
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<th>Material Property</th>
<th>Normal</th>
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