Customized Osteochondral Grafts for Cartilage Resurfacing: Effects of Contour and Placement on Biomechanics of Femoro-Tibial Contact in the Goat

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Introduction: A variety of tissue and material implants have been introduced for the repair of articular cartilage damage that ranges from small focal defects to large lesions afflicting contoured joint surfaces. The surgical placement of osteochondral grafts (recessed, matched, or proud implant with respect to the host) can affect repair results, and has been evaluated ex vivo for contact pressure in 3-D joint models and tissue deformation in 2-D tissue models.¹, ² Recent advances in imaging, materials, and 3-D printing technologies have established the potential for personalized grafts that are contoured according to the targeted repair site, and have viscoelastic properties similar to those of articular cartilage.³, ⁴ While the mechanobiology of implanted and adjacent host tissue is an important determinant of repair success, currently, there are limited models and methods for assessing the contact biomechanics of repaired joints, and systematically examining the effects of implant geometry and placement parameters. The aims of the present study were to establish additional foundations for biomechanical evaluation of relatively large resurfacing constructs for the adult goat by determining (1) surface contour and cartilage thickness of the normal medial femoral condyle (MFC), and (2) the effects of placement and contour of 3-D fabricated osteochondral surrogates (OCS) on contact mechanics during ex vivo femoro-tibial loading.

Methods: Study 1: The articular surface contour and cartilage thickness variation were assessed in an un-operated knee of adult Boer goats (n=11). The distal femora were isolated, and scanned by μCT. The MFC was positioned in a standard orientation, and an 8mm diameter region comprising an osteochondral cylinder used typically for cartilage repair studies was analyzed further.⁵ The articular surface and the bone-cartilage interface were identified, allowing maps and means to be computed for the deviation of the cartilage surface from a best-fit sphere and the vertical height of the articular cartilage. Statistics: The variation in these parameters at the center, anterior, posterior, medial, and lateral positions were assessed by repeated measures ANOVA.

Study 2: The effects of OCS geometry and surgical implant position on the contact biomechanics of the medial femoro-tibial compartment of the adult goat were examined. Three implant conditions were tested, combining graft geometry (flat, contoured) and placement height (proud, flush). Repair Model: With the knee joint set to a physiological load-bearing flexion angle, the distal femur and proximal tibia were transected, and the bone ends machined to fit loading platens. A 9mm diameter x 10mm depth osteochondral core was removed from the load-bearing region of the MFC. Repair Constructs: Flat and contoured OCS were fabricated to mimic certain specimen-specific structural and material properties of
cartilage and bone of the adult goat MFC. The isolated osteochondral core was imaged by μCT. The OCS bone portion was 3-D printed to contain both the trabecular and subchondral structures using a photolithography-based system and methacrylate resin. The cartilaginous portion was created by fitting the OCS bone portion to a 3-D printed mold, matching either the cartilage contour or a flat surface, and then injecting agarose (5% w/v) with hydroxyapatite particles (1% w/v). Ex Vivo Repair Biomechanics: The OCS were then implanted into the 9mm diameter defect in the MFC with shims to provide placement heights, proud (by 0.5mm) or flush. MFC and MTP were mounted in a custom μCT-compatible mechanical compression device with in-line load monitoring. Hemi-joints were subjected to 0 or 40N of static compression after 2N tare load and allowed to relax for 10 minutes, and imaged by μCT. Images were analyzed for OCS surface deformation.

**Results:** Study 1: The geometry and cartilage thickness of the 8mm cylindrical target repair region of the adult goat MFC vary substantially (Fig. 1). The articular surface in the center of the region fits well, within 0.001±0.025mm from the sphere; however, the edges deviate distinctly from a sphere (p<0.001), with the anterior and posterior regions being higher (0.100±0.054mm and 0.045±0.073mm, respectively), and the medial and lateral regions being lower (-0.089±0.064mm and -0.098±0.071mm, respectively). The vertical heights of the articular cartilage are also non-uniform (p<0.001), increasing from the central 1.65±0.35mm height laterally and posteriorly (1.69±0.35mm, +2.7% thicker, and 2.03±0.43mm, +22.5% thicker, respectively) and decreasing medially and anteriorly (1.40±0.32mm, -15.2% lower, and 1.46±0.28mm, -11.9% lower, respectively).

![Fig. 1. Maps of average (A) vertical deviation from a best-fit sphere and (B) vertical cartilage height for goat OCA sites.](image)

Study 2: The local and overall deformation of the cartilaginous layer was sensitive to placement height and contour. Aggregate particle deformation was significantly less for the contoured-flush OCS than for the contoured-proud (50% decrease) and flat-proud (39% decrease) groups (Table 1). Local particle deformation maps showed regional variation along OCS surface in μCT images (Fig. 2A-C) and calculated deformations (Fig. 2D-F).
Discussion: This study provides foundations for, and an approach to, examining the biomechanics of large resurfacing osteochondral grafts for the adult goat MFC, an established model that distinguishes graft features governing long-term success or failure. The shape of goat MFCs deviates substantially from a sphere, but in a consistent anatomical fashion, suggesting that personalized repairs may be either individualized or pre-fabricated to a certain size and shape. While the vertical height is not equivalent to the normally-directed thickness of the articular cartilage, it is a useful metric in that it is assessed clinically during preparation of cylindrical osteochondral cores. The substantial compression of agarose-containing constructs that are either proud or a poor geometric fit suggests that these variables should be addressed carefully in strategies for joint-scale resurfacing. In addition, the effects of mechanical properties of the cartilage and bone portions of the OCS can be investigated.

Significance: These results provide foundations for designing grafts for resurfacing large cartilage defects with desired biomechanical properties by (1) providing cartilage contour and thickness information of the adult goat MFC, and (2) demonstrating how OCS, combining imaging and materials with new test methodologies, can delineate the extent of variations in graft shape and placement variables on initial biomechanics at high resolution and in 3 dimensions.

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