REGIONAL VARIATIONS IN THE DEPTH-DEPENDENT STRAIN DISTRIBUTION IN THE TIBIAL PLATEAU

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INTRODUCTION

The topological variations in cartilage matrix organization and composition across the tibial plateau suggest local adaptations to regional loading. These local topological variations have important implications for understanding the causes of osteoarthritis [Andriacchi et al, 2004], as well as the mechanical integrity of tissue engineered constructs. While it has been shown that the compressive strain distribution through the depth of articular cartilage is highly non-uniform [Shinagl et al.1997, Wang et al. 2002], it is not known if this depth-dependent strain distribution varies regionally in a manner similar to that described above for the superficial zone.

The purpose of this study was to analyze the effect of matrix organization on the axial strain distribution through the thickness of the tissue. It was hypothesized that the depth-dependent strain distribution varies among the different (central and peripheral) topographical regions of the tibia.

METHODS

Full-depth osteochondral plugs were removed from the central (not covered by the meniscus) and peripheral (covered by the meniscus) regions of porcine lateral tibial plateaus (n =3). Cylindrical samples, 6mm in diameter, from each region were halved longitudinally to provide a flat surface for imaging during mechanical testing and incubated in medium until experiments were performed.

Chondrocytes were fluorescently labeled with a live/dead stain consisting of 5μM calcein-AM and 5μM propidium-iodide, respectively, for 30 minutes. The plugs were then immersed in fresh medium and placed in a custom compression device affixed to a confocal microscope. Images of the unloaded plugs were taken and the cartilage thickness was estimated with the microscope viewer software. A bulk strain of approximately 10% was applied and a second image was taken after allowing sufficient relaxation time. Corresponding chondrocytes were then located between the two images.

Custom code written in MATLAB R14 was used to record each chondrocyte's original location as well as its displacement due to loading. Linear triangular elements were constructed from nodes placed at the chondrocyte locations with a Delaunay triangulation algorithm. The measured displacements were applied as boundary conditions, and the axial compressive strains in each element were calculated.

The local strains were normalized by the bulk strain and the resulting strain profile in each plug was visualized using ABAQUS v6.5 (Figure 1). The average normalized strains in the superficial (upper 20%), transitional (20-40%), and deep (lower 60%) zones were then calculated and compared between specimens of the two regions.

RESULTS AND DISCUSSION

The results support the hypothesis in that the peripheral region had higher strain in the superficial and transitional zones and lower

strain in the deep zone than in the corresponding zones of the central region (Figure 2). Interestingly, the transitional zone strains were higher in the peripheral region than in the central region.
The axial strain distribution was non-uniform in the peripheral region, with strains of approximately 1.5 times the bulk strain in the superficial and transitional zones, while the deep zone experienced less than 0.65 times the bulk strain. In contrast, the average strains in the central region were nearly uniform.

The topological variations agree with previous findings concerning cartilage matrix organization and composition. It has been shown that superficial tissue in the central region has more random fiber orientation while the peripheral cartilage exhibits a thick, well-defined superficial zone of tangentially oriented fibers [Briant, 2006]. In addition, it has been demonstrated that collagen, which resists tensile loads, is most abundant in the peripheral region while proteoglycans, which resist compressive loads, are most abundant in the central region [Appleyard, 2003].

The results of this study suggest that cartilage in the central region (cartilage-on-cartilage loading) has a more uniform strain distribution than cartilage in the peripheral region (protected by the meniscus). Likewise tissue with an organized matrix (central region) has a more uniform strain distribution than cartilage with random matrix organization (peripheral region).

In conclusion, the results of this study support the theory that cartilage health can be highly sensitive to kinematic changes in joint loading. Shifts in the locations of high joint loads during ambulation may result in very different cartilage deformation due to the different matrix structures. This supports the potential for accelerated OA progression following an injury which results in altered gait kinematics such as traumatic injury to the ACL [Andriacchi, 2004].

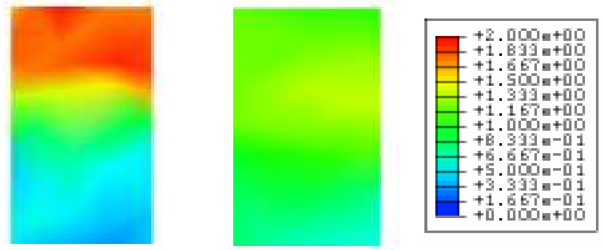

Figure 1: Example contour plots of the normalized axial strain in the peripheral (left) and central (right) regions of the knee.

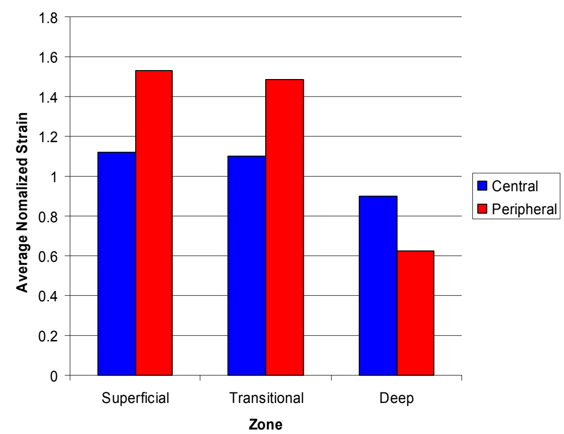

Figure 2: Average normalized strain in histological zones for the central and peripheral regions.

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ACKNOWLEDGEMENTS

This study was funded in part by NIH grant AR049792-01