The Relationship between the Composition and Mechanical Properties of Articular Cartilage

Submitted by James Stephen Bell, to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Physics, December 2010.

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

.... James Bell

Abstract

Articular cartilage (AC) is a soft connective tissue that lines the ends of synovial bones in joints. It is responsible for absorbing impact loads and resisting shear associated with joint articulation. Pathologies such as osteoarthritis have symptoms including degradation and sometimes complete loss of the articular cartilage, which can lead to poor load support and considerable pain. There has been considerable work in the field of cartilage mechanics. The transient deformation behaviour of loaded cartilage has been examined using several different experimental approaches, and complex models have been developed to accurately describe this behaviour.

The microstructural response of AC to load is less well understood, however. The aim of this work was to investigate the anisotropy and heterogeneity of cartilage and its effect on the load bearing characteristics. Firstly, existing experimental data were used to create a layered finite element model of cartilage under load. Using this model, three sets of material parameters were evaluated for their suitability in reproducing experimentally observed strains, as well as minimising peak stresses. It was found that only by including the heterogeneity associated with collagen fibre orientation could the layer boundary deformations be exactly modelled, whilst preventing potentially damaging interfacial shear.

Tensile testing of cartilage from the equine metacarpophalangeal joint, using samples obtained from each individual layer, was performed to validate findings from the model as well as to determine the variation in mechanical properties in regions of different weight bearing characteristics. It was found that the tensile stiffnesses varied with depth as predicted by the model, demonstrating an average value of 31.3 MPa at the surface and 9.4 MPa in the radial zone, although there was considerable variation. Polarised light microscopy was used to determine the preferential collagen orientation, as well as qualitatively assess the angular spread and other patterns in collagen organisation. It was found that the appearance of the collagen network varied both with depth and location on the joint, with high weight bearing regions showing more isotropic fibre distributions below the surface than low weight bearing regions.

To directly probe the microstructural response of AC to load, the tensile loading rig

was modified to allow simultaneous imaging of the sample using two photon fluorescence microscopy. This allowed the relative displacement of cells and elastin fibres, which are intrinsically fluorescent, to be observed at increasing levels of strain. From locations and orientations of these features, the strain field could be calculated at two length scales: in the vicinity of specific elastin fibres (microns) and intercellular strains averaged over whole stacks (hundreds of microns). The strains at the two different scales did not correlate, suggesting that the microscopic strain environment varies considerably. The elastin fibre network was also investigated, and it was found that fibres appear to interconnect both at pericellular matrices, as well as at 'nodes' in the extracellular matrix.

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