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OPTICAL MEASUREMENT OF IN SITU STRAIN FIELDS WITHIN OSTEOCHONDRAL TISSUE UNDER INDENTATION

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INTRODUCTION

A method is described to measure the 2D strain field over the cross sectional area of articular cartilage layers bonded to subchondral bone, under various loading conditions. This technique extends the methodology of previous studies which measured strain fields in articular cartilage [1-4] and employs digital image correlation. The long term objective is to analyze the strain fields in articulating joints under physiological loading conditions.

MATERIALS AND METHODS

Cylindrical osteochondral samples (∅8.23mm) were harvested from the tibia of 2-4 months old calf knee joints using a 3/8 inch diamond tipped drill bit. Leaving the articular surface intact, the bony surface was cut to produce a plane approximately parallel to the cartilage-bone interface. The samples were then placed in a custom made holder and cut perpendicularly across the diameter to produce two semicircular plugs. As described by Narmoneva et al. [3], a Badger Model 200 airbrush was used to spray the cross sectional surface with black waterproof enamel markers to produce an optically textured surface.

The textured cross-section of the sample was placed flush against the glass face of a semicircular specimen chamber. Samples were immersed in a 0.15M physiological buffered saline (PBS) at room temperature at all times apart from preparation and handling. The loading apparatus consisted of a stepper micrometer for displacement actuation (Model 18503, Oriel Instruments, Stratford CT, step size 1µm) connected in series with a linear variable differential transformer (LVDT) for displacement measurement (PR-812-200, Macro Sensors, Pennsauken, NJ) and a uniaxial load cell to measure the applied force (Sensotec, Ohio model GM, 10lb capacity). Data control and acquisition was executed using a personal computer operation with a data acquisition card, running through Labview software interface (National Instruments, Austin, TX). The cartilage samples were loaded with a semi-cylindrical rigid impermeable flat indenter (∅3.3 mm) at a constant displacement rate of 100 µm/s to achieve a 15% reduction in thickness (Fig.1). Images were captured with a video camera (Sony SSC-C50A, Japan) mounted on a stereoscope (Olympus model SZ40, Olympus America, Melville NY). Images of the sample were captured in a reference configuration under a tare load of 0.45N, and in the deformed configuration immediately upon completion of loading. Pre- and post-compression images were analyzed with digital image correlation as described in our recent study [4].

An axisymmetric finite element analysis of an equivalent loading configuration was also performed for comparison with the experimentally measured strain field. The articular layer was modeled with the biphasic conewise linear elastic (biphasic-CLE) model with cubic symmetry [5] and the underlying subchondral bone was assumed rigid and impermeable. Representative material properties were taken from our recent experimental study [5]. Cartilage dimensions were used to match those of the sample (thickness= 1.71mm, diameter= 8.23mm).

Figure 1: Image of textured cartilage acquired after indentation

RESULTS AND DISCUSSION

Representative results from one sample are presented here, to illustrate the methodology. Digital image correlation yielded displacement fields with components parallel ("lateral") and perpendicular ("axial") to the articular surface (Fig. 2). As expected, the greatest axial deformation occurred under the indenter, symmetrically about its axis.

However, the lateral displacement exhibited some asymmetry. Differentiation of the displacement fields yielded normal strain components along the lateral and axial directions, as well as the in-plane shear strain component (Fig. 3). Axial normal strains were generally compressive with peak values under the indenter, near the articular surface. The lateral normal strain alternated from tension under the indenter to compression in the outer periphery. The peak shear strains occurred away from the centerline of contact, with greatest magnitude near the cartilage-bone interface.

The strain fields predicted from the finite element analysis (Fig. 4) were generally in good qualitative agreement with the experimental measurements, given the idealized assumptions employed here. In summary, this study demonstrates that it is possible to measure 2D strain fields in full-thickness osteochondral samples. The methodology employed here can be just as easily extended to two contacting articular layers.

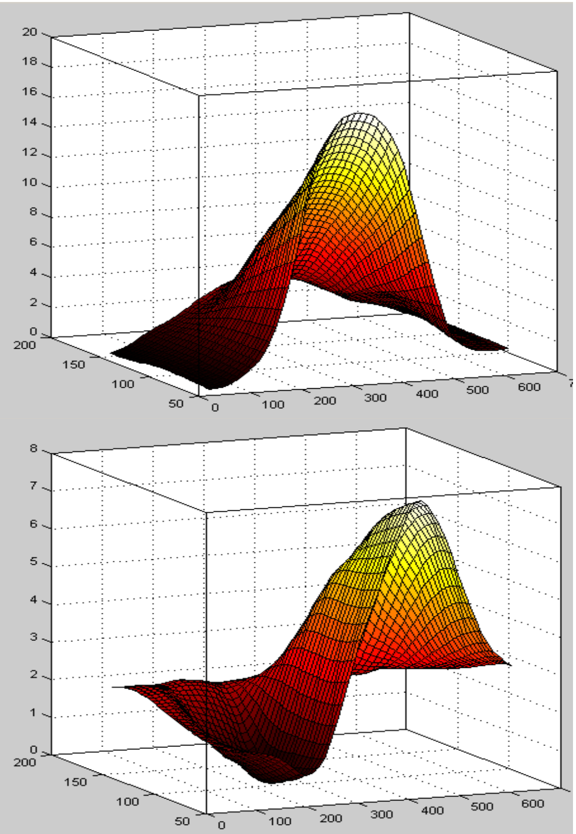

Figure 2: 2D Displacement Fields in axial (top) and lateral (bottom) directions, in pixel units.

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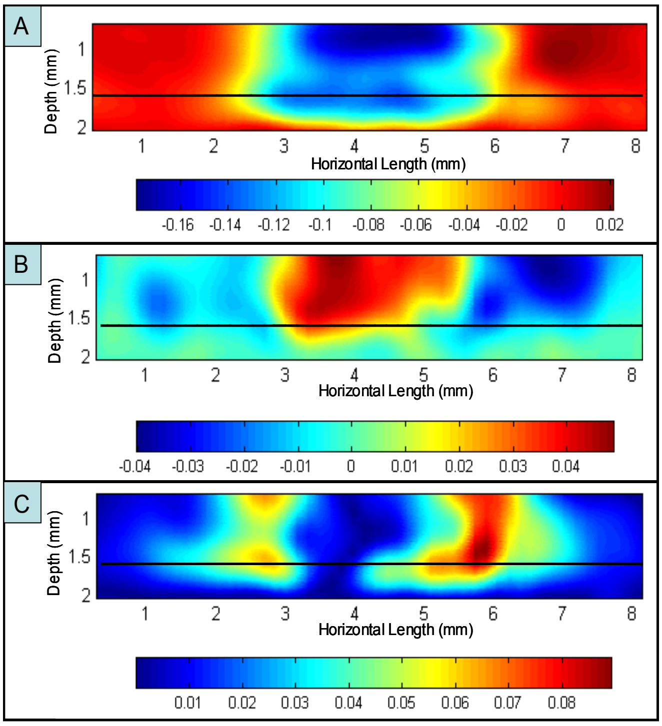

Figure 3: Strain contour plots of (A) axial normal strain, (B) lateral normal strain and (C) shear strain. Strain range given by color legend below each plot. In all plots, horizontal black line represents cartilage bone interface adapted from original image.

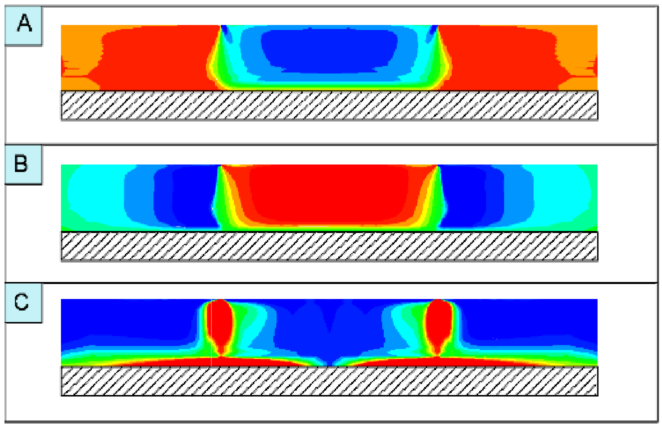

Figure 4: Equivalent finite element analysis, with (A) axial normal strain, (B) radial normal strain and (C) shear strain. Shaded boxes represent corresponding bony regions of experimental strain fields. Contour legends are the same as in corresponding strain plots of Fig. 3.