

DEPTH-DEPENDENT RELAXATION OF ARTICULAR CARTILAGE IN UNCONFINED COMPRESSION

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INTRODUCTION

Articular cartilage (AC) is an inhomogeneous, anisotropic and multiphasic composite. Depth-dependent strain distribution in full thickness AC has previously been investigated with optical methods (Guilak, 1995; Schinagl, 1997; Wang, 2003). Depth and time-dependent compressive strain has been predicted with theoretical models (Li, 2000; Wang, 2001). Most recently, Electronic Speckle Pattern Interferometry (ESPI) has been employed to measure depth-dependent strain on AC cross-sections in response to incrementally applied strain (Erne, 2003).

In this study, we used ESPI to measure depth and time-dependent strain over the cross-section of AC. We hypothesized, that the strain in the superficial zone of AC will increase during relaxation, while strain in the deep zones will decrease.

METHODS

Specimens: Osteochondral plugs (\varnothing 9mm) were harvested from fresh-frozen porcine patello-femoral joints of skeletally mature animals. Plugs, extracted from the medial aspect of both joint members, were cut with a diamond saw to cubes with a base of 5x5mm, including full thickness AC and subchondral bone. These osteochondral cubes were stored in phosphate buffered saline and protease inhibitors (PBS+PI) at -40°C . At the day of testing, each specimen pair ($n=5$) was thawed in PBS+PI, and stained with Hematoxylin and Eosin to ensure adequate reflective properties for ESPI measurements.

Experimental setup: Each pair of corresponding specimens was subjected to

unconfined compression in a custom cartilage compression setup (Fig. 1). Displacement was induced using the actuator of a servo-hydraulic material test system (8841, Instron, Canton, MA). Each specimen remained submerged in PBS+PI, and optical access to the specimen cross-section for ESPI measurements was provided by a glass window. An ESPI system (Q100, Etemeyer, Nersingen, Germany) in combination with a custom magnification optics was used to assess full-field compressive strain on the specimen surface with 42 pixel/mm spatial resolution. After alignment of the specimen, the femoral and patellar AC thickness of each specimen pair was optically assessed. Prior to testing, a pre-strain of 4% was applied and the AC was allowed to relax for 60 minutes.

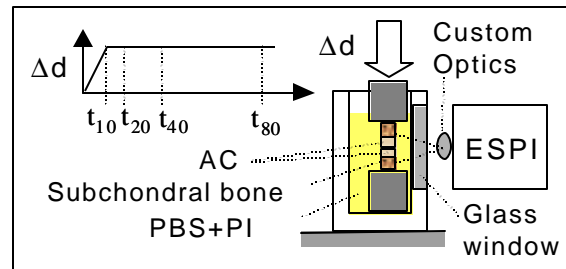


Figure 1: Section view of cartilage compression setup with ESPI sensor

Loading protocol: All specimens were subject to incremental compression by $\Delta d=0.5\mu\text{m}$ over a ramp duration of 10s, followed by 90s relaxation. Full-field ESPI strain distributions of the femoral cartilage cross-section were recorded directly after Δd was applied ($t_{10}=10\text{s}$), and subsequently at $t_{20}=20\text{s}$, $t_{40}=40\text{s}$ and $t_{80}=80\text{s}$. This sequence (i.e., application of Δd , followed by four ESPI recordings) was repeated 100 times

until a total displacement $d=50\mu\text{m}$ was applied.

Data evaluation: The cumulative strain reports over 100 steps were computed for t_{10} , t_{20} , t_{40} , and t_{80} . These strain reports were normalized to account for differences in femoral cartilage thickness. To reduce the full-field strain maps, average strain values over the specimen width (i.e., parallel to the articular surface) were computed to obtain compressive strain profiles \mathbf{e}_{t10} , \mathbf{e}_{t20} , \mathbf{e}_{t40} , and \mathbf{e}_{t80} . To further reduce the strain profiles, averaged zonal compressive strains \mathbf{e}_s , \mathbf{e}_m , and \mathbf{e}_d , were extracted from the superficial (20%), middle (50%), and deep (30%) cartilage zones, respectively, for \mathbf{e}_{t10} , \mathbf{e}_{t20} , \mathbf{e}_{t40} , and \mathbf{e}_{t80} . Differences in strain magnitudes obtained at specific times were statistically analyzed using two-tailed paired Students T-tests.

RESULTS

ESPI strain reports at specific times, t_{10} to t_{80} , yielded time-dependent compressive strain distributions over the cartilage thickness (Fig. 2). At the articular surface, \mathbf{e}_{t80} was 11% higher compared to \mathbf{e}_{t10} .

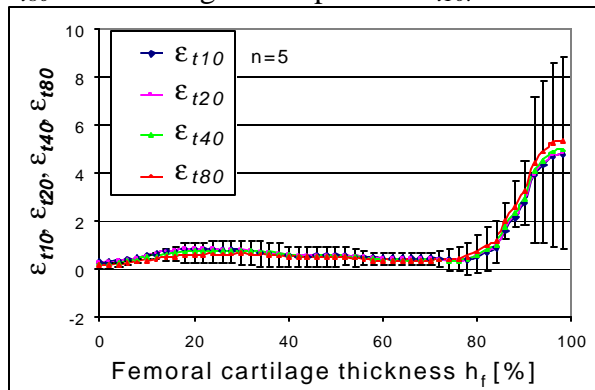


Figure 2: Time-dependent strain over femoral cartilage thickness ($h_f=100\%$ indicates articular surface).

At all times, strain at the superficial zone was larger as compared to the middle and deep zone (Fig. 3). During relaxation (i.e., $t_{10}-t_{80}$) strain \mathbf{e}_s at the superficial zone increased significantly, while strain \mathbf{e}_d at the deep zone decreased.

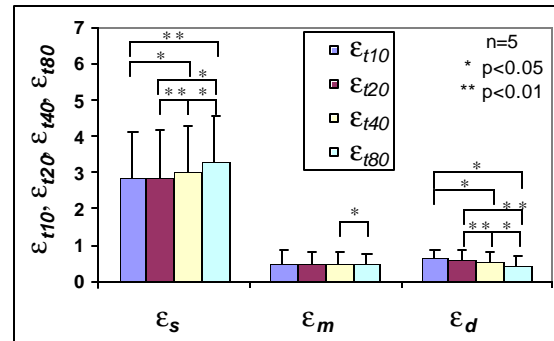


Figure 3: Time-dependent zonal strain across articular cartilage.

DISCUSSION

This study demonstrates direct measurements of time-dependent strain distributions over the cross-section of AC in response to small incrementally applied compression. Results are in line with previously reported equilibrium strain distributions (Guilak, 1995; Schinagl, 1997; Wang, 2003). In addition, the high sensitivity of ESPI allowed to detect subtle and consistent changes in the strain distribution during relaxation. Similar results were predicted in a fibril reinforced non-homogeneous poroelastic model (Li, 2000) and measured using ultrasound (Zheng, 2002). While ultrasound measurements are affected by material properties, ESPI captures full-field strain independent of the material. However, since ESPI can only capture relatively small strain increments per measurement step, 100 serial measurements were used to determine strain in response to $50\mu\text{m}$ compression.

REFERENCES

- Erne, O., et al. (2003). 49th ORS, 292
- Guilak, F., et al. (1995). *J Orthop Res* **13**(3): 410.
- Li, L., et al. (2000). *J BioMech* **33**: 1533.
- Schinagl, R., et al. (1997). *J Orthop Res* **15**(4): 499-506.
- Wang, C., et al. (2001). *J BioMech* **34**: 75.
- Wang, C., et al. (2003). *J BioMech* **36**: 339.
- Zheng, Y., et al. (2002). *Phys Med Biol* **47**: 3165-3180.