3D Full-Field Residual Strain Distribution Across the Cartilage-Bone Interface During Osteoarthritis Progression

Sarah Davis[1,2], Aikaterina Karali [2], Jurgita Zekonyte[2], Marta Roldo[1], Gordon Blunn[1].
[1]School of Pharmacy and Biomedical Science, University of Portsmouth, UK, [2]School of Mechanical and Design Engineering, University of Portsmouth, UK.
Sarah.davis@port.ac.uk

INTRODUCTION: Strain changes across the cartilage-bone interface are thought to play a crucial role in osteoarthritis (OA) initiation and progression. X-ray Computed Tomography (XCT) combined with Digital Volume Correlation (DVC) can measure 3D strain changes across the osteochondral interface. The aim of this study was to compare the residual strain distribution in both early and late-stage osteoarthritis.

METHODS: Cylindrical osteochondral plugs (Ø = 4 mm) were cored from the tibias of Dunkin-Hartley guinea pigs of ages 2, 4, and 24-months (n = 3) and stained with a 1:2 hafnium-substituted Wells-Dawson polyoxometalate (Hf-WD POM) for XCT imaging and DVC analysis. XCT imaging was performed using a high-resolution 3D X-ray microscope (Versa 520, Zeiss, Germany) with the following settings: 60kV/ 5W, 1.01 voxel size, 2001 projections and 5s exposure. DVC strain uncertainties were evaluated following two-consecutive unloaded XCT scans, and residual strains, including the third principal (ε_{p3}) and shear strain (γ) were computed following load-controlled unconfined (ex-situ) compression, corresponding to twice body weight. The severity of OA was confirmed in contralateral tibias using routine histology and modified Mankin scoring.

RESULTS: In pre-OA, 2-month specimens, regions of high ε_{p3} strain up to ~ 200,000 με and maximum γ strain ~ 160,000 με, corresponded to regions in the articular cartilage, at the cartilage-bone interface and in the subchondral bone. In contrast, early-OA (4-month) specimens, which had histological signs of OA, had 25% higher ε_{p3} strain and 12.5% higher γ strains, (~ 250,000 με and ~ 180,000 respectively) at the articular surface. In these areas the strain intensity was associated with, but not restricted to, surface fibrillation and high proteoglycan loss that occurred mostly at the cartilage surface and decreased throughout the cartilage depth. The highest strain was observed in severe OA (24-month) specimens, with 50% higher peak ε_{p3} and 25% higher peak γ strains compared to the 2 months specimens, which were distributed across a larger volume of the superficial zone and also decreased throughout the cartilage zones.

DISCUSSION: In conclusion, this study successfully combines XCT imaging with DVC to detect alterations in residual strain distribution patterns throughout OA progression and indicates the role of strain in localized regions in the articular cartilage, across the interface and in subchondral bone during early stages of OA pathology. It highlights strain distribution changes with OA progression where regions of the highest stains are found near the surface of the cartilage and are associated with proteoglycan loss.

SIGNIFICANCE: This study shows higher strain at the osteochondral interface in pre-OA specimens before histological signs of OA are detected which then intensifies and is redistributed towards the cartilage surface as OA progresses. Understanding the complex relationship between articular cartilage and subchondral bone during OA may allow for early and improved treatment before significant degenerative changes occur.

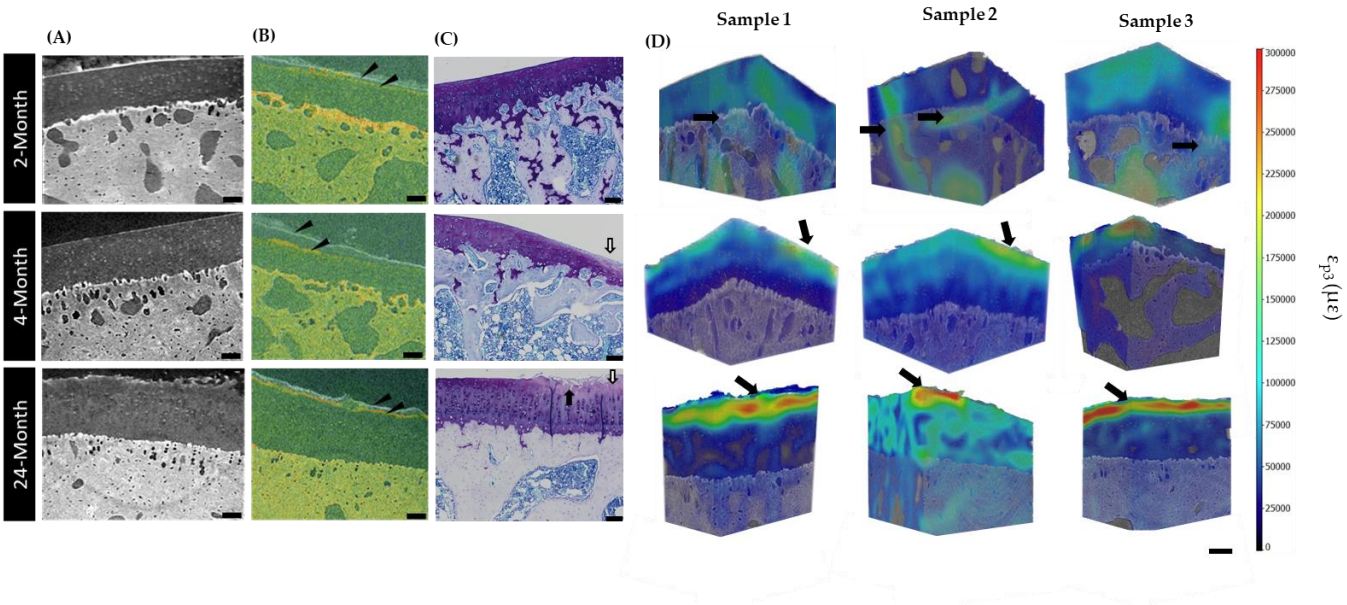

Figure 1: Residual strain distribution in Dunkin-Hartley (DH) guinea pigs at 2, 4, and 24-months of age (n = 3). (A) Representative slices of unloaded XCT tomograms of each age group with visible chondrocytes used as features in the AC for DVC strain analysis. (B) Residual deformation between the post-load (green) tomograms that have been registered and overlayed onto the original unloaded (grey) XCT tomograms, showing a reduction in volume of AC following compression (Black arrows). (C) Histological assessment of the osteochondral specimens from the medial tibial condyle by toluidine blue staining, with reduction in proteoglycan content with increasing age (white arrows) and areas of surface fibrillation and fissuring (black arrows). (D) 3D full-field residual strain distribution of the Third Principal Strain (ε_{p3}) after unconfined compression testing across the cartilage-bone interface using a multipass scheme with a final subvolume of 30 voxels (n = 3). Black arrows indicate regions of interest with high strain. (Scale bar = 100 μm).