Unexpected Behaviour of Water in Lumbar Discs under Repeated Flexion-Compression

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I. INTRODUCTION

Despite the substantial global burden from lower back pain, the etiology of most injuries that contribute to pain are not understood or even detected. Of the patients presenting clinically with low back pain (LBP), ~90% are diagnosed with 'non-specific' LBP because a specific pathology cannot be determined [1]. There is strong evidence, however, that disc injury is associated with repeated loading [2], which likely provides the predicate conditions for pain. Flexion superimposed on compression with increasing duration and amplitude of loading increases the risk of injury in experimental models (e.g. [3]). Water content within the intervertebral discs (IVDs) plays a crucial role in the mechanical function and pathophysiology of the lumbar spine [4]. It is well established that diurnal water flow occurs under daily physiological loads when water is lost from the nucleus pulposus (NP) of the IVD. Then, during periods of rest, the water content of the disc is restored over timescales comparable to the daily loading cycle (~8 hours). Quantitative magnetic resonance imaging (MRI) techniques have been used to non-invasively visualise the flow of water from the NP into the annulus fibrosus (AF) under axial loads [5]. MRI, owing to limited resolution, cannot differentiate between the microstructural components of the disc, such as details of NP and AF lamellae. Thus, it is difficult to determine how the structure of the NP and AF are altered due to water flow. In this study, we use novel high-contrast, high-resolution micro-CT to visualise the water flow on the NP/AF under combined flexion-compression loading conditions in porcine functional spinal units (FSUs). This study offers fascinating and important insights into the interaction between water, NP, and AF under loading.

II. METHODS

Experimental Testing and Imaging

Nine porcine lumbar FSUs (mean area ± SD, 596 ± 97.85 mm^2) were secured in a biaxial testing apparatus. During testing, FSUs were surrounded by an environmental chamber to provide physiologically appropriate temperature and humidity conditions. Eight FSUs underwent repeated flexion-compression loading modeled after occupational loading exposures of high-speed boat operators [6]. Peak oscillatory compressive stress applied was chosen to be 2.75 MPa, with oscillating flexion angle from 0^0 to 6^0 applied at 1 Hz for all loading tests. Loading duration depended on the intended final strain. One FSU was used as a control, for which all test procedures remained the same except no load was applied. A range of loading exposures was used to induce IVD changes at final endplate-to-endplate strain levels ranging from 0% (control) to 46%. FSUs were imaged pre- and post-test with a microCT (Nikon XT H225 ST) at ~90 kVP and ~20 μm/side voxel resolution. Contrast on the images was set to enhance soft tissue differences in the IVD. The distance between the endplates superior and inferior to the IVD was measured from the pre-test microCT, which was used to calculate endplate-to-endplate creep strain during testing. MicroCT volumetric images were rotated to centre the stack to mid-IVD (NIH ImageJ). These were used to measure the change in the area of the IVD components between pre- and post-test images. The NP was determined to be the well-defined region with no visible lamellae. The perimeter of the AF and total disc area were outlined using polygon selection (NIH ImageJ). The AF area was calculated by subtracting the NP area from the total area. The percentage area of each region was calculated as the fraction of the total midplane disc area.

III. INITIAL FINDINGS

Axial creep strain developed under flexion-compression loading with constant peak amplitude was approximately log linearly correlated with the duration of loading with $\%strain = 0.0529\ln(duration) - 0.0029$ ($R^2 = 0.8$) for durations of 20 s to 3,800 s. This dependence is expected based on measured creep behaviour in IVDs. For fixed amplitude cyclic oscillations, there is strong evidence for a threshold effect (Fig. 1A)

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at a strain of ~30% where substantial growth of the AF area is apparent. The AF area increases up to 11% in the longest duration test (3800 s, 46% strain), providing strong evidence of a complex combined strain/duration effect on the water intrusion into the AF under repeated flexion-compression load. High resolution imaging at ~20 um/side voxel (Fig. 1B) shows clear separation of AF lamellae in both transverse and coronal views in the post-test microCT images, particularly in the direction of the anterior disc. The lamellae appear homogeneously crenulated with separations that vary along the fibers. The post-test gap between lamellae is large in some local areas.

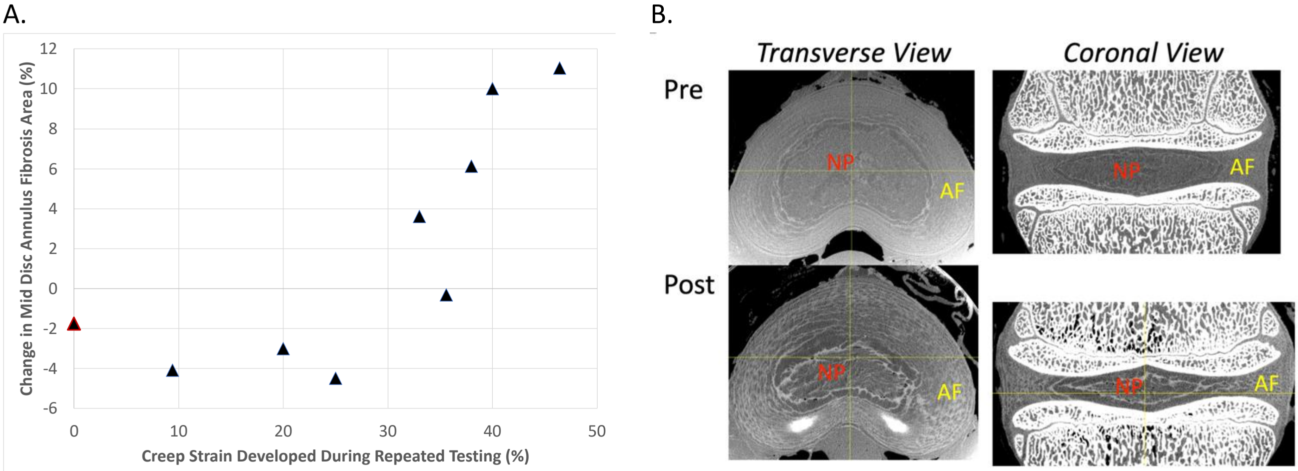

Fig. 1. A. Percentage change of total disc area on microCT (20 um/side voxels @~90 kVp) from pre-test to post-test. Red Triangle denotes control specimen. B. Representative pre-test and post-test microCT images (transverse and coronal) for AFDam1.1 (46% end-of-test engineering strain in the disc/endplate FSU). The post-test imaging shows that the AF has 11% increased area relative to the NP. The dark regions interspersed in the post-test AF indicate water intrusion between and among lamellae. The complex internal structure of the NP and the lamellae are clearly visible with these high-resolution, high contrast microCT images. *Note:* owing to the high contrast required for this study, the ventral AF in the post-test transverse view has two small areas of overexposure.

IV. DISCUSSION

This study found increases in AF area relative to the NP from cyclic flexion-compression loading that were associated with increasing duration at constant amplitude. We found an apparent threshold effect where the area increase in the AF remained approximately constant at -3% for all tests below 30% developed strain. Above this level, there was a clear increase in AF area with loading duration. We expected a linear or monotonically increasing nonlinear trend with homogeneous water intrusion into the AF under increasing duration with disc viscoelastic creep in poroelastic flow [7]. Instead, this threshold effect suggests that there is a level of creep strain in the IVD under the test conditions that does not substantially alter AF/NP structure. Beyond this level, increasing disruption in the AF may lead to short-term disc and endplate injury and chronic inflammation and pain.

These findings provide strong evidence of the complex interrelation between flexion-compression loading, AF and NP biomechanics. The unexpected results suggest that water disperses from the NP causing the AF to swell at a threshold value of flexion-compression amplitude and duration. This separates lamellae in the AF, particularly in the anterior (ventral) area for these FSUs with complex AF/NP interplay between diurnal hydration state, repeated motion, and potential disc injury, and endplate injury. A principal unknown in this process is the timescale for rehydration or recovery of the typically lamellae structure (aligned fibers) following water intrusion. If this occurs over hours/days (as in diurnal spinal disc height recovery [8]), this is likely a dramatic and compelling hypothesis supporting the recently recognised role of NP proteins on neurite outgrowth potentially leading to pain (cf. [9]). This repeated migration and separation may likely increase the potential for outgrowth and the potential for acute and chronic pain resolving the essential mystery of the etiology of discogenic pain (eg. [10]).

V. REFERENCES

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