POISSON'S RATIO OF NUCLEUS PULPOSUS TISSUE: COMPARISON OF EXPERIMENTAL RESULTS WITH A BIPHASIC POROVISCOELASTIC FINITE ELEMENT MODEL

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ABSTRACT: Experimental values for the Poisson's ratio of the nucleus pulposus (NP) are limited. Unconfined compression tests were conducted on bovine NP samples to determine apparent and true values of Poisson's ratio. A biphasic poroviscoelastic (BPVE) finite element model was created to mimic the experimental conditions for comparison. The true Poisson's ratio of the solid phase of NP tissue was found to be 0.125±0.072. The model captured the key mechanical behaviour of the tissue: future modelling should not model the NP as an incompressible fluid, but rather as a BPVE tissue.

1. INTRODUCTION

Mathematical and finite element models of the intervertebral disc (IVD) either describe the nucleus pulposus (NP) as an incompressible fluid, or assume a Poisson's ratio value between 0.35 and 0.49. Only one study has directly determined the Poisson's ratio of NP reporting a value of 0.62±0.15 [1]. The Poisson's ratio of a biphasic material may be described in terms of true (υ_T) and apparent (υ_A) values [2], wherein υ_A is the observed Poisson's ratio of the tissue, whilst υ_T is determined at stress equilibrium, i.e. the Poisson's ratio of the solid phase. One objective of this study is, therefore, to characterise the apparent and true Poisson's ratio of the nucleus pulposus to better inform future models of the IVD. According to theory [2], the apparent υ_A should equal 0.5 due to the incompressible fluid phase, however interfacial shear stresses between the platens and tissue may play an important role in the measured values of both υ_A and υ_T. Therefore we also aimed to experimentally characterise the interfacial shear stress and numerically model its effect on experimental outcomes.

2. METHODS

Sixteen cylindrical plugs of NP tissue (ø5.5mm, height 1544 ± 252 µm) orientated in the axial direction were harvested from the central region of bovine tail IVDs. The plugs were subjected to unconfined compression to 5% axial strain between glass platens using an aqueous lubricant mixed with 3M NaCl to reduce swelling effects [3]. Tests were conducted on a Bose® Electroforce 3200 with ramp speeds of either 30µm/s or 0.3µm/s and pre and post ramp hold phases of 1 hour. The resultant lateral displacement was determined using the Bose® 2D Digital Video Extensometer. The specimen-platen static friction coefficient was determined by measuring the angle of the platen that initiated a sliding motion. υ_A and υ_T were calculated from strain data at the onset and end of the post ramp hold phase respectively. Pilot tests were performed on silicone rubber to validate the methodology.

A biphasic poroviscoelastic finite element (BPVE FE) model of the nucleus pulposus and platen was created and solved using FEBio [4]. The model, meshed using 18021 nodes and 14000 8-node hexahedral elements, replicated the experimental conditions. The model incorporated interfacial shear forces, by including friction at the interface for both strain rates. This was achieved by tying an elastic surface to the tissue as an interface between the tissue and the platen. Nodal displacement at the interface was used to determine a Poisson's ratio measure, mimicking the experimental method. The matrix's viscous phase was characterised by two time constants of 7s and 102s of equal importance [5] and characterised by 99% stress relaxation overall. Matrix permeability was kept constant at $1\text{x}10^{-15}$ m^4/Ns. The modulus of the elastic phase of the viscoelastic solid elastic interface was manually adjusted for a qualitative fit and υ_T was taken from the experiment.

3. RESULTS

Pilot tests on silicone rubber resulted in constant υ measures of 0.49. The static coefficient of friction for the NP-glass interface was found to be 0.44±0.08 and 0.26±0.05 for the silicone rubber-glass interface. Minimal swelling and no contraction occurred in the pre-ramp hold phase. Lateral recoil occurred for NP tissue in the post-ramp hold phase, resulting in υ_T being less than υ_A ($p < 0.001$). The lowest mean υ_T was 0.125±0.072 (Fig 1a). The relationship of υ with strain rate also varied between apparent and true values ($p < 0.001$) with υ_A decreasing and υ_T slightly increasing with decreasing strain-rate (Fig 1a). The BPVE FE model qualitatively agreed with the results when E≈10MPa (Fig 1b): the ramp speed affected the Poisson's ratio measures in the same manner as the experiment. Shear stress at the interface slowed down the mechanics, particularly in the hold phase, but ultimately did not affect the numerically mimicked υ_A and υ_T values.

4. DISCUSSION

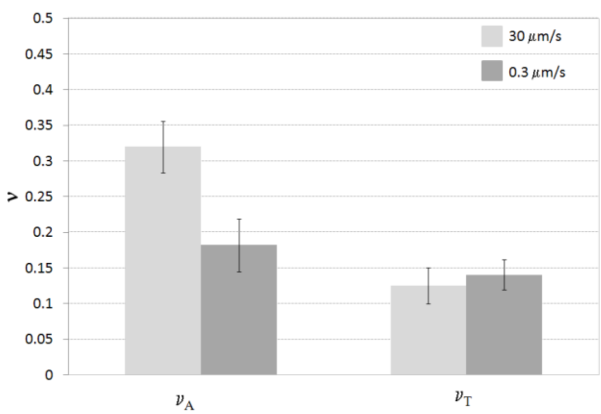
The near incompressible result for silicone rubber provided confidence in our experimental technique. The lowest mean υ_T of nucleus pulposus determined by this study was much less than the previously reported value of 0.62 [1] (which was possibly high due to sample swelling) and similar to measured values for articular cartilage [6]. The observed recoil suggests that the interfacial shear force was overcome by the radial tensile stress in the hold phase giving confidence that the lowest achieved υ_T is indicative of the actual tissue parameter. However, the fact that υ_A did not achieve the theoretical value of 0.5 [2] may either mean that friction did affect the measured υ_A in the ramp phase, or the assumptions of the model [2] (e.g. incompressible solid phase) may not be appropriate. Also, the value of E required for this qualitative fit is higher than previously reported for this tissue [3].

In a fast ramp, a high fluid pressure is created in the tissue resulting in greater radial fluid velocity. The viscous drag associated with this fluid flow would augments the radial strain and υ_A. In the slow ramp, radial fluid flow is slower with a concomitant reduced radial viscous drag reducing υ_A in comparison to the fast ramp case. The significant interaction of strain rate with the two Poisson's ratio measures suggests that stress relaxation of the collagenous matrix affected the tissue's recoil: stress relaxation would have decreased the elastic radial tensile stress required to recoil the tissue opposed by the interfacial shear force. We believe the elastic interface elements in our BPVE FE model prevented this phenomenon to be observed numerically; improved modelling would require the friction at the interface to be modelled for BPVE elements.

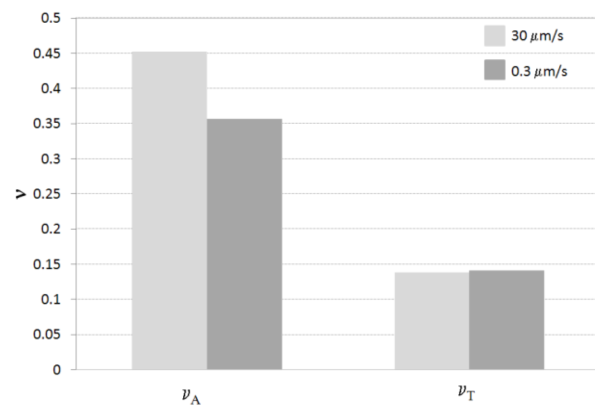
In the IVD, the NP transfers its radial stress to the annulus fibrosus (AF). Our data suggest that this stress may drop significantly with time reducing the radial and circumferential stresses in the AF. We suggest future models of the IVD should not model the NP as an incompressible fluid, since this may result in erroneous implications for AF stress and strain at long times. Our data further suggest that a BPVE model can characterise the key mechanical characteristics of the NP, although the ionic environment and solute transfer should also eventually be included.

5. CONCLUSIONS

The Poisson's ratio of the solid phase of NP tissue is close to 0.125±0.072. A BPVE model can describe the salient mechanical characteristics of the NP, but the interfacial stresses are not easily modelled, with consequential difficulties for inverse procedures in parameter estimation.



(a)



(b)

Figure 1 – (a) Experimental υ_A and υ_T for NP tissue under 5% compressive axial strain at two different strain rates (mean ± one standard error of the mean, N = 8), (b) BPVE model of same experiment

6. REFERENCES

[1] Cloyd JM, Malhotra NR, Weng L, Chen W, Mauck RL. Elliott DM. Material properties in unconfined compression of human nucleus pulposus, injectable hyaluronic acid-based hydrogels and tissue engineering scaffolds. Eur Spine J 2007; 16: 1892-1898

[2] Armstrong CG, Lai WM, Mow VC. An analysis of the unconfined compression of articular cartilage. J Biomech Eng., 1984; 106: 165-173.

[3] Heneghan P, Riches PE. The strain-dependent osmotic pressure and stiffness of the bovine nucleus pulposus apportioned into ionic and non-ionic contributors. J Biomech. 2008, 41: 2411-2416.

[4] Maas SA, Ellis BJ, Rawlins DS, Weiss JA: A Comparison of FEBio, ABAQUS, and NIKE3D Results for a Suite of Verification Problems. SCI Technical Report, 2009

[5] Shen ZL, Kahn H, Ballarini R, Eppell SJ. Viscoelastic Properties of Isolated Collagen Fibrils, Biophys J, 2011, 100: 3008-3015.

[6] Chegini S, Ferguson SJ. Time and depth dependent poisson's ratio of cartilage explained by an inhomogeneous orthotropic fiber embedded biphasic model, J. Biomech, 2010, 43: 1660–1666