The possible role of poro-elasticity in the apparent viscoelastic behaviour of passive muscle: a case study

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1. Introduction

Soft tissues are sensitive to prolonged compressive loading, eventually leading to tissue necrosis in the form of Pressure Ulcers (PU). Understanding the determinants of pressure ulcer onset remains challenging as many factors such as mobility, tissue perfusion and skin status have been identified (Coleman et al. 2012). The development of Finite Element models represents a viable paradigm to identify the characteristics of load-tolerant soft tissues and explain soft tissue injury risk factors. Studies in the literature are generally conducted with the assumption of quasi-static loading and response (Al-Dirini et al. 2016). Yet, the knowledge of the local mechanical condition alone is not sufficient to predict tissue damage initiation. The loading history is essential, because the time that a tissue is subjected to a sustained compression is a major determinant of tissue damage. Attempts to characterise the time-dependence of skeletal muscle tissue generally assume a viscoelastic formulation and typically ignore the biphasic nature of the tissue (Simms et al. 2012). Conversely, poro-elastic constitutive models use allow for a fully comprehensive, physically based view of the history-dependent response of soft tissues under static and dynamics loading. Porous media models also represent a promising approach for the integration of multiscale/multiphysics data to probe biologically relevant phenomena at a smaller scale and embed the relevant mechanisms at the larger scale (in particular, biochemistry of oxygen and the biology of inflammatory cytokines). The aim of this study is therefore to investigate the contribution of extracellular fluid to the apparent viscoelastic behaviour of passive muscle tissue under confined compression, using a poro-elastic model.

2. Methods

2.1. Experimental data

The average experimental stress-relaxation curve of confined compression of tibialis anterior porcine muscles samples previously reported by (Vaidya and Wheatley 2020) and reproduced here with permission from the authors were used. The experimental details are briefly recalled hereafter. 15 cylindrical porcine samples (average height 8.0 mm and average radius 3.2 mm) were tested under Confined Compression (CC) and were strained to 15% at a strain rate of 1.5%.s^{-1} and maintained during 400s at this deformation.

2.2. Finite Element Modelling

A Finite Element model was developed in the general purpose finite element software Abaqus (Abaqus 2019) and an inverse analysis was performed to fit a quasi-incompressible, isotropic (no experimental information available on the samples' fiber orientation), poro-elastic constitutive model (solid saturated by an incompressible viscous fluid) to reproduce the mean experimental mechanical response (stress relaxation). Such a model is governed by the coupled resolution of the mass balance of the fluid, the mass balance of the solid and the momentum conservation of the whole system, considering a total stress which is a combination of the solid stress with the pore pressure. In our model, the solid behaviour is governed by a linear elastic law and the fluid interplay with the solid scaffold is modelled with a Darcy's law, with a dynamic viscosity of 1Pa.s. Finally, the model is completed by the definition of the soil grain and fluid bulk moduli (respectively equal to 0.799 MPa and 2.2 GPa). A 2D axisymmetric model was proposed for the CC test ($n = 96$ CAX4PH elements) for the porous models (Figure 1).

Displacement Boundary Conditions (BCs) were imposed on the top surface to reproduce the experimental BCs of (Vaidya and Wheatley 2020) and fluid leakage was authorised on the cylinders' top surface. The mean experimental stress relaxation curve of confined compression were fitted using the @lsqnonlin() of Matlab (Matlab R2019a). Specifically, we used Matlab to call Abaqus with an initial guess for the material model parameters (Young's modulus, Poisson's ratio, hydraulic permeability, void ratio), performed a forward simulation in Abaqus, read the simulation-based output forces in Matlab, computed the root mean square error metric over the whole curve, the maximum peak

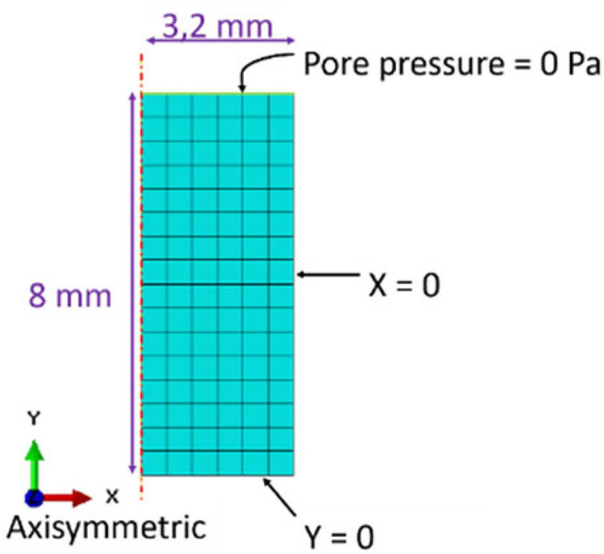

Figure 1. Discretized FE model of skeletal muscle specimen employed to simulate the uniaxial confined compression. Sample dimensions and assumed boundary conditions are indicated.

stress and the final derivative of the curve, and repeated this process iteratively until reaching the cost function local minimum.

3. Results and discussion

The identified parameters were Young's modulus of 7.7 kPa, Poisson's ratio of 0.4879, void ratio e of 0.47 (which corresponds to a porosity of 32%) and hydraulic permeability of $k = 3.1e\text{-}14\ m^2.\ Pa^{-1}.s^{-1}$. The stress-relaxation curve predicted by the poro-elastic model is given in Figure 2. The average experimental result and the result of the uncoupled Yeoh/Prony hyper-viscoelastic model calibrated by (Vaidya and Wheatley 2020) are also superposed. These preliminary results are encouraging because they show that a poro-elastic model allows to capture the peak stress and the time rate of the consolidation settlement as well as the characteristic relaxation time. Further work however is required to improve the model capacity to capture the toe region of the curve. We think that this toe region behaviour could be the result of a parallelism default at the initiation of the experiment between the sample and the loading plate.

The values obtained are consistent with those reported in the literature. For example, (Debbaut et al. 2012) reported an interstitial hydraulic permeability to fluid flow in the range $k \in$ [3.64e-14; 1.56e-9] $m^2.\ Pa^{-1}.s^{-1}$.

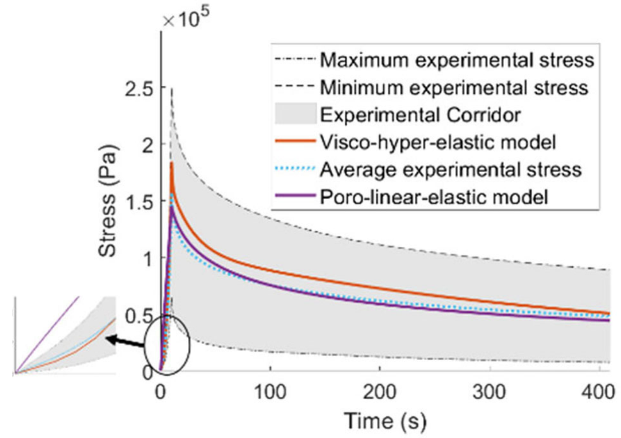

Figure 2. Experimental average response and calibrated constitutive models.

4. Conclusions

This preliminary result supports the hypothesis that poro-elasticity can account for the measured visco-elastic-type effects in the muscle passive behaviour under compression. These results also suggest that extracellular fluid filtration, not tissue viscoelasticity, dominates the apparent viscoelastic behaviour of passive muscle. Our comparison seems to provide evidence that poro-elasticity is significant in muscle mechanics. This is an important step for investigating and understanding Pressure Ulcer development.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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