Fitting of a Hyper Quasi-Linear Viscoelastic Model for Brain Tissue and Assessment in Head Impact Scenario

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I. INTRODUCTION

Head and brain injuries are serious injuries with long-term health and socio-economic consequences. Finite Element (FE) head models can be used to investigate and predict the potential for brain injuries but require a biofidelic representation of tissue mechanical properties and validation. Many contemporary FE head models [1–4] utilize the Kelvin-Maxwell Linear Viscoelastic (LV) constitutive model to represent the mechanical properties of the cranial nervous tissues. The LV model is limited, however, in characterizing materials that exhibit stress-strain non-linearity, viscoelastic stiffening throughout multiple strain rate decades, and asymmetry in tension and compression. Recently published experimental data [5-6] characterized the porcine cranial nervous tissue in tension, compression and shear over a range of strain rates (0.01 s^{-1}, 1 s^{-1}, 50 s^{-1}). The experimental results [5-6] confirmed that porcine brain tissue exhibited stress-strain non-linearity, viscoelasticity in a broad strain rate regime, and asymmetry. The current study aimed to address the limitations imposed by the LV material model by: (1) multimodal fitting of a Non-Linear Hyperelastic material model with Quasi-Linear Viscoelasticity (QLV) to the tissue level experimental data [5-6]; and (2) biofidelity comparison between LV and QLV using the FE Head Model (GHBMC 50th percentile male) in rapid head movement simulation [7].

II. METHODS

The tissue-level experiments in compression (Fig. 1a), tension and shear were simulated and a commercial optimization software (LS-OPT, LST, Livermore, California, US) was used to fit the material parameters. The optimization algorithm fit the hyperelastic (C_{01}, C_{10}) and viscoelastic parameters (G_i) of the QLV model, with the objective to minimize the difference between simulation and nine experimental [5-6] stress-strain curves (3 modes of loading and 3 strain rates). Next, the fit material properties were implemented in the GHBMC average stature (M50) head model. Two versions of the head model ($M50_{QLV}$ and $M50_{LV}$) were simulated using the kinematics applied to the head from a rapid head movement experiment [7] (experiment number C755-T2) with neutral density targets (NDTs) to track brain tissue motion (Fig. 1b). The models were solved using a commercial FE code (LS-DYNA v9.2 MPP, double-precision, LST, Livermore, California, US). The cranial nervous tissue deformation traces for 6 NDTs were compared with the experimental data (Fig. 1c), and cross-correlation (CC) ratings were calculated.

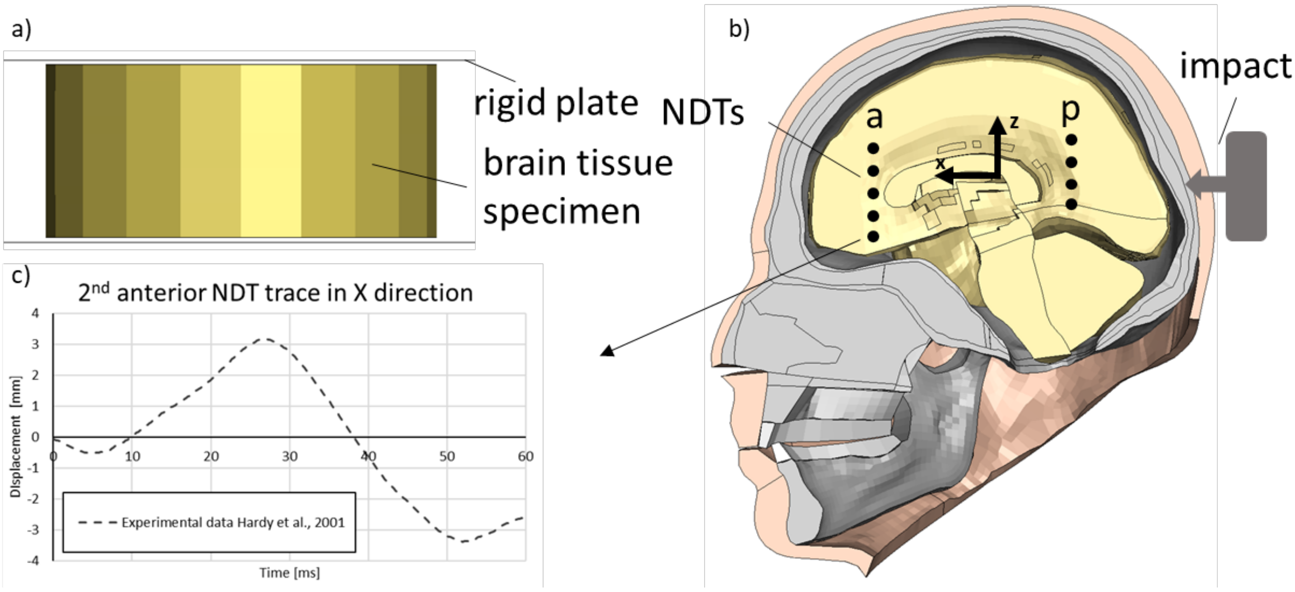

Fig. 1. a) Tissue-level compression FE model for parameter optimization; b) GHBMC M50 Head model with schematic of anterior and posterior Neural Density Targets (NDTs); c) exemplar experimental trace of 2nd anterior NDT in the X-direction.

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III. INITIAL FINDINGS

The optimized QLV material model represented all nine stress-strain curves with a cumulative coefficient of determination (R^2) of 0.57, and a good fit to the compression data [6] (Fig. 2a). The LV had a lower coefficient of determination of 0.41. Comparison of NTDs traces between the GHBMC $M50_{QLV}$ head model correlated better to the experimental results (CC = 0.656) compared to the GHBMC $M50_{LV}$ Head model (CC = 0.581).

TABLE I
SUMMARY OF MATERIAL PARAMETERS USED IN THE STUDY

Model	Parameters					
QLV	C_{01} = 0.00 kPa	C_{10} = 0.65 kPa	K = 2.19 GPa	G_1 = 1.09 [-] T_1 = 1000 ms	G_2 = 3.21 [-] T_2 = 20 ms	G_3 = 0.79 [-] T_3 = 2 ms
LV	G_{inf} = 1.20 kPa	G_{insta} = 6.00kPa	K = 0.20 GPa	β = 0.2 ms^{-1}		

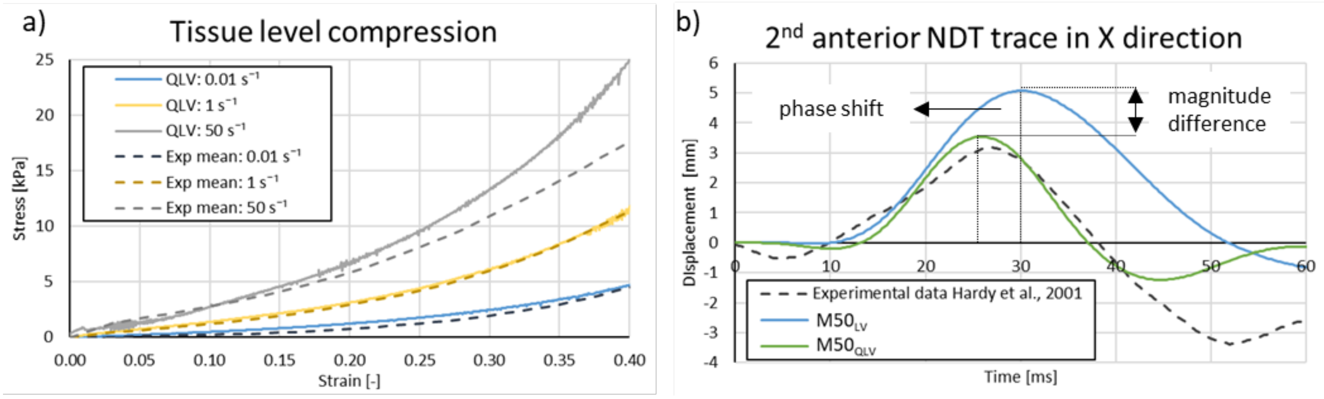

Fig. 2. a) Fit QLV model compared to the compression test data [6]; b) Comparison of traces between experimental data [7] and both versions of the GHBMC M50.

IV. DISCUSSION

Simultaneous fitting of the constitutive model to multimodal data is challenging. The fitted QLV material model better represented the tissue-level data compared to LV material model. Firstly, the QLV material model utilized a hyperelastic function that more accurately represented the non-linearity and asymmetry measured in the experimental data. Secondly, the quasi-linear viscoelasticity represented the change in slope of the curves at higher strain rates. The improved model reflected a relative increase in the coefficient of determination of 39%. Further improvement could be achieved by incorporating the reported brain tissue anisotropy into the material model. The simulation of the GHBMC M50 head model with the QLV ($M50_{QLV}$) model generally improved the correspondence to the experimental data [7] by lowering the magnitude of the observed displacement (Fig. 2b), and by shifting the peak deformation in time in all 12 NDTs traces. Further, 9 out of 12 NDTs traces showed improved correlation with the experimental data that is highlighted by a 13% increase of the CC rating. Overall, the fitted QLV material model represents more biofidelic tissue-level experimental data in three modes of loading and shows better correspondence to the reported PHMS brain deformation data.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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