ELSEVIER

Journal of Biomechanics 41 (2008) 235–238

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Compression testing of very soft biological tissues using semi-confined configuration—A word of caution

Leith Morriss, Adam Wittek, Karol Miller*

Intelligent Systems for Medicine Laboratory, School of Mechanical Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, Perth, WA 6009, Australia

Accepted 25 June 2007

Abstract

We analyse semi-confined (i.e. using no-slip boundary conditions) compression experiment of very soft tissue sample using finite element method. We show that the assumption that the planes perpendicular to the direction of the applied force remain plane during the experiments is not satisfied for compression levels lower than previously stated in Miller [2005. Method for testing very soft biological tissues in compression. Journal of Biomechanics 38, 153–158]. Therefore, we recommend that the parameters for constitutive models of very soft tissues be determined by fitting a solution of the finite element models of the experimental set-up to the measurements obtained using semi-confined compression experiments.

Keywords: Very soft tissues; Compression experiment; No-slip boundary conditions; Finite element method

1. Introduction

The mechanical properties of very soft biological tissues—such as the brain, liver and kidney—are of interest to several fields, including computer-integrated surgery and biomechanical analysis of injury due to impacts. Determination of the mechanical properties of these soft tissues remains an experimental and analytical challenge.

In our previous publications, we suggested a way to reliably test very soft tissues in compression (Miller, 2005) and extension (Miller, 2001) using a semi-confined configuration. This method relies on attaching cylindrical samples of low aspect ratio to stress–strain machine platens using surgical glue, which allows using no-slip boundary conditions in the analysis of measurement results. The semi-confined test configuration has been used by a number of researchers, e.g. Cheng and Bilston (2007), Cheng and Chen (2003), Miller and Chinzei (2002), and Snedeker et al. (2005).

The applicability of the analytical relationships between stress and strain derived in our previous papers depends on the major assumption that the planes within the sample perpendicular to the direction of the applied force remain plane during the test is satisfied. In this paper, we analyse in detail the semi-confined compression experiment using the finite element method in an attempt to evaluate the validity of this assumption.

2. Finite element analysis of compression experiment

The semi-confined compression experiment set-up proposed by Miller (2005) is essentially the same as those used previously (Estes and McElhaney, 1970; Miller and Chinzei, 1997) but replaces a no-friction boundary condition at the tissue–platen interfaces, that is difficult to implement in practice, by a no-slip boundary condition (see Fig. 1).

We constructed a finite element model of the semi-confined compression experiment using the ANSYS software (ANSYS, Inc., Canonsburg, PA, USA). Cylindrical soft tissue samples of 30 mm diameter and 25 mm height were modelled with the no-slip boundary conditions prescribed in previous study (Miller, 2005).

*Corresponding author. Tel.: +61 8 6488 8545; fax: +61 8 6488 1024.
E-mail address: kmiller@mech.uwa.edu.au (K. Miller).
URL: http://www.mech.uwa.edu.au/ISML (K. Miller).

0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.06.025

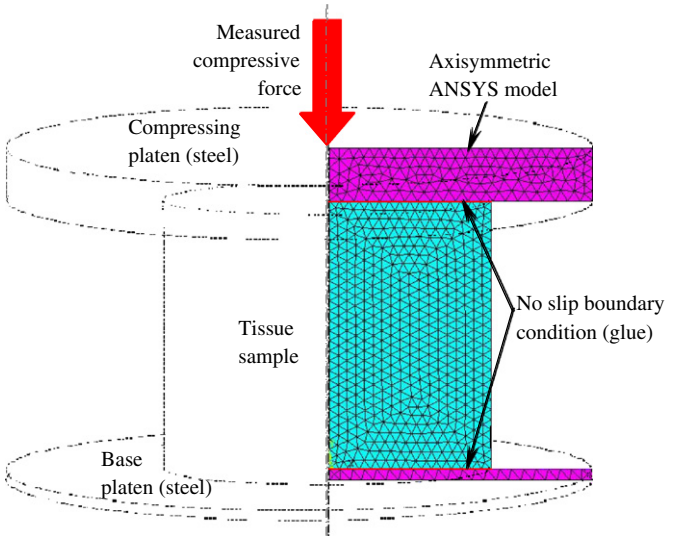

Fig. 1. Schematic representation of the experimental set-up and the set-up finite element model.

For computational efficiency, we chose an axisymmetric model of the compression experiment. We used the six-node triangular PLANE183 element (ANSYS Realease 9.0 Documentation). The meshed axisymmetric model is shown in Fig. 1.

For the analysis, we chose a Neo-Hookean material model (shear modulus of 1500 Pa, Poisson's ratio of 0.49) describing a commercially available silicone-based gel Sylgard-527 (Dow Corning Corporation, Midland, MI, USA) commonly used as a brain phantom (tissue substitute) material (Brands et al., 2000; Ivarsson et al., 2000; Margulies et al., 1990). Whilst very soft tissues are usually assumed to be incompressible—Poisson's ratio tending to 0.5 (Miller and Chinzei, 1997)—our experience (Wittek et al., 2007) indicates that compression modelling with Poisson's ratios greater than 0.49 does not provide significantly different results. Increased computational demands of modelling a more incompressible material are therefore unnecessary. As the model is loaded through the

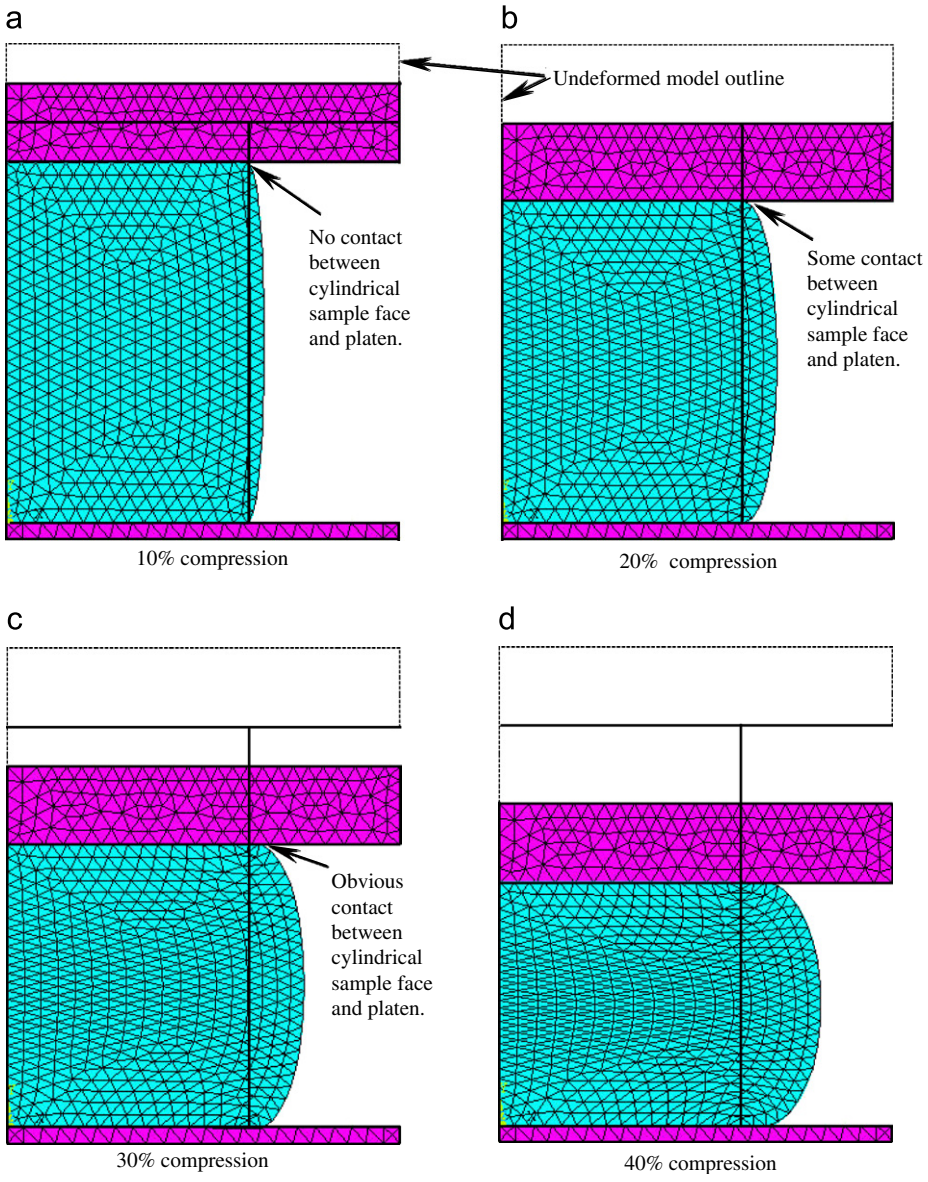

Fig. 2. Stages in compression progression.

enforced motion of the boundary (i.e. upper platen) the choice of the constitutive model has negligible influence on the computed displacements (Ciarlet, 1988; Miller, 2002, 2005; Miller and Wittek, 2006).

3. Results

When simulating the compression experiment, we found that the cylindrical surface of the material sample came in contact with the platens at much lower compressions than initially thought. This material behaviour is best observed in Fig. 2.

Clearly, the increase of the contact surface demonstrates that the assumption stating that the planes perpendicular to the direction of the applied force remain plane is violated. Consequently, part of the measured reaction force is carried through the increased contact surface (the "expansion ring", see Fig. 3). This behaviour is not accounted for in Miller (2005).

The percentage of the load supported by the expansion ring was calculated and is presented in Fig. 4.

Thus, our results show that the cylindrical surface of the tissue sample comes in contact with the compressing platens at approximately 15% compression for the sample dimensions used. At 30% compression, a sizeable proportion (10%) of the reaction force is transmitted through the expanded portion of the interface.

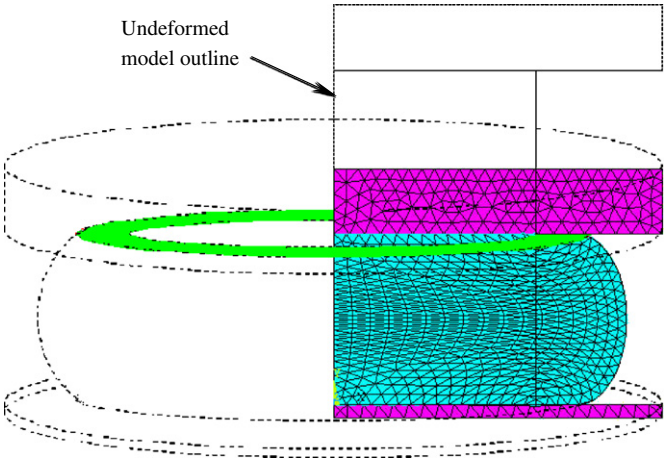

Fig. 3. The expansion ring (i.e. increase of the contact surface through contact between the cylindrical surface of the sample and platen) at 50% compression.

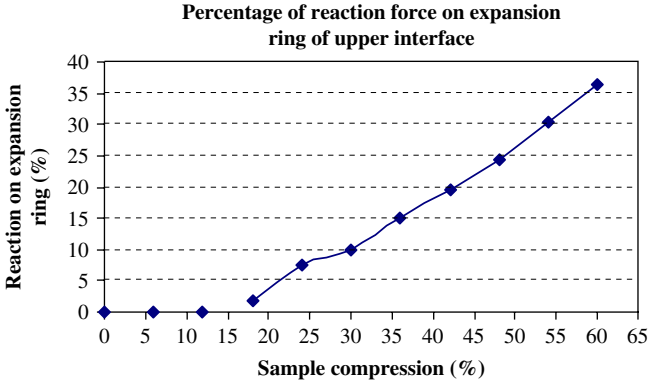

Fig. 4. Percentage of reaction force on the expansion ring.

4. Discussion and conclusions

Assumption 3 of Miller (2005) states: 'the planes perpendicular to the direction of the applied force remain plane'. This assumption is invalid when the cylindrical surface of the material sample comes in contact with the compressing platen (formation of the expansion ring). Thus the model proposed by Miller (2005) for analysis of semi-confined compression experiments of very soft tissues is limited to analysis before formation of the expansion ring. We find that this occurs at a compression of approximately 15% for the sample dimensions used. Initially the proposed analytical model was thought to be suitable for analysis of soft tissue material responses for compressive strains up to 30% (Miller, 2005). We conclude this limit is lower however. Not accounting for the increased contact surface when using the model from Miller (2005) will result in an overestimation of the stresses, and therefore of the tissue stiffness.

Therefore, we recommend that the parameters for constitutive models of very soft tissues be extracted from force–displacement measurements obtained using semi-confined compression experiments by means of fitting a solution of the finite element model of the experimental set-up. A simple axisymmetric model presented in this paper may be used for this purpose. If this route is followed, the assumption that the planes perpendicular to the direction of the applied force remain plane can be abandoned.

5. Conflict of interest

We have no conflicts of interest to report. All other than the employment sources of financial support (The Australian Research Council and The National Institute of Health) are disclosed in Acknowledgements.

Acknowledgements

The financial support of the Australian Research Council (Grants no. DP0770275 and DP0664534) and the National Institute of Health (Grant no. R03 CA126466-01A1) is gratefully acknowledged.

References

ANSYS Realease 9.0 Documentation: ANSYS Elements Reference. 〈http://www.ansys.com/services/documentation〉.

Brands, D.W.A., Bovendeerd, P.H.M., Peters, G.W.M., Wismans, J.S.H.M., 2000. The large strain dynamic behaviour of in-vitro porcine brain tissue and a silicone gel material model. Stapp Car Crash Journal 44, 249–260.

Cheng, M., Chen, W., 2003. Experimental investigation of the stress–stretch behavior of EPDM rubber with loading rate effects. International Journal of Solids and Structures 40, 4749–4768.

Cheng, S., Bilston, L.E., 2007. Unconfined compression of white matter. Journal of Biomechanics 40, 117–124.

Ciarlet, P. G., 1988. Mathematical Elasticity, North-Holland, Amsterdam.

Estes, M.S., McElhaney, J.H., 1970. Large strain behaviour of brain tissue in shear: some experimental data and differential constitutive model. Biorheology 38, 335–345.

Ivarsson, J., Viano, D.C., Lövsund, P., Aldman, B., 2000. Strain relief from the cerebral ventricles during head impact: experimental studies on natural protection of the brain. Journal of Biomechanics 33, 181–189.

Margulies, S.S., Thibault, L.E., Gennarelli, T.A., 1990. Physical model simulations of brain injury in the primate. Journal of Biomechanics 23, 823–836.

Miller, K., 2001. How to test very soft biological tissues in extension. Journal of Biomechanics 34, 651–657.

Miller, K., 2002. Biomechanics of Brain for Computer Integrated Surgery. Warsaw University of Technology Publishing House, Warsaw.

Miller, K., 2005. Method for testing very soft biological tissues in compression. Journal of Biomechanics 38, 153–158.

Miller, K., Chinzei, K., 1997. Constitutive modeling of brain tissue: experiment and theory. Journal of Biomechanics 30, 1115–1121.

Miller, K., Chinzei, K., 2002. Mechanical properties of brain tissue in tension. Journal of Biomechanics 35, 483–490.

Miller, K. and Wittek, A., 2006. Neuroimage registration as displacement—zero traction problem of solid mechanics (lead lecture). In: Proceedings of Computational Biomechanics for Medicine Workshop, Medical Image Computing and Computer-Assisted Intervention MICCAI 2006. Copenhagen, Denmark, 1st October, ISBN 10:87-7611-149-0, pp. 2–13.

Snedeker, J.G., Niederer, P., Schmidlin, F.R., Farshad, M., Demetropoulos, C.K., Lee, J.B., Yang, K.H., 2005. Strain-rate dependent properties of the porcine and human kidney capsule. Journal of Biomechanics 38, 1011–1021.

Wittek, A., Miller, K., Kikinis, R., Warfield, S.K., 2007. Patient-specific model of brain deformation: application to medical image registration. Journal of Biomechanics 40, 919–929.