Short communication

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

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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.

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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).
For computational efficiency, we chose an axisymmetric model of the compression experiment. We used the six-node triangular PLANE183 element (ANSYS Release 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

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

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 propor-
tion (10%) of the reaction force is transmitted through the 
expanded portion of the interface.

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 
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