CHALMERS
UNIVERSITY OF TECHNOLOGY

Calibration of Adipose tissue material properties in LS-DYNA

REPORT 2022:03, Version 1.0

Hosein Naseri

This work has received funding from Swedish Research Council (VR), Grant No. 621-2013-3909, and the European Union's Horizon 2020 research and innovation program (the OSCCAR project), Grant No. 768947, which are gratefully acknowledged. Simulations were performed on resources at Chalmers Centre for Computational Science and Engineering (C3SE) provided by the Swedish National Infrastrcture for Computing (SNIC).

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY

REPORT 2022:03
Gothenburg, Sweden, April 2022
www.chalmers.se

Contents

1. Introduction

In this report the development and calibration of a LS Dyna model of adipose tissue are presented. The model is intended to capture the tissue behavior at large deformation and wide strain rates. There are few studies for characterizing the mechanical properties of adipose tissue [1-6]. Lack of experimental data and high variation in the adipose tissue mechanical properties make calibration of models of adipose tissue challenging. Hence, for a more reliable model calibration an average response of several test results was considered.

2. Material parameter identification

An unconfined experiment was conducted in [4] at large strain levels and different ranges of strain rates defined as low, intermediate and high strain rates. At low strain rates, a strain range between 0.002/s - 0.25/s was applied using a screw-driven compression test machine with 5 N load cell and sensitivity of 20 mN. In the intermediate strain rate, a servohydraulic compression test machine was used to prescribe strain rate range of 20/s – 260/s. Finally, for the high strain rates a split Hopkinson pressure bar was used to achieve a strain rate range of 1000/s – 5700/s. Since the high strain rate range is higher than strain rates relevant for vehicular crashes, only the experimental data of low and intermediate strain rates were used. A schematic illustration of unconfined compression test at low and intermediate strain rates is presented in Figure 1.

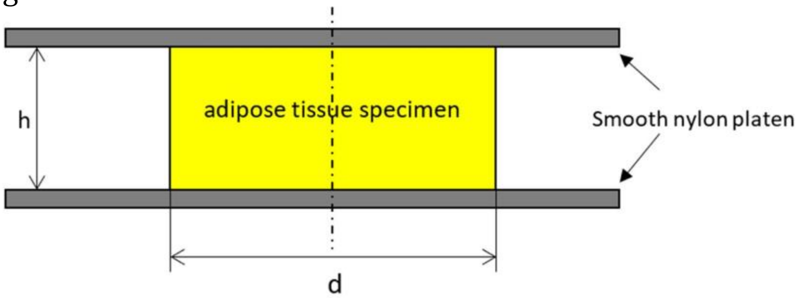

Figure 1. Schematic illustration of the unconfined compression test [4]. Specimen diameter is d=10 mm, and the height is h=8 mm and h=3 mm for low and intermediate strain rates, respectively.

MAT_HYPERELASTIC-RUBBER (MAT_077_O) in LS-Dyna was used as the material model. The model is based on the Ogden material model, a hyperelastic material model used to describe the non-linear stress–strain behavior of complex materials such as rubbers, polymers, and biological tissues, with the possibility of including linear viscoelasticity by Prony series terms. Three terms of Prony series were enough to cover adipose tissue behavior at the given strain rate range. The corresponding key card in LS-Dyna with identified material parameters, corresponding to the average material behaviour, is shown in Figure 2.

```
*MAT_OGDEN_RUBBER_TITLE
Ogden model - Average
$#      mid          ro          pr           n          nv           g        sigf         ref
          19.00000E-7     0.49978           0           6         0.0         0.0         0.0
$#      mu1         mu2         mu3         mu4         mu5         mu6         mu7         mu8
3.50000E-8          0.0         0.0         0.0         0.0         0.0         0.0         0.0
$#   alpha1      alpha2      alpha3      alpha4      alpha5      alpha6      alpha7      alpha8
       20.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0
$#       gi       betai       vflag
8.00000E-7        0.006           0
$#       gi       betai       vflag
1.80000E-6         0.05           0
$#       gi       betai       vflag
2.20000E-6          0.6           0
```

Figure 2. The keycard for average material model of adipose tissue in LS-Dyna, MAT_077_O. Units, ms, mm, kg, and kN.

The results of model prediction at low strain rates is shown in Figure 3. In the experiment there was no continuous increasing stiffness from low to high strain rates. Therefore, only one curve (0.2 s-1) was chosen for parameter identification.

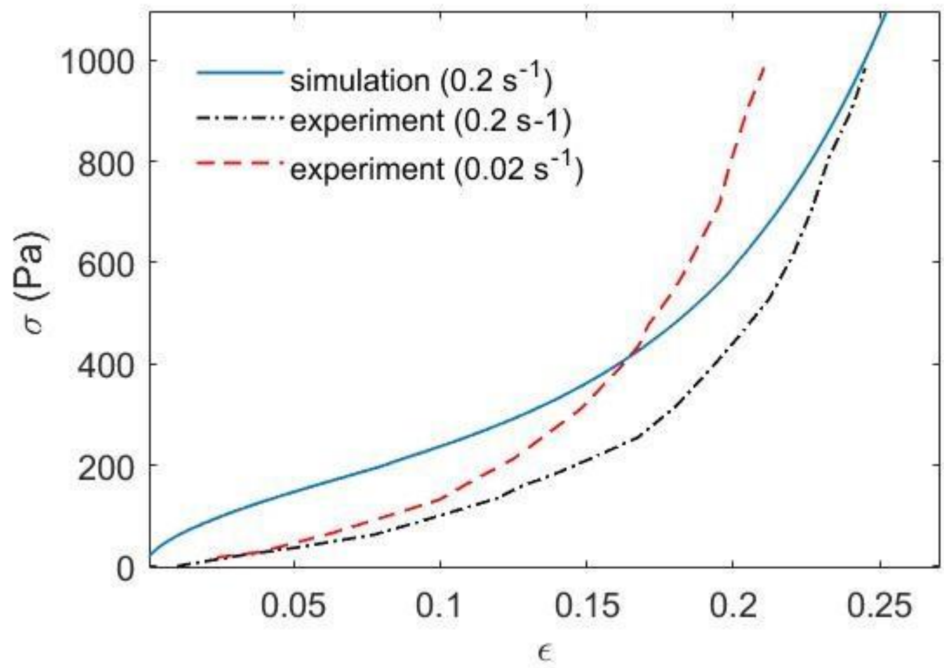

Figure 3. The unconfined compression test on porcine adipose tissue [4] at low strain rates. .

Figure 4 shows model prediction at intermediate strain rates. As for low strain rates, there was no continuous increasing stiffness from low to high strain rates in this range. So, only one curve (20 s-1) was used for fitting the model to the experiment.

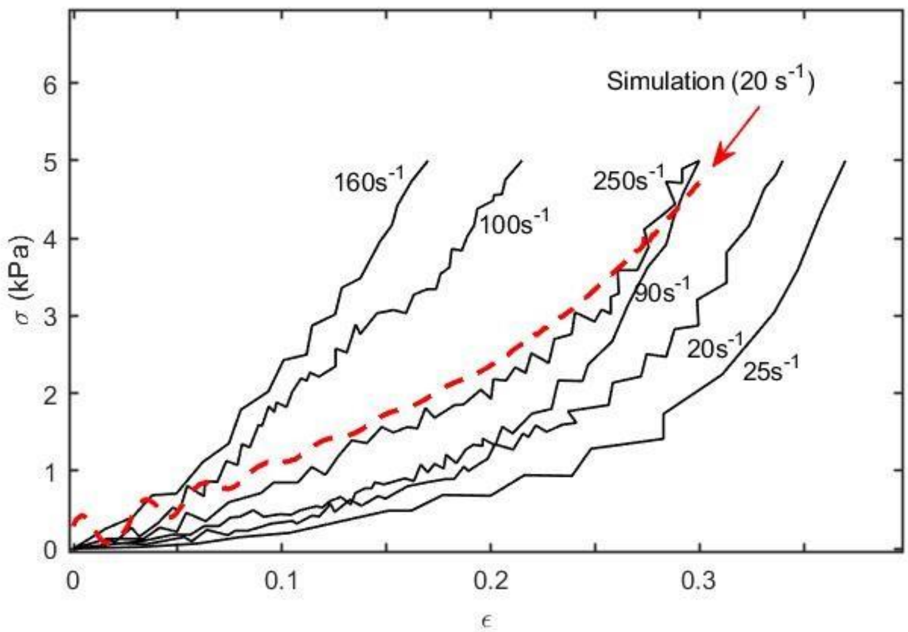

Figure 4. The unconfined compression test [4] on porcine adipose tissue at intermediate strain rates.

The rotational shear test [2] was also compared with the model prediction. Based on rheological methods, the apparent stress is defined as $\tau_a(t, \gamma_R) = \frac{2T}{\pi R^3}$, where R is the radius of the sample and T is the reaction torque at the upper plate, see Figure 5. Cylindrical specimens with a height of 1.5 mm and a diameter of 8 mm were tested at three constant shear strain rates of ($\dot{\gamma}_R$=) 0.01/s, 0.1/s and 1/s to 0.15 shear strain (γ_R) at the periphery of the sample. Strain rates of 0.1/s and 1/s were compared with model prediction. Figure 6 shows the apparent shear stress as a function of shear strain (in the periphery of the sample); comparison of model prediction to the experiment. In general, a good match between the model response and the experiment is obtained. Particularly, despite the hardening behavior of the Ogden model, the model still captures the softening behavior of adipose tissue because of appropriate incorporation and calibration of parameters in Prony series. The softening behavior of adipose tissue would be better captured with a nonlinear viscoelastic model [7], whereby a nonlinear relation for viscous stress relaxation can be applied. But, in the Ogden model (MAT_077_O), only linear viscoelasticity is available.

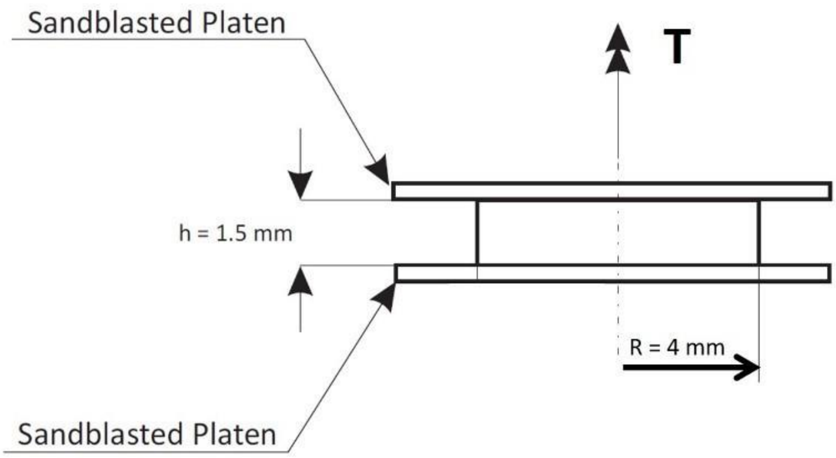

Figure 5. Schematic illustration of rheological shear test by [2] on porcine adipose tissue.

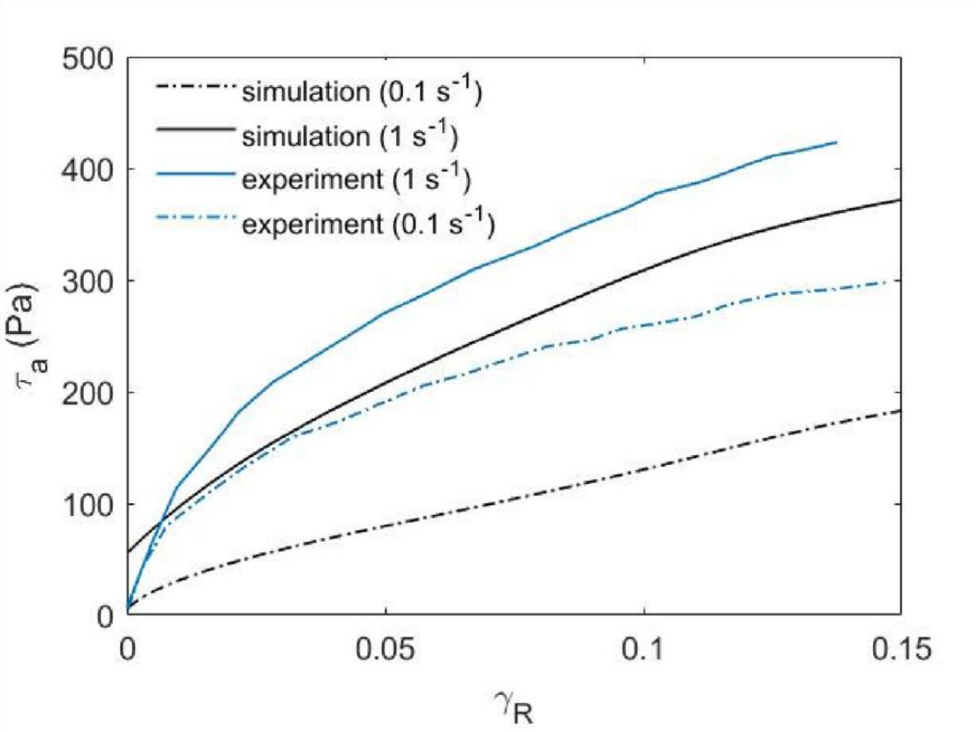

Figure 6. The apparent shear stress to shear strain at the sample edge at two strain rates of 0.1/s and 1/s on porcine adipose tissue [2].

3. Material tissue population variability

Two additional sets of materal parameters were defined representing the upper and lower range of responses for the unconfined compression tests in [4],which were visualized in Figure 4. The parameter set for the lower bound (soft response) can be seen in Figure 7 and the parameter set for the upper bound (stiff response) can be seen in Figure 8. The alpha1 and beta_i parameters are kept constant between the different versions, also including the average response presented in Figure 2. The difference is in the Poisson ratio, the mu1 and the G_i parameters.

```
*MAT_OGDEN_RUBBER_TITLE
Ogden model - Soft
$#     mid        ro        pr         n        nv         g      sigf       ref
         19.00000E-7   0.49800         0         6       0.0       0.0       0.0
$#     mu1       mu2       mu3       mu4       mu5       mu6       mu7       mu8
3.50000E-8       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$#  alpha1    alpha2    alpha3    alpha4    alpha5    alpha6    alpha7    alpha8
      20.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$#      gi     betai     vflag
5.60000E-7     0.006         0
$#      gi     betai     vflag
1.26000E-6      0.05         0
$#      gi     betai     vflag
1.54000E-6       0.6         0
```

Figure 7. The keycard for soft material model of adipose tissue in LS-Dyna, MAT_077_O. Units, ms, mm, kg, and kN

```
*MAT_OGDEN_RUBBER_TITLE
Ogden model - Stiff
$#     mid        ro        pr         n        nv         g      sigf       ref
         19.00000E-7   0.49998         0         6       0.0       0.0       0.0
$#     mu1       mu2       mu3       mu4       mu5       mu6       mu7       mu8
3.50000E-8       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$#  alpha1    alpha2    alpha3    alpha4    alpha5    alpha6    alpha7    alpha8
      20.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$#      gi     betai     vflag
1.08000E-6     0.006         0
$#      gi     betai     vflag
2.43000E-6      0.05         0
$#      gi     betai     vflag
2.97000E-6       0.6         0
```

Figure 8. The keycard for stiff material model of adipose tissue in LS-Dyna, MAT_077_O. Units, ms, mm, kg, and kN

4. Comparison with human adipose tissue

Previous tests were on porcine adipose tissue. The model behaviour is also compared with human calcaneal fat tissue [8] at different strain rates. The test setup can be seen in Figure 9. The simulation results compared to the physical test results are seen in Figure 10 to Figure 13. Generally the simulation results match the test results very good.

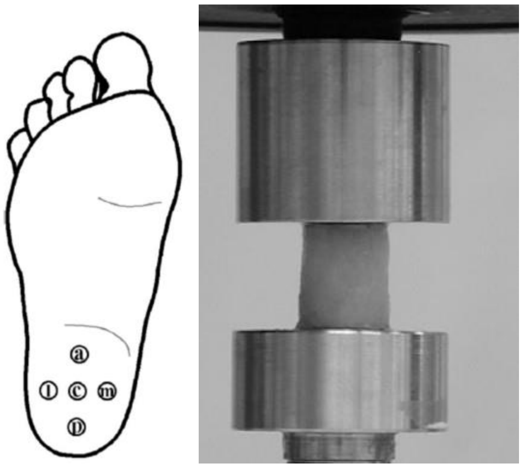

Figure 9. Location of fat samples and unconfined compression test setup in [8]

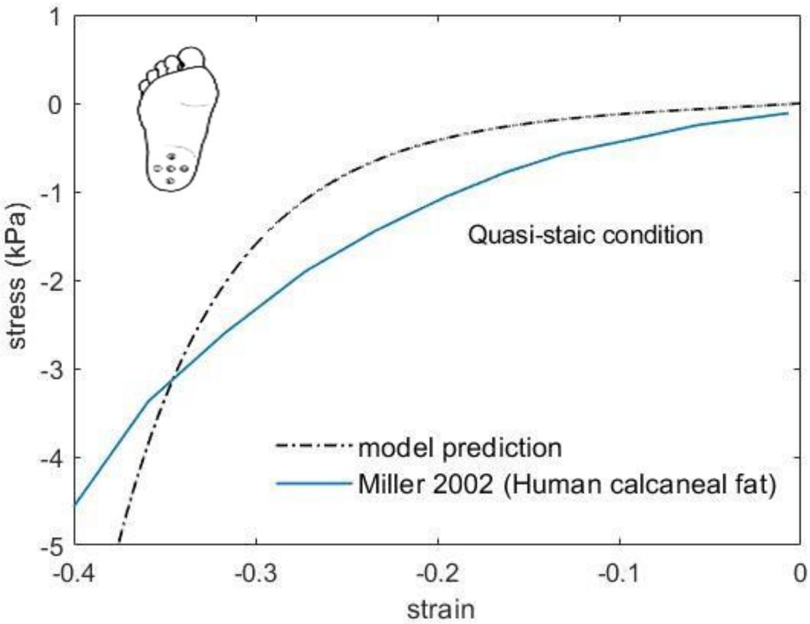

Figure 10. Human adipose tissue behaviour under an unconfined compression test [8] at quasi-static condition (Engineering stress-strain).

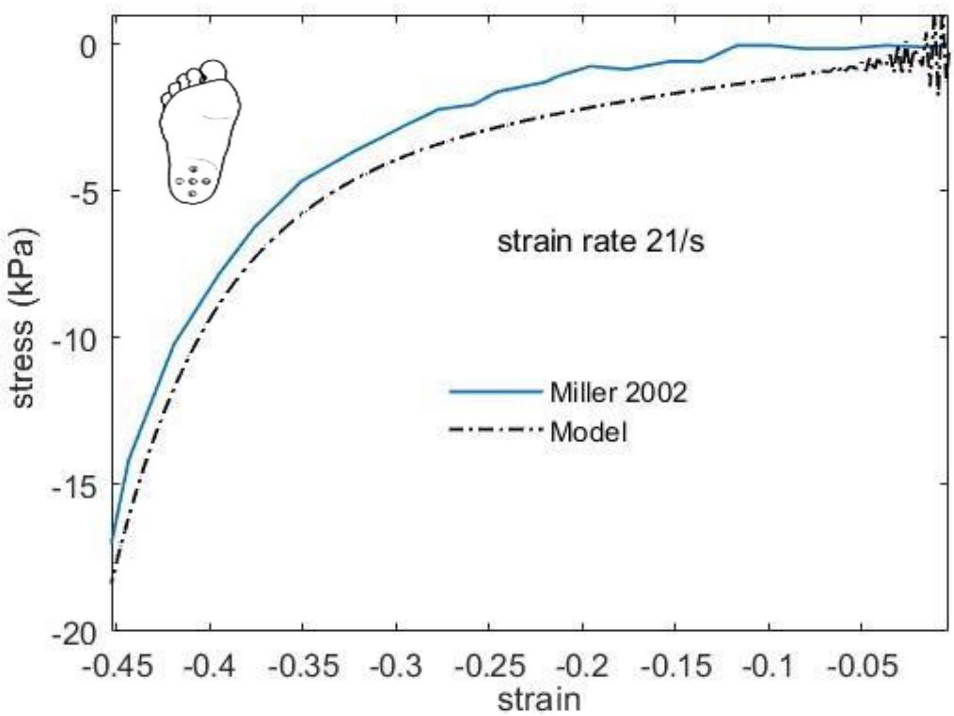

Figure 11. Human adipose tissue behaviour under an unconfined compression test [8] at strain rate of 21/s, (Engineering stress-strain).

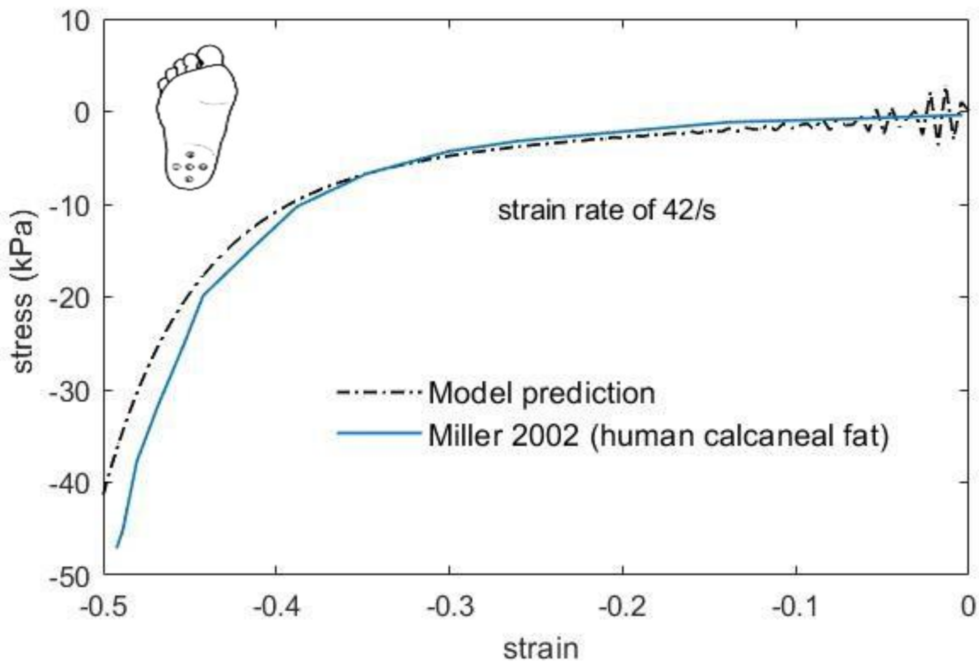

Figure 12. Human adipose tissue under an unconfined compression test [8] at strain rate of 42/s, (Engineering stress-strain).

Finally, the unconfined compression test in [9] on abdominal human adipose tissue at a low strain rate was compared with the model.

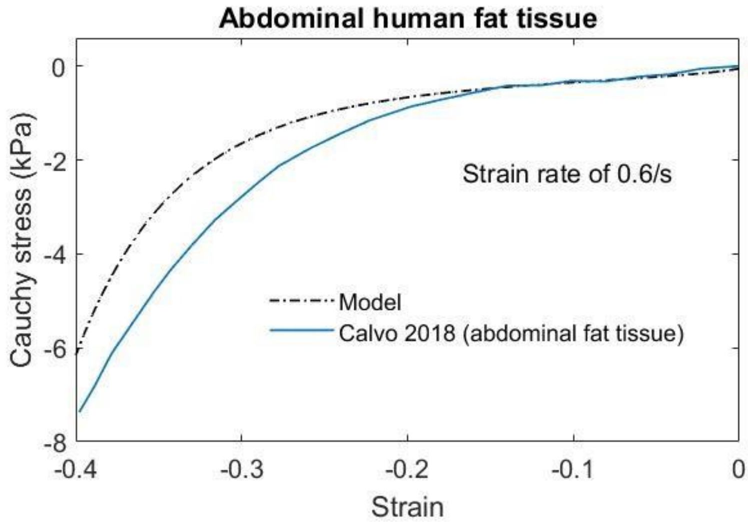

Figure 13. Abdominal human adipose tissue in an unconfined compression test [9], (Cauchy stress-nominal strain).

5. Alternative Ogden formulation, VFLAG=1

An alternative way to formulate Prony series in the Ogden model is to relate stress to the instantaneous stress from the internal strain energy function. Prony series therefore correspond to normalized relaxation modulus instead of elastic modulus. To have this form, VFLAG is set to one in the material keycard.

```
*MAT_OGDEN_RUBBER_TITLE
Ogden model for adipose tissue
$#      mid         ro        pr
          2     9.0E-7   0.49970
$#      mu1
   2.52E-8
$#   alpha1
       20.0
$#       gi      betai     vflag
       0.30      0.006         1
$#       gi      betai
       0.29       0.05
$#       gi      betai
       0.25        0.6
```

Figure 14. The keycard for material model of adipose tissue, MAT_077_O, with VFLAG=1. Units, ms, mm, kg, and kN.

This will give similar results as for the VFLAG=0 parametrization presented above, see Figure 15 to Figure 17.

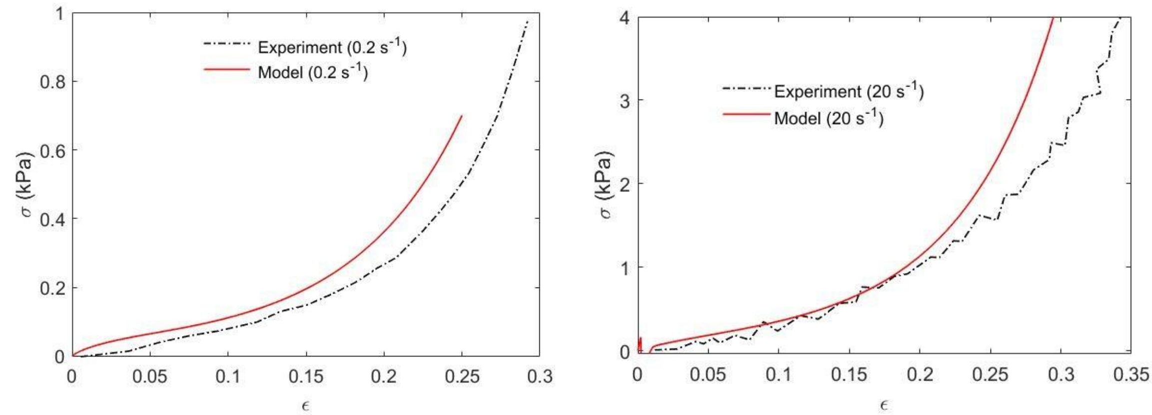

Figure 15. The unconfined compression test on porcine adipose tissue in [4]; VFLAG=1 in the model.

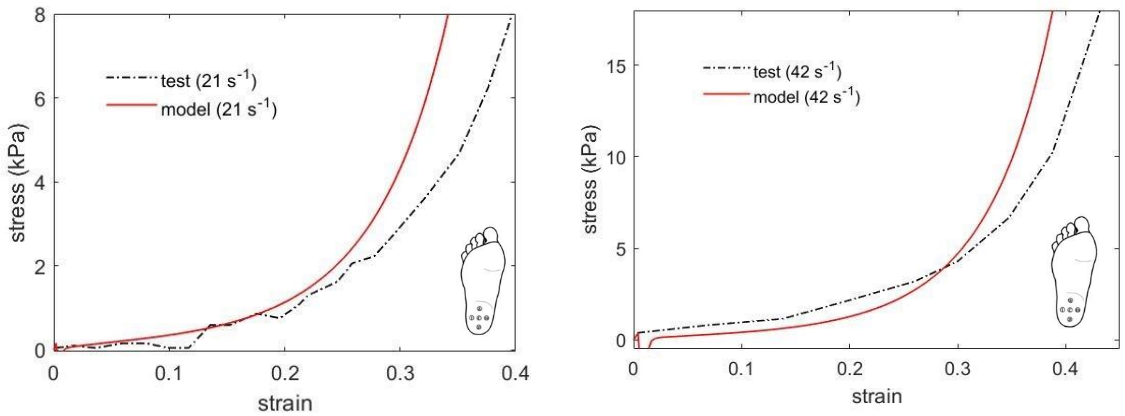

Figure 16. The unconfined compression test on human calcaneal fat in [8]; VFLAG=1 in the model.

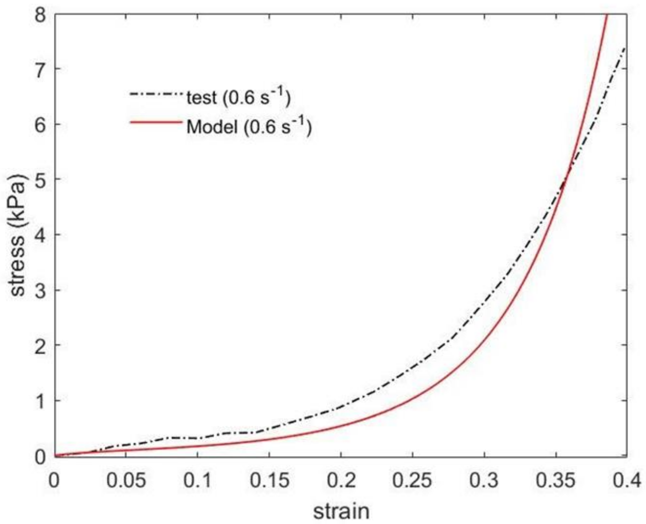

Figure 17. Unconfined compression test on abdominal human adipose tissue in [9]; VFLAG=1 in the model.

6. Effect of Poisson's ratio on the incompressibility

The effect of Poisson's ratio on the incompressibility and stiffness of adipose tissue at compressive strains up to 50% was virtually investigated. This is shown below for both VFLAG=0 in Figure 18 and for VFLAG=1 in Figure 19. For Poisson's ratio close to 0.49 there is significant volumetric change, up to 25-30%. However, for Poissons ratio close to 0.5 (0.49998) the volumetric change is marginal (0.1-0.2%).

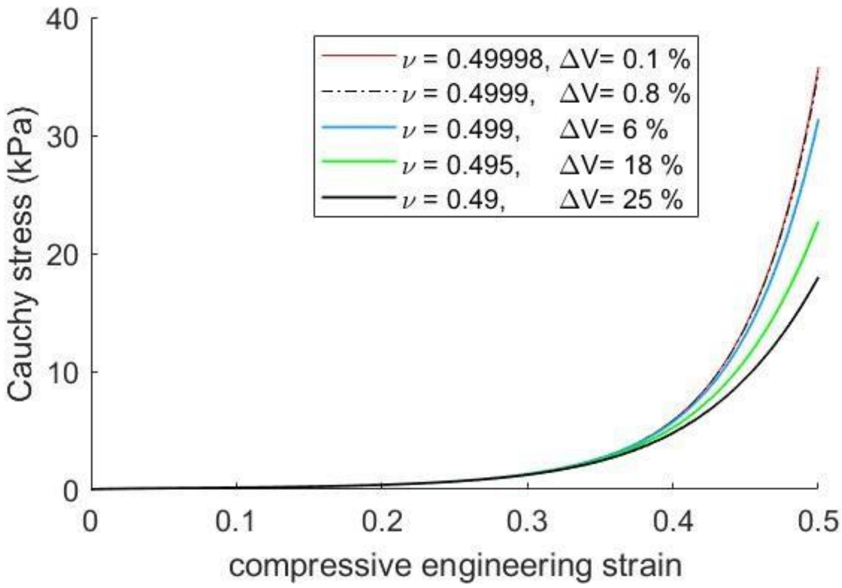

Figure 18. The effect of Poisson's ratio; tissue stiffness and volume change for Ogden model with VFLAG=0 in the material keycard. The delta value corresponds to the volume change.

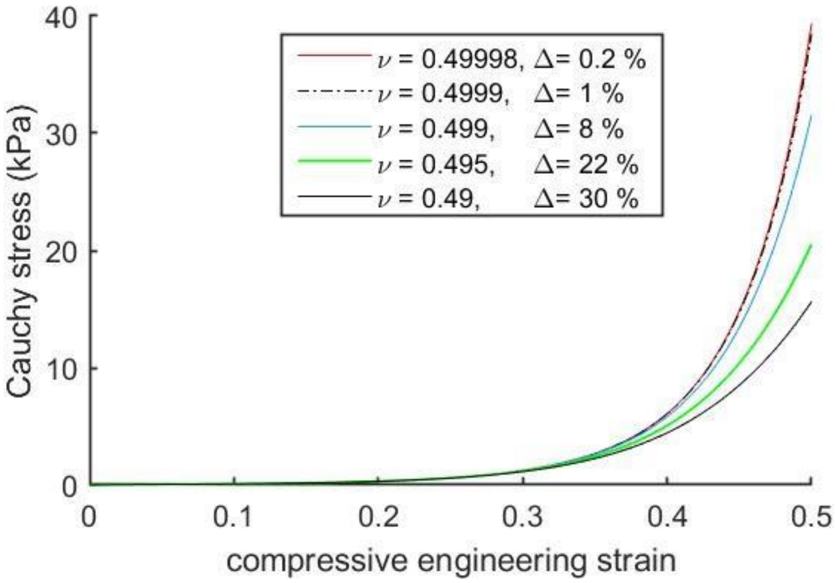

Figure 19. The effect of Poisson's ratio; tissue stiffness and volume change for Ogden model with VFLAG=1 in the material keycard. The delta value corresponds to the volume change.

7. References

1. Gefen, A. and E. Haberman, Viscoelastic properties of ovine adipose tissue covering the gluteus muscles. 2007.
2. Geerligs, M., et al., Does subcutaneous adipose tissue behave as an (anti-) thixotropic material? Journal of biomechanics, 2010. 43(6): p. 1153-1159.
3. Geerligs, M., et al., Linear viscoelastic behavior of subcutaneous adipose tissue. Biorheology, 2008. 45(6): p. 677-688.
4. Comley, K. and N. Fleck, The compressive response of porcine adipose tissue from low to high strain rate. International Journal of Impact Engineering, 2012. 46: p. 1-10.
5. Sommer, G., et al., Multiaxial mechanical properties and constitutive modeling of human adipose tissue: a basis for preoperative simulations in plastic and reconstructive surgery. Acta biomaterialia, 2013. 9(11): p. 9036-9048.
6. Comley, K. and N.A. Fleck, A micromechanical model for the Young's modulus of adipose tissue. International Journal of Solids and Structures, 2010. 47(21): p. 2982-2990.
7. Naseri, H., H. Johansson, and K. Brolin, A nonlinear viscoelastic model for adipose tissue representing tissue response at a wide range of strain rates and high strain levels. Journal of biomechanical engineering, 2018. 140(4).
8. Miller-Young, J.E., N.A. Duncan, and G. Baroud, Material properties of the human calcaneal fat pad in compression: experiment and theory. Journal of biomechanics, 2002. 35(12): p. 1523-1531.
9. Calvo-Gallego, J.L., et al., Comparison of different constitutive models to characterize the viscoelastic properties of human abdominal adipose tissue. A pilot study. Journal of the mechanical behavior of biomedical materials, 2018. 80: p. 293-302.