Identification of Orthotropic Material Parameters for Healing Myocardial Infarcts in the Rat

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INTRODUCTION

Research has been devoted to study the biomechanical aspects of myocardial infarction (MI) and its emerging intramyocardial injection treatment. Finite element (FE) models have been effectively utilized in such research. Although the rat is a widely used animal model for MI, there is a lack of data on anisotropic material models for rat infarcts in literature. This study aimed at identifying the parameters of Fung orthotropic constitutive model for different healing stages of rat infarcts through inverse FE analysis utilizing biaxial (cardiac circumferential and longitudinal axes) tensile mechanical data obtained in a related study. The temporal stages of healing infarcts were represented by four groups: immediate (0 day), 7, 14 and 28 days.

METHODS

Biaxial tension finite element model: Abaqus CAE was employed to build and run a 3D biaxial tensile FE model, Fig.1(b), mimicking the experimental setup, Fig.1(a). The eight suture needles (C1 to C8) used in the experiment were modelled using cylindrical transmural partitions. Four reference points (RP1 to RP4) were defined at the central area of the epicardial surface of the model representing the four optical markers. The model was meshed using C3D8RH elements. ORIENT user-defined subroutine was used to incorporate the orientation of fibres from -50° at epicardium to 80° at endocardium (Chen et al.,Am J Physiol Heart Circ Physiol, 2003). Displacement boundary conditions were applied to to restrain and load the model.

Constitutive model: Fung orthotropic model available in Abaqus was utilized to model the material properties of the infarct. The generalized Fung strain energy function (W) has the following form:

$$W = \frac{c}{2}\left(e^{Q}-1\right) \quad , \quad Q = \bar{\varepsilon}^{G} : b : \bar{\varepsilon}^{G} = \bar{\varepsilon}^{G}_{ij} b_{ijkl} \bar{\varepsilon}^{G}_{kl}$$

b_{ijkl} is a dimensionless symmetric fourth-order tensor of anisotropic material parameters. $\bar{\varepsilon}^{G}_{ij}$ and $\bar{\varepsilon}^{G}_{kl}$ are the modified Green strain tensor. In the unloaded configuration, matrix D should be positive definite in order to obtain numerical stability. Matrix D is given by:

$$D = \frac{c}{2}\begin{bmatrix} b_{1111} & b_{1122} & b_{1133} & 0 & 0 & 0 \\ b_{1122} & b_{2222} & b_{2233} & 0 & 0 & 0 \\ b_{1133} & b_{2233} & b_{3333} & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{1212} & 0 & 0 \\ 0 & 0 & 0 & 0 & b_{1313} & 0 \\ 0 & 0 & 0 & 0 & 0 & b_{2323} \end{bmatrix}$$

The positive definiteness implies the constraints as shown in Fig.2.

Computation of stress and strain: The biaxial stress was computed based on the following equations:

$$S_{xx} = \frac{f_x}{l\,T} \ , \ S_{yy} = \frac{f_y}{l\,T}$$

The biaxial nodal strain calculation is given by:

$$E_{xx} = \frac{\Delta u}{\Delta x} + \frac{1}{2}\left[\left(\frac{\Delta u}{\Delta x}\right)^2 + \left(\frac{\Delta v}{\Delta x}\right)^2\right] , \ E_{yy} = \frac{\Delta v}{\Delta y} + \frac{1}{2}\left[\left(\frac{\Delta v}{\Delta y}\right)^2 + \left(\frac{\Delta u}{\Delta y}\right)^2\right]$$

where Δx and Δy are the change in nodal coordinates and Δu and Δv are the change in nodal displacement.

Optimization of material parameters: Fung parameters were optimised to fit the model predictions to the experimental stress-strain data through minimizing the objective function (OBJ) given by:

$$\mathrm{OBJ} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{S_{exp,t} - S_{cmp,t}}{S_{exp,t}}\right|$$

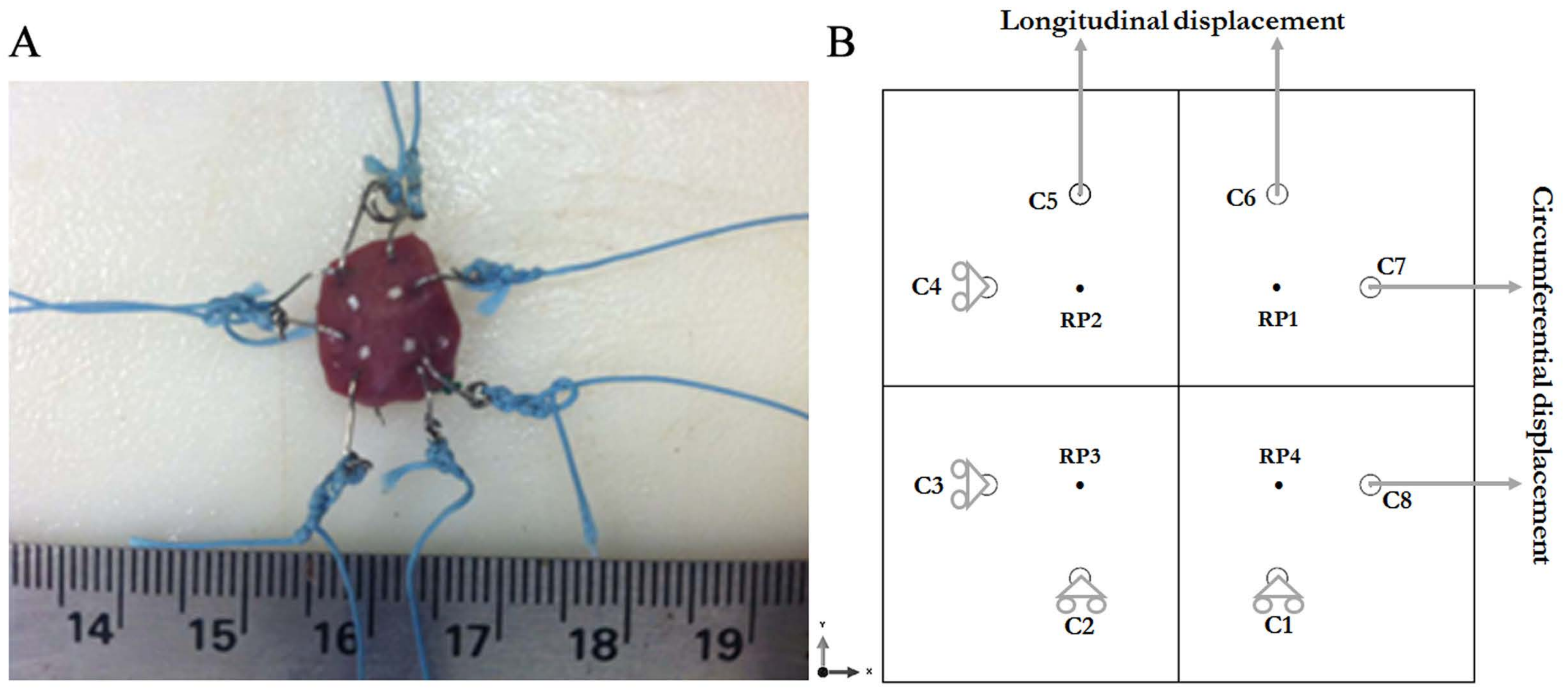
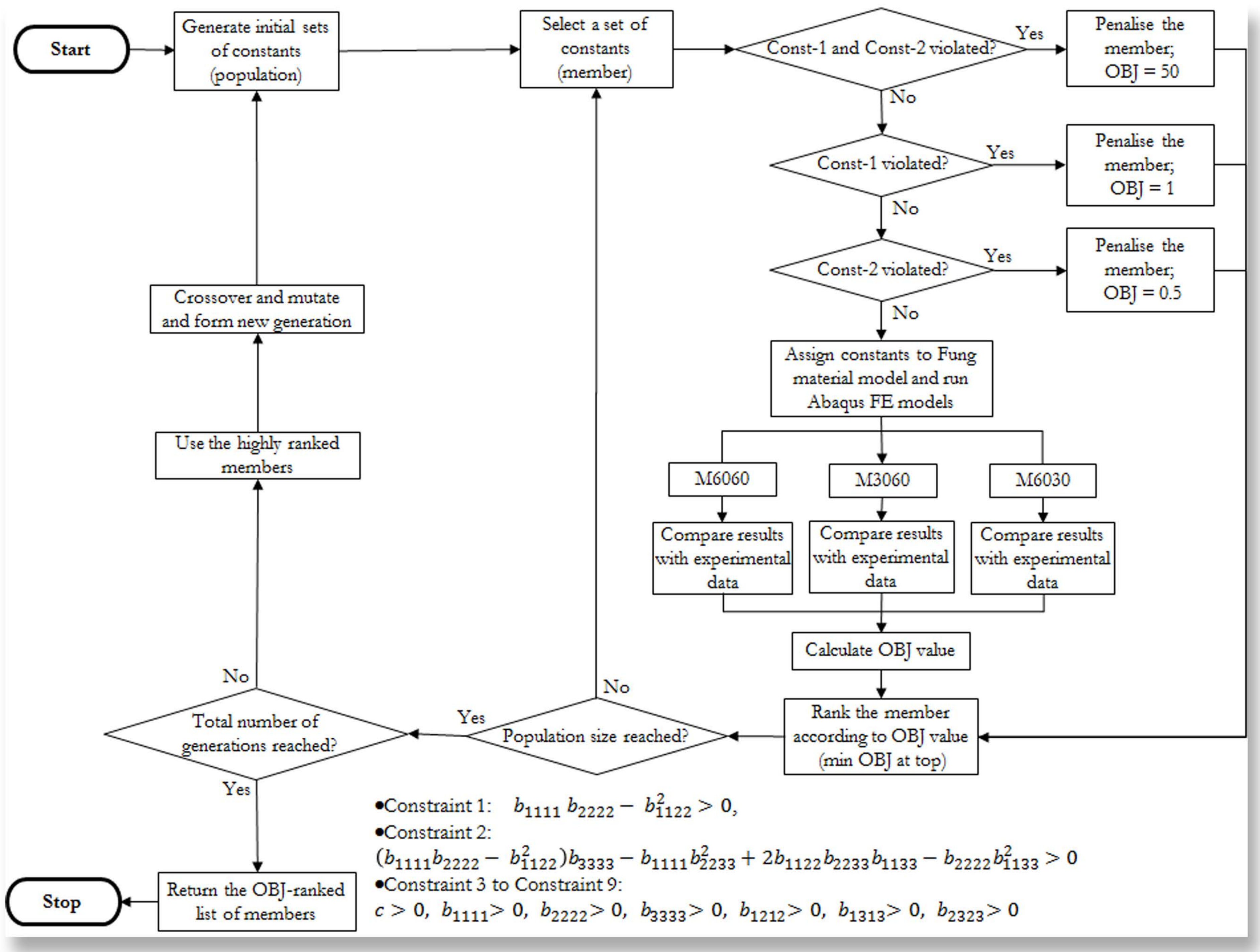


Figure 1: *Experimental (a) and computational (b) biaxial tensile test setup.*

where S_{exp} and S_{cmp} are the experimental and computational stresses. The Genetic algorithms (GA) toolbox in SCILAB was utilized to minimize the objective function.The flow chart of the optimization loops is shown in Fig.2.



- Constraint 1: $b_{1111}\, b_{2222} - b_{1122}^2 > 0,$
- Constraint 2:
$(b_{1111}b_{2222} - b_{1122}^2)b_{3333} - b_{1111}b_{2233}^2 + 2b_{1122}b_{2233}b_{1133} - b_{2222}b_{1133}^2 > 0$
- Constraint 3 to Constraint 9:
$c > 0,\ b_{1111} > 0,\ b_{2222} > 0,\ b_{3333} > 0,\ b_{1212} > 0,\ b_{1313} > 0,\ b_{2323} > 0$

Figure 2: *Flow chart of optimization loop.*

RESULTS

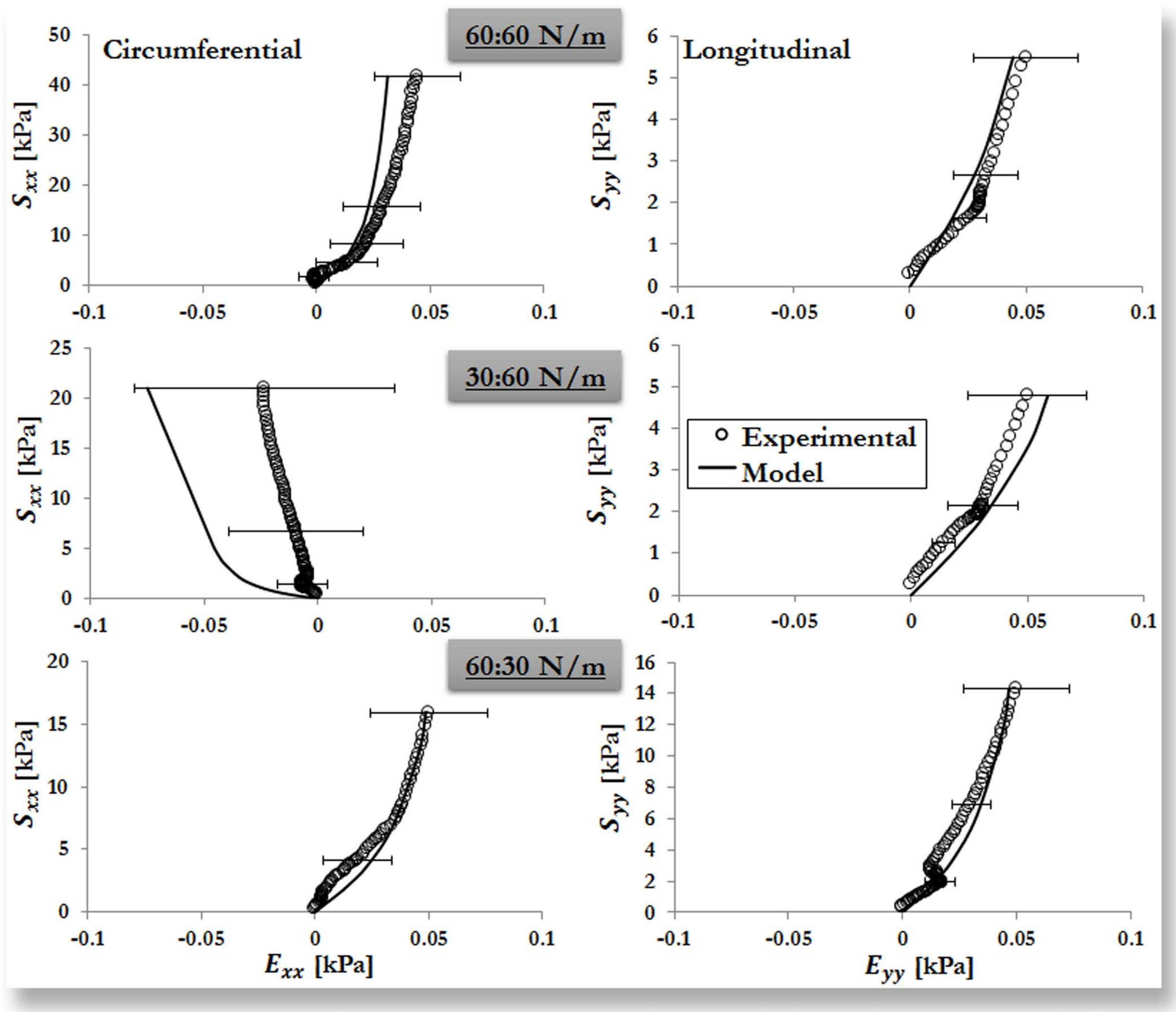


Figure 3: *Best fit of FE model predictions to the experimental data for the 28d infarct.*

Table: *Identified Fung orthotropic material parameters for different infarct stages.*

Material parameter	**0d**	**7d**	**14d**	**28d**
b_{1111}	64.31	176.09	16.38	159.65
b_{1122}	14.08	-70.92	-16.16	-25.52
b_{2222}	48.60	83.95	128.78	38.15
b_{1133}	20.51	81.15	-11.62	1.10
b_{2233}	-39.35	-84.99	-6.94	-31.44
b_{3333}	152.06	175.57	172.58	116.40
b_{1212}	68.31	176.54	77.86	18.56
b_{1313}	111.94	175.11	130.73	127.89
b_{2323}	63.54	158.40	189.56	65.77
c (kPa)	0.201	0.133	0.146	0.695
MAPE	0.032	0.036	0.032	0.030

CONCLUSIONS

The experimental stress-strain data of healing rat infarcts could be successfully approximated using inverse FE methods and GA. The material parameters identified in this study will provide a new platform for FE investigations of biomechanical aspects of MI towards the development of therapies.

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