Can the octahedral shear strain solely predict tissue differentiation during normal fracture healing?

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Background

The mechano-regulation algorithm proposed in [1], which used interstitial fluid velocity (FV) and octahedral shear strain (OSS) is well-accepted for predicting normal fracture healing. However, the ability of OSS as a single bio-feedback variable to predict the normal healing pattern is still a place of debate. In [2], it was claimed that OSS can solely predict normal healing process, but in [3] it was reported that the prediction made by using just OSS does not offer reliable data. Some recent studies, e.g. [4,5,6], used OSS as a single bio-feedback variable based on the report of [2], in which their simulations were done in an elastic medium (EM).

Purpose

This work is an attempt to check the validity of the hypothesis that the OSS could solely regulate tissue differentiation in a poroelastic medium (PM), as well as to investigate whether or not the OSS could solely regulate tissue differentiation in an

Materials & Methods

A two dimensional finite element model was developed. The model consists of three parts: cortical bone, bone marrow, and callus (Figure 1), and it was modelled as a biphasic system. The gap length was considered 3mm, and the peripheral surface of external callus and bone marrow assumed to be impermeable [1,2]. An 8-node bilinear pore pressure element (CPE8RP) was used. Analysis was done in Abaqus (6.11-1) by transient Soil step as a consolidation of fluid and solid, and load applied on the cortical bone as a axial ramp for 0.5 s. The procedure divided into two steps: 1: Modelling of cellular processing: migration and proliferation of mesenchymal stem cells (MCs), modelled as a simple diffusion process in which MCs could invade callus from 3 different areas: boundaries of peripheral external callus; cortical bone periosteum; and bone marrow. Cell concentration over time was extracted for each element by use of Python scripting and exported to the next step; 2: Iterative simulation of callus maturation: intramembranous and endochondral ossifications could happen together without any restrictions, i.e. tissue differentiation can occur from granulation tissue to any other tissues, e.g. fibrous tissue, cartilage, immature bone, and mature bone. It is assumed that callus is initially filled with granulation tissue.

Maturation of elements was implemented as an iterative process in which each iteration equalled to one day. After each iteration, based on the determined thresholds [1], material properties of favoured tissue is replaced during 10 iterations. As granulation tissue could co-exist with another tissue simultaneously, a rule of mixture theory was used to calculate material properties. In this study, three different models were developed which is presented in Table 1. Two different loading types were applied: first: 500N which leads to interfragmentary movement (IFM) of 33%, and second: 300N which results in IFM of 24%.

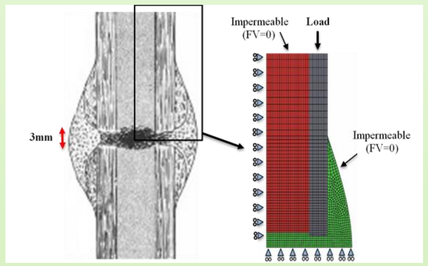

Figure 1: Axisymmetric FEM of a fracture ovine tibia with a 3mm fracture gap. Load applied at the end of cortical bone.

Table 1: Three different models were used in this study.

	First model [1]	*Second model [2]*	*Third model*
Biophysical stimulus	$Stim = OSS/3.75 + FV/3$	*OSS*	*OSS*
Analysis medium	*Poroelastic*	*Poroelastic*	*Elastic*

Results

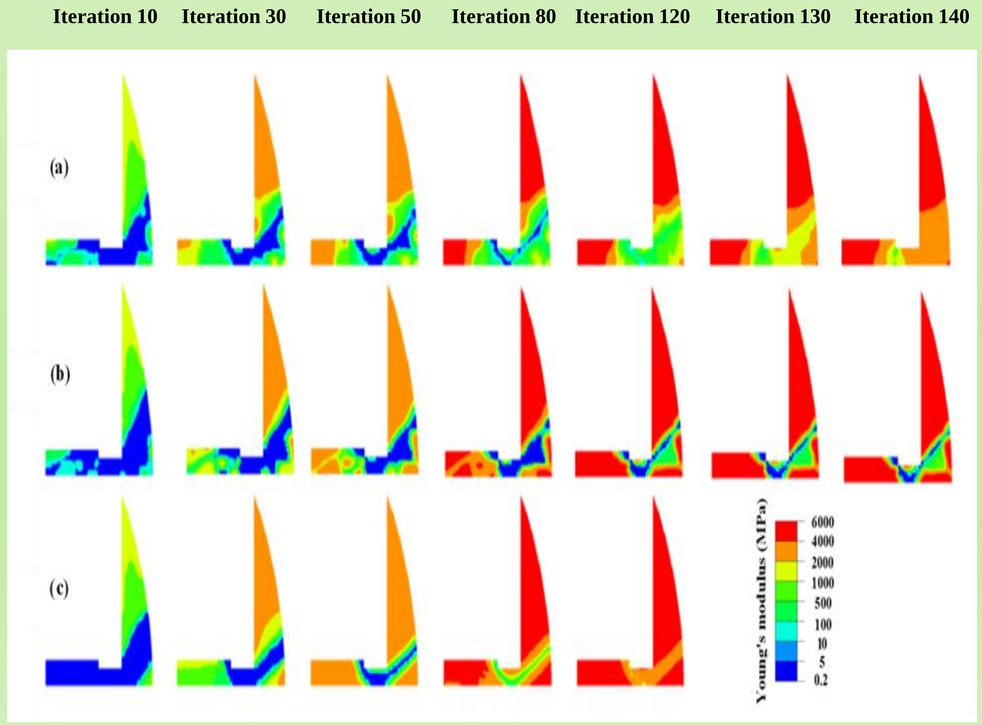

Figure 2: FEA results of fracture healing patterns for an external load of 500N. (a): using 1st model [1]; (b): using 2nd model [2]; (c): using 3rd model [4,5,6].

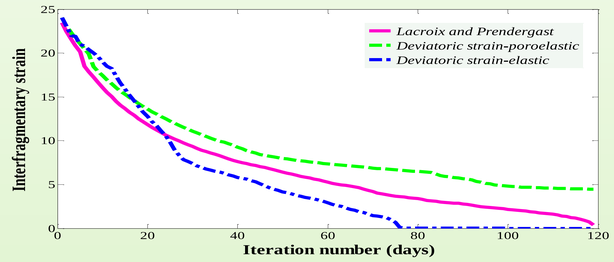

Figure 3: Interfragmentary strain for an external load of 300N. It can be seen that the interfragmentary strain for the 2nd model does not approach zero, which means that healing is not completed and leads to non-union.

Conclusions

- In the poroelastic model, results of this study showed that OSS can successfully predict bone formation at the callus tip and the intramedullary canal, as well as its progress toward intracortical gap. However, it failed to predict bony bridge at the external callus and a narrow strip area was left filled with fibrous tissue, which restricts completion of bone healing process.
- In the elastic model, OSS correctly predicted healing process, but the completion of process occurred much faster than that of normal healing process, which is not acceptable.
- Thus, based on our results, one can conclude that OSS cannot be considered as a single regulator of tissue development in the normal fractured bone healing process

References

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