FINITE ELEMENT ANALYSIS OF STRESS FRACTURES IN A RAT MODEL

Amit Gefen, Michal Stern-Perry, Nogah Shabshin and Yoram Epstein

Department of Biomedical Engineering, Tel Aviv University, Division of Diagnostic Imaging, Sheba Medical Center, Heller Institute of Medical Research, Sheba Medical Center, Sackler Faculty of Medicine, Tel Aviv University, Israel.

SUMMARY
The objective of this study was to develop a finite element (FE) modeling methodology for studying the aetiology of a stress fracture (SF). Several variants of a three-dimensional (3D) FE model of a rat hindlimb, which differed in length or stiffness of tissues, enabling the analyses of mechanical strains and stress in the tibia, were created. We compared the occurrence of SFs in an animal model to validate locations of peak strains/stresses in the FE models. Four rats were subjected to mechanical cyclic loads, which were delivered to their hindlimb for 30 min, 3 times/week, up to 12 weeks. The results showed that: (i) FE modeling predicted the maximal strains/stresses between the mid and proximal thirds of the tibia; (ii) Longer shin was associated with greater and more inhomogeneous tensile strains/stresses; (iii) Anatomical variants in shin length influenced the strain/stress distributions to a greater extent than changes in mechanical properties of tissues; (iv) The effect of bone stiffness was more substantial than that of muscle stiffness. The location of the identified SF in the rat limb verified the FE model.

INTRODUCTION
A stress fracture (SF) is a partial or complete fracture of a bone resulting from its inability to withstand cyclic sub-yield mechanical loads. There is no satisfactory animal model for investigating risk factors for SFs, which is why only a few studies used non-human in vivo models for studying SF aetiology. In many of these studies the actual tissue-level loads causing the fracture and the anatomical locations where SFs occurred were not reported. FE models have been developed to evaluate strains and stresses within the bone in the context of SF aetiology. However, those studies were limited because they considered an isolated bone, while the overlying soft tissues were not incorporated. By running chronic animal experiments and comparing the outcomes with the strain/stress data obtained from the FE model, it will be possible to characterize anatomical and biomechanical factors contributing to SFs. The objective of this study was, therefore, to develop an experimentally validated FE modeling methodology for studying SFs.

METHODS
Computational model
The 3D anatomy of the undeformed rat shin was obtained from axial MRI scans of a rat. The MRI scans were loaded into parallel planes. The contours of cortical bone, trabecular bone and bone marrow of the tibia and fibula, the enveloping muscle and fat, and distal and proximal cartilage tissues, were manually drawn for each slice and lofted into 3D bodies by means of a solid modeling software (SolidWorks). The 3D geometrical model was imported to an FE solver (ABAQUS). Specifically, bone and cartilage tissues were considered isotropic linear-elastic materials, whereas soft tissues other than cartilage were considered hyperelastic homogeneous isotropic solids. The boundary conditions applied were as follows: based on preliminary analyses, we applied a uniformly-distributed force of 3.4N on the distal surface of the cartilage of the shin. The proximal end of the shin was constrained to prevent any translational or rotational motions. Simulations were then designed as follows: we built variant model configurations where the shin length was varied by ±30% to represent longer or shorter limbs; we further built model configurations which simulated altered tissue mechanical properties with respect to the reference configuration, to represent biological variability of ±30% in tissue bone and muscle stiffness. Each such model configuration was analyzed for the distributions of principal tensile strains/stresses in the cortical bone of the tibia. These distributions were plotted along a path, which was defined by the site where peak principle tensile strain occurred and by the proximal and distal edges of the bone.

Figure 1: The process of modeling: (a) from MRI scans to 3D bodies; (b) The meshed 3D model.
Animal experimentation

Four male rats were used as an in vivo model for inducing a SF. The anaesthetized rat was laid on a horizontal rigid surface. Cyclic loading was delivered through the hindfoot, using a custom-made electromechanical apparatus. The cyclic loads, with a triangle wave shape, frequency of ~1.2Hz which is typical for physiological gait of a man or a rat, and pre-set peak of 7N, were delivered for ~30min per session, 3 times a week, for a period of two weeks up to 12 weeks. Outcome measures were the presence or absence of a tibial SF based on X-rays scans. The anatomical location of an established SF was compared to the location of maximal strains within the tibial cortical bone, as predicted by the FE models. In addition, we recorded the load waves and the number of loading cycles to enable the calculation of the total number of loading cycles delivered to each animal.

RESULTS AND DISCUSSION

FE models

Overall, strains and stresses were found to peak between the mid and proximal thirds of the tibia. The results from the FE modeling indicated that: (i) more inhomogeneous and higher tensile strains/stresses occurred in longer shins (Figure 2).

(ii) anatomical variants in shin length influenced the strain/stress distributions to a greater extent with respect to changes in mechanical properties of tissues; (iii) the effect of bone tissue stiffness was more dominant than this of muscle tissue stiffness in affecting the strain/stress distributions in tibial cortical bone.

Animal model

The four animals were subjected to loading cycles in a range between 8,894 and 47,957 cycles. The animal which was exposed to the highest number of loading cycles and to the highest peak force was diagnosed as suffering a SF in the proximal third of its left tibia, based on the routine X-ray scans. This occurred following ~35,000 loading cycles that were delivered during 9 weeks of testing. The X-rays of the other 3 animals, which were exposed to fewer loading cycles and lower average peak forces, did not demonstrate SF.

CONCLUSIONS

The present FE model enables a full mapping of the strain/stress distributions within the tibia, showing that the engineering data are comparable to the actual location of a SF occurring in a respective animal model. The approach taken in the present study could be extended in the future for studying various aspects of SFs in humans as well.

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Figure 2: Principal tensile strains: (a) Reference-length tibia, (b) 30%-longer tibia, (c) 30%-shorter tibia. (d) A path passing through the site of peak tensile strain/stress as well as through the proximal and distal edges of the tibia.