Development of a Finite Element Model of the Tibia for Short-Duration High-Force Axial Impact Loading

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INTRODUCTION

Experimental testing of cadaveric specimens may provide the most realistic representation of the human response to loading, but they are often not a practical option. Tests for safety standards are often conducted using computer simulations; as such, finite element (FE) models offer a useful method for evaluating injury risk. The models are advantageous in that they allow a variety of experimental conditions to be readily investigated. Models have been developed for this purpose (*e.g.,* [1]), but with little direct comparison with experimental results. The purpose of this study was to construct a FE model based on a representative cadaveric tibia subjected to experimental impacts [2] for future injury predictions.

METHODS

One cadaveric specimen was strain gauged at four locations and CT scanned (0.625 mm slice thickness) prior to experimental testing. The scans were imported into Mimics® (Materialise, Leuven, Belgium) to extract the geometry of the bone and strain gauge locations. Surfaces were generated defining the cortical, cancellous, and marrow regions. The mesh was developed using TrueGrid® (XYZ Scientific Inc., Livermore, CA, USA). It was manually manipulated to match the bone surfaces, with special emphasis on the distal areas of high curvature. This resulted in a mesh of 14848 linear 8-node hexahedral elements. The mesh quality was assessed, with element Jacobians ranging from 0.102 – 8.001, element angles of 13˚ - 177˚, and aspect ratios between 1.1 – 13.4. FE analysis was conducted using LS-DYNA® (LSTC, Livermore, CA, USA), with bone properties selected from the literature and a family of curves defining strain rate effects. Impact was simulated at speeds corresponding to both low-force (non-fracture) and high-force (fracture) tests. Axial load, loading duration, impulse, and strains (non-fracture only) were compared to experimental values [2].

RESULTS

The model attained a peak axial force for the non-fracture simulation of 10.4 kN (87% of experimental), with a loading duration of 3.1 ms (86%), resulting in an impulse of 17.0 Ns (106%) (Figure 1). For the fracture simulation, the peak force was 15.7 kN (126%), over a time span of 3.3 ms (110%), creating an impulse of 25.4 Ns (132%). Distal strains did not correlate well with experimental, but improved proximally. Maximum principal strains were found to exceed the critical strain value in the cortical bone for the fracture case (Figure 2).

DISCUSSION

The aim of the model built in this study is for use in predicting injury in natural bone. The current model was built from CT scans of one specimen tested experimentally, and was compared to the measured data.

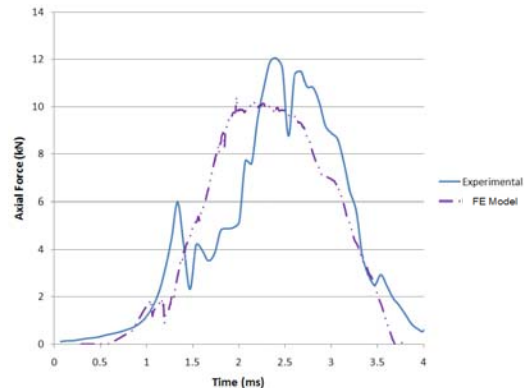

Figure 1: Force-time curves for the experimental and FE impacts at non-fracture speeds. The model peak force was 87% of the experimental, with a corresponding impulse of 106% of the experimental.

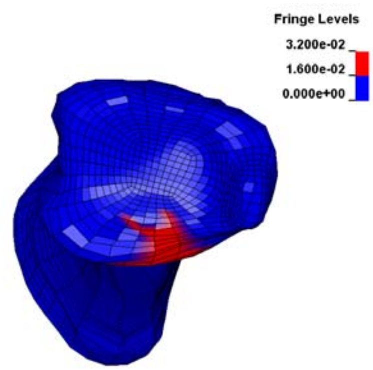

Figure 2: The region of maximum principal strain for the fracture simulation. The area in red indicates the region which exceeded the critical cortical strain level of 0.016.

For the non-fracture test, the force, time duration, and impulse showed good agreement between model and experimental responses. The model exceeded the experimental force for the fracture test due to the inability to simulate the energy absorbed. Therefore, the model performs best for non-fracture scenarios. The lack of strain gauge agreement will need to be addressed in future model refinements. Maximum principal strain was shown to be a good indicator of injury risk, with numerous 'failed' elements in the fracture simulation.

This study has resulted in an initial FE model of the tibia's response to axial impact loading. Once optimized, this model can be implemented into future injury risk assessment studies, allowing better investigation into the effect of protective systems on injury potential.

REFERENCES

1. Untaroiu *et al.* 2005, *Stapp Car Crash Journal*, p. 157.
2. Quenneville CE *et al.* 2009 ASB Meeting (#1035).