FINITE ELEMENT PREDICTION OF SURFACE STRAIN AND FAILURE LOAD AT THE DISTAL RADIUS USING SIMPLIFIED BOUNDARY CONDITIONS

W. Brent Edwards and Karen L. Troy

1University of Illinois at Chicago, Chicago, IL, USA
email: edwardsb@uic.edu, web: http://www.uic.edu/ahs/biomechanics

INTRODUCTION
In an effort to improve bone strength and prevent fracture at the distal radius, we have developed a mechanical loading intervention in which females cyclically load their forearm. To relate the applied stimulus with the bone adaptation response, an accurate characterization of the mechanical environment within the bone must be known. Finite element (FE) models have been an effective tool for both strain and fracture-risk assessment. An ideal model would simulate physiological loading scenarios with simplified boundary conditions, allowing for computationally efficient strain determination for numerous subjects. We are also interested in the ability of the FE method to predict fracture strength as a means to assess the effectiveness of our loading protocol. Here, we compared experimental surface strains and fracture loads with specimen-specific FE models for the purpose of validating our simplified boundary conditions and model generating algorithm.

METHODS
Five freshly frozen female cadaver forearms (mean age 78 yrs, range 59-93 yrs) were obtained for this study. Specimens were stored at -20 ºC, but thawed to room temperature for: 1) computed tomography (CT) data acquisition (voxel size: 625 x 234 x 234 µm), 2) specimen preparation, and 3) testing.

Specimens had radial/ulnar osteotomy 14 cm proximal to Lester’s Tubercle; the proximal most 8 cm of the forearms were embedded in polymethylmethacrylate (Fig 1). Six strain gage rosettes (Micro-Flextronics Ltd, Coleraine, N. Ireland) were adhered circumferentially to the periosteal surface of the radius (3 distal & 3 proximal; Fig 1). Prior to strain gage attachment the periosteum was removed, the surface was cleaned with isopropyl alcohol, sanded, and recleaned with isopropyl alcohol.

For strain assessment, specimens were loaded in compression under displacement control (0.1 mm/s), to 300 N (MiniBionix 858, MTS Systems, Eden Prairie, MN). Force was applied to the palm with the hand extended 60º to simulate falling conditions [1]. Following five trials to 300 N, the specimens were loaded in the same configuration until failure occurred, as indicated by a rapid decrease in the force/displacement curve and (usually) an audible crack. After testing, dissected cross-sections were overlaid with CT images to determine FE nodes associated with strain gage location.

Stereolithographic models based on segmented CT data were imported into IA-FEMesh (University of Iowa, Iowa City, IA) for FE model creation. The models consisted of 15,763 ± 2,478 8-node hexahedral elements with 18,198 ± 2,700 degrees of freedom depending on specimen size. A nominal element size of 1 mm³ was chosen in accordance with a mesh convergence analysis. Models were assigned inhomogeneous linearly-isotropic material properties based on relationships between Hounsfield units, apparent density, and Young’s modulus [2]. Moduli were binned to 230 ± 4 values.
ranging from 0.02 to 20,900 MPa, each having a Poisson’s ratio of 0.4.

Finite element analyses were performed using FEBio software (Musculoskeletal Research Laboratories, Salt Lake City, UT). The proximal end of the radius was fully constrained at the location of potting. A ramped quasi-static load of 300 N was distributed over four nodes in the center of the radial articular surface. The unit vector of the applied load was based on an unsymmetrical beam theory analysis using proximal strain gage rosette information and CT data. Modeled and experimentally determined principal strains at 300 N were compared using simple linear regression.

Failure was simulated with a ramped load to 3 kN. Failure was predicted using distortion energy (DE) failure theory [3]:

\[
(\sigma_{ii} - \sigma_{2i})^2 + (\sigma_{2i} - \sigma_{3i})^2 + (\sigma_{3i} - \sigma_{ii})^2 \geq 2\sigma_{yi}^2,
\]

where \(\sigma_{ii}, \sigma_{2i}, \) and \(\sigma_{3i}\) are the principal stresses and \(\sigma_{yi}\) is the yield strength for the \(i^{th}\) element. Element yield strengths were proportional to Young’s modulus [4]. Fracture was assumed after a contiguous volume of 350 mm\(^3\) had failed [3].

RESULTS AND DISCUSSION

A significant correlation between modeled and experimental strains was observed \((r = 0.82, SE = 140 \, \mu\varepsilon, p < 0.001)\). When separate regressions were run for proximal and distal gage locations, a strong correlation was observed for proximal locations \((r = 0.97, SE = 51 \, \mu\varepsilon, p < 0.001; \text{Fig 2})\). The respective correlation for the distal locations was more moderate \((r = 0.79, SE = 171 \, \mu\varepsilon, p < 0.001; \text{Fig 2})\).

Of the five specimens loaded until failure, three fractured at the distal radius (mean failure load 999 ± 202 N). The DE theory overestimated failure by 163 ± 76 %. Similar overestimations were obtained using other stress- and strain-based failure theories such as Coulomb-Mohr, modified Mohr, max normal strain, and strain energy density. In an effort to determine radius failure load under non-physiological loading conditions, the ulna and all soft tissue were removed from one of the unfailed radii. Epoxy putty was formed over the distal articular surface of the radius and left to harden. This allowed for a subsequent mechanical test until failure with a distributed load over the entire distal articular surface. In this scenario, the radius failed at 2,344 N and FE analysis with DE theory estimated failure at 2,266 N; a 3 % difference.

CONCLUSIONS

The present study has shown that simplified boundary conditions, along with our model generating algorithm, provides realistic measures of radius bone strain under physiological loading conditions. Unfortunately, these simplified boundary conditions can lead to an overestimation in radius fracture strength during a simulated fall due to potential disagreements in distal strain distributions. The DE failure theory does however predict fracture under non-physiological loading conditions (e.g. a distributed load over the entire distal articular surface) and can be used as an outcome measure to predict failure strength.

REFERENCES