Application of a Density-Elastic Modulus Equation Developed for the Distal Ulna to Multiple Forearm Positions: A Finite Element Study

INTRODUCTION:

Compared to experimental studies using strain gauges, finite element (FE) models are not limited to strain measurements at discrete locations and can be used to examine the continuous strain and stress field throughout bone. As such, they can be a useful tool for biomechanical investigations interested in stress/strain changes as a result of multiple loading conditions, implant designs, etc. Critical to their development is the assignment of material properties.

Recent studies have shown that subject-specific FE models, which relate density information from CT scans to elastic modulus, are an accurate method to assign material properties (Schileo et al., 2007). Furthermore, as bone material properties can vary throughout the body, using a site-specific relationship can be important, as shown in a recent study of the distal ulna (Austman et al., 2009).

The authors’ long-term goal of developing a subject-specific finite element model of the distal ulna is to examine changes in bone density over time due to alterations in stress/strain following joint replacement. An important step towards this goal is to demonstrate that model output correlates with experimentally measured strains through a range of forearm rotation. Subject-specific finite element models of the ulna using an ulnar-specific density-modulus relationship have been previously validated (Austman et al., 2009); however, the strains predicted by the models were compared to experimental results in the neutral rotation position only. The purpose of this study is to expand upon this previous work and ensure that the ulnar-specific equation produces accurate results when applied to other forearm positions.

METHODS:

Six fresh-frozen right ulnae (mean age = 66 ± 8 years; 5 male, 1 female) were cleaned of all soft tissue, thawed, and fixed proximally into a custom jig. Six pairs of uniaxial strain gauges were applied to the medial and lateral surfaces of the bone (Figure 1). Each strain gauge pair was integrated into a Wheatstone half-bridge configuration and output to a data acquisition system.

The jig was placed in a materials testing machine (Instron 8872, Canton, MA, USA). Strain data were recorded while a 20N load was applied to the distal articular surface of the ulnar head. The load application point was varied by rotating the jig relative to the actuator, corresponding to loading in 40° of pronation or supination.

Figure 1 – Strain gauge locations and loading directions (only lateral gauges shown; P = pronation, N = neutral, S = supination).

Each ulna was scanned using a micro-CT scanner with isotropic 152 μm voxel spacing (Xplore Ultra, GE Healthcare, London, Canada). Surface geometry was extracted using Mimics (Materialise, Leuven, Belgium) and imported into the finite element software Abaqus (Simulia, Providence, RI, USA) where a 3-D model of the bone was created. Each model was meshed with second-order tetrahedral elements of characteristic length 0.75 mm. Inhomogeneous material properties were assigned to each bone using custom software that applied the ulnar-specific density-modulus equation developed by Austman et al. (2009) (i.e., $E = \frac{834\mu Pa}{g1831 = 8346/g2025}$).

Modeling the experimental set-up, a 20 N force was applied to the articular surface of each model at 40° of pronation and supination. The mesh elements corresponding to each strain gauge location were identified for all models. The strains predicted at these locations were compared to the experimental strain readings.

Two-way repeated measures (RM) ANOVAs with post-hoc Student-Newman-Keuls test ($\alpha = 0.05$) were used to compare model and experimental strain output values across all gauge levels. RMSE and average percent error using all six gauge locations were calculated for each specimen. Intraclass correlation coefficients (ICCs) were calculated to examine the correlation between experimental and predicted strain. Bland-Altman plots were also constructed to detect any biases or systematic errors.

RESULTS:

The two-way RM ANOVAs found no differences between experimental and modeled strain values for both pronation ($p = 0.53$) and supination ($p = 0.87$). The average RMSE, percent error, and ICCs calculated from the six specimens are shown in Table 1. Figure 2 shows the Bland-Altman plot constructed from the data obtained in pronation.

Table 1 –RMSE, percent error, and ICCs comparing experimental and model strains.

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<tr>
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<th>Pronation</th>
<th>Supination</th>
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<tbody>
<tr>
<td>Average RMSE ($\mu \varepsilon$)</td>
<td>35.1</td>
<td>29.8</td>
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<tr>
<td>Average Percent Error (%)</td>
<td>11.6</td>
<td>4.0</td>
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<tr>
<td>ICC</td>
<td>0.89</td>
<td>0.88</td>
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<td>(Lower Bound, Upper Bound)</td>
<td>(0.80, 0.95)</td>
<td>(0.77, 0.94)</td>
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Figure 2 – Bland-Altman plot comparing experimental and model strains in pronation. Similar results were found in supination.

DISCUSSION:

This study provides an important step towards an overall goal of developing a validated, strain-adaptive finite element model of the distal ulna. It has demonstrated that a previously developed density-modulus equation specifically defined for the ulna (Austman et al., 2009) and originally validated for the neutral position only is applicable in forearm pronation and supination. Applying this equation, the ANOVA analyses showed that overall the FE model predicted strains that were not different from those measured experimentally across the six specimens tested. Using neutral position data, Austman et al. (2009) showed this equation was an improvement over other equations available in the literature and provided ICCs, RMSE and percent error values of 0.94 (0.80, 0.97), 29.2 µε, and 9.2%, respectively. These are similar to the magnitudes of the measures found in the present study. The Bland-Altman plots, used to compare a new measurement method (i.e., model strains) to an existing standard (i.e., strain gauge measurements), showed excellent agreement. Combined, these data suggest the density-elastic modulus relationship proposed by Austman et al. (2009) can be applied throughout the range of forearm rotation.

REFERENCES: