

COMPUTED-TOMOGRAPHY-BASED FINITE-ELEMENT MODELS OF LONG BONES CAN ACCURATELY CAPTURE STRAIN RESPONSE TO BENDING AND TORISON

Bino Varghese, Thomas Hangartner

Wright State University, Dayton, OH, USA

email: varghese.2@wright.edu, web: <http://www.wright.edu/academics/bmil/bmil.htm>

INTRODUCTION

Finite element (FE) models constructed from computed tomography (CT) data are emerging as an invaluable tool in the field of bone mechanics [1]. Their clinical application has been limited due to the lack of high level of automation and reliable estimation of accuracy [2].

METHODS

In this study, a combined numerical–experimental study is performed comparing FE-predicted surface strains with strain gauge measurements. 40 major, cadaveric, long bones (humerus, radius, femur and tibia), which cover a wide variety of geometries, are tested under both three-point bending and torsion. The FE models are constructed from trans-axial volumetric CT scans, and a generalized mathematical relationship between bone density and the Young’s modulus is used for the trabecular region of all bones [3,4].

RESULTS AND DISCUSSION

The calculated maximum principal strains at the nodes corresponding to the sensing area of each strain gauge were averaged and compared to the strains obtained from the attachment sites on the bones. Strain graphs of a representative femur are displayed in bending (Fig.1A) and in torsion (Fig.1B). The calculated FE strain is represented as a solid line, and the experimentally measured strain values are represented as points.

The exact positions of the strain gauges on all bones for both loading configurations are tabulated in Table 1. As a rule, the strain gauges were applied in regions of the bone containing trabecular bone and also providing high maximum principal strain values under three-point bending and torsion.

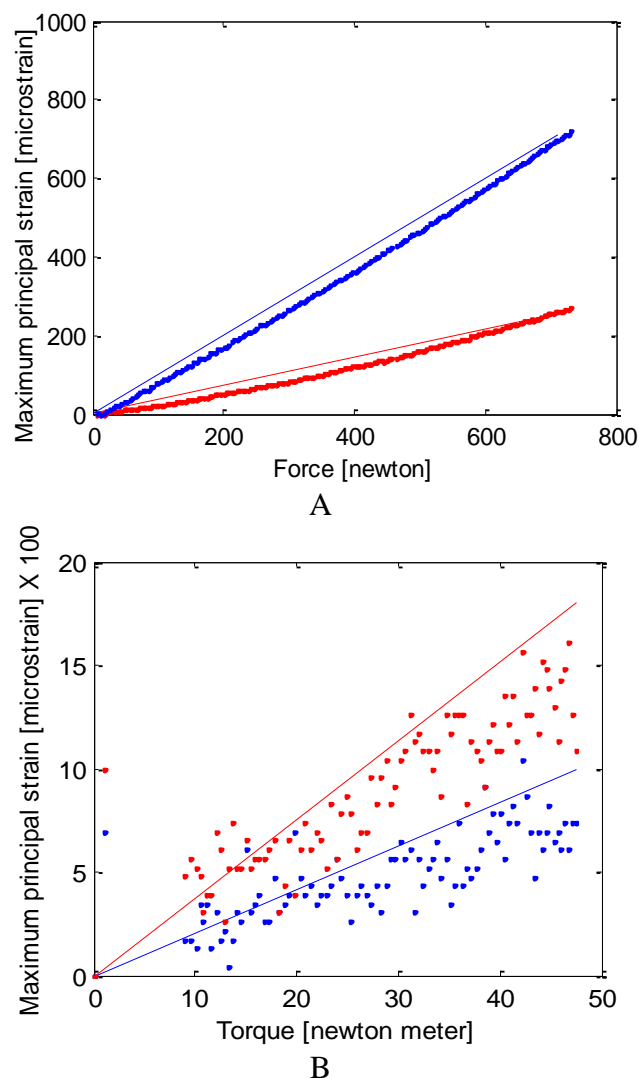


Figure 1: Measured strains from mechanical testing (points) and calculated strains from FE-models (solid lines) for three-point bending (A) and torsion (B) of a sample femur. The lines and data points with the higher slope in (A) represents the strains at the mid-diaphysis (B_{100}); those with the lower slope represent the strains relating to the epiphyses (B_{50}). Similarly in (B), the higher slopes relate to T_{50} and the lower slopes to T_{25} .

To assess the performance of the FE models in capturing the true bone response for bending, only loading beyond 100 N was considered. In the case of torsion, the lower limit of the linear region was set at 2 Nm and the upper limit at the end of the linear range (due to the destructive nature of the test). Within this range, the R^2 values of the measured strains versus load under three-point bending are 0.96 – 0.99 in all bones. Under torsion, the R^2 values range from 0.61 – 0.99 in all bones; however, the majority (88%) of the bones have an R^2 value ranging from 0.82 – 0.95. These R^2 values are reasonable to claim linearity [2], which is indicative of the validity of the experiments.

To quantify the error of the FE-calculated strains from the measured strains, the error between the line fit through the measured strains and the line represented by the FE-calculated strains was computed for all bones under all loading conditions (Table 1). The errors for all bones ranged from -13 to 27% under bending and from -61 to 30% under torsion. For the purpose of comparison, the errors recorded in the literature between FE-calculated and measured strain range from 27 - 60% for bending of the proximal femur [4,5,6]. Therefore, the error range of 5 – 14% found in the femurs of this preliminary study is an improvement.

Further, to the best of our knowledge, comparison of the strains calculated from FE-torsion analysis and strains measured from torsion experiments have

not been recorded in any published studies. We compared FE-calculated and strain-gauge-measured maximum principal strains, and the results are quite encouraging. Additionally, in this study, long bones other than the femur i.e., the tibia, the radius and the humerus have been considered. These bones were included in the study to evaluate the accuracy of the FE technique over a wide range of bone geometries and material properties in 3-D.

CONCLUSIONS

In summary, we have shown that the method of constructing 3-D FE models from CT data predicts strain-gauge-measured surface-strains on major long bones, tested under three-point bending and torsional loads *in-vitro*, reasonably well. In subsequent studies, the material properties will be optimized to minimize the errors of the FE models across all bones.

REFERENCES

1. Schileo E, et al. *J Biomech* **41**, 2483-2491, 2008.
2. Taddei F, et al. *J Biomech* **39**, 2457-2467, 2006.
3. Morgan EF, et al. *J. Biomech* **36**, 897-904, 2003.
4. Taddei F, et al. *Med. Eng. Phys* **29**, 973-979, 2007.
5. Taddei F, et al. *Clin. Biomech* **23**, 1192-1199, 2008.
6. Bessho M, et al. *J Biomech* **40**, 1745-1753, 2007.

Table 1: Range of R^2 values for various strain gauge locations (location indicated in parentheses) obtained by fitting a linear model to the measured strains over the linear range for all bones under three-point bending and torsion. The range of percent errors recorded between the measured strains and the FE-calculated strains are displayed beside the range of R^2 values. Positions of the strain gauges, B for bending and T for torsion, are also tabulated. The subscript number indicates approximately the percentage of maximum strain recorded at that site. N: number of samples. The notation P_{end} indicates proximal end and D_{end} indicates distal end.

FEMUR (N=10)	B₅₀ (18% from P_{end})	B₁₀₀ (50% from P_{end})	T₂₅ (15% from P_{end})	T₅₀ (17% from P_{end})
	0.96 - 0.99, 6 - 14%	0.97 - 0.99, 5 - 11%	0.61 - 0.99, -2 - 16%	0.82 - 0.99, -61 - 16%
TIBIA (N=10)	B₅₀ (18% from D_{end})	B₁₀₀ (50% from D_{end})	T₂₅ (11% from D_{end})	T₅₀ (14% from D_{end})
	0.98 - 0.99, -11.3 - 12%	0.98 - 0.99, -4 - 19%	0.90 - 0.92, -30 - 30%	0.90 - 0.92, -40 - 20%
HUMERUS (N=10)	B₅₀ (20% from P_{end})	B₁₀₀ (50% from P_{end})	T₂₅ (13% from P_{end})	T₅₀ (15% from P_{end})
	0.99, -10 - 14%	0.99, -11.9 - 17%	0.64 - 0.95, -28 - 22%	0.95 - 0.97, -7 - 9%
RADIUS (N=10)	B₅₀ (20% from D_{end})	B₁₀₀ (50% from D_{end})	T₂₅ (15% from D_{end})	T₅₀ (18% from D_{end})
	0.96 - 0.99, -10 - 13%	0.96 - 0.99, -9 - 3%	0.73 - 0.97, -5 - 16%	0.75 - 0.97, -15 - 3%