Finite Element Prediction of *In Vivo* Bone Strains in a Novel Rabbit Hindlimb Loading Device

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Summary

We have developed a novel *in vivo* rabbit hindlimb loading device to explore the role of mechanobiology in bone metabolism. The objective of this study was to develop a finite element (FE) model to predict tibial strains in response to the applied load. Strain predictions were exceptionally sensitive to the assumed force orientation, resulting in root-mean errors up to 2,600 $\mu\epsilon$. Using optimization, we determined a force orientation that minimized strain prediction errors, explaining 97% of the variance in experimental measurements.

Introduction

The role that targeted intracortical remodeling plays in the maintenance of bone quality is not well understood. Rabbits exhibit natural Haversian remodeling, making them an ideal animal model for studying the role of mechanobiology in cortical bone metabolism [1]. Our group has recently constructed a novel *in vivo* mechanical loading device, specifically designed to noninvasively fatigue load rabbit hindlimbs. With this device, we hope to establish the relationships between applied load, strain environment, microdamage accumulation, and bone remodeling. Our objective was to develop a computed tomography (CT)-based FE model of the rabbit hindlimb and validate the force vector orientation. This will serve to elucidate the mechanical strain environment produced by our *in vivo* loader.

Methods

The hindlimbs of eight (8) newly euthanized rabbits were fit into a custom fixture, such that the tibia was roughly aligned with the vertical axis of loading. Strain gauge rosettes were attached to the distal-anterior and distal-posterior surfaces of the tibiae. Hindlimbs were then mechanically tested in cyclic uniaxial compression between -25 N and -200 N at a loading frequency of 0.5 Hz for 20 loading cycles and subsequently disarticulated at the hip joint. Strain gauge rosettes were replaced with radiopaque markers. The excised hindlimbs were fixed to 3D-printed replicas of the knee fixture and phantom calibrated CT scans were obtained. Segmented tibiae were meshed into FE models with ~250,000 tetrahedron elements. Material properties were assigned according to previously determined density-elasticity relationships. The distal surface of the tibia was fixed, and a compressive 200 N load was applied to a kinematically coupled proximal tibia surface. Bounded brute force global optimization and Nelder-Mead optimization routines were used to determine the relative force vector orientation that minimized the error between FE predicted and experimentally measured strains. The average optimal orientation was determined, and a final global optimization routine bounded by +/- 2 standard deviations (SD) in the mean force orientation was performed.

Results and Discussion

Concurrent force vector optimizations were run for all sixteen (16) FE tibia models, converging to a mean (SD) azimuth angle of, $\varphi = 174°$ (34°), and mean (SD) inclination angle of, $\theta = 173°$ (2°), with 180° representing purely vertical. Optimized FE models demonstrated strongly correlated strain predictions (Figure 1), explaining 97% of the variation in experimental strain measurements. The linear regression slope was not statistically different from unity; however, the regression intercept was different from zero. A Bland-Altman analysis revealed a bias of -24 $\mu\epsilon$ (LoA: -181 $\mu\epsilon$ to 132 $\mu\epsilon$), resulting in a $Y = X$ type of relationship after bias adjustment. The final global optimization bounded by +/- 2 SD resulted in a global error minimum at a force orientation of $\varphi = 195°$ and $\theta = 173°$. Strain predictions are exceptionally sensitive to a changing force orientation, even within the tightly bounded region where 95% of the vectors are likely oriented.

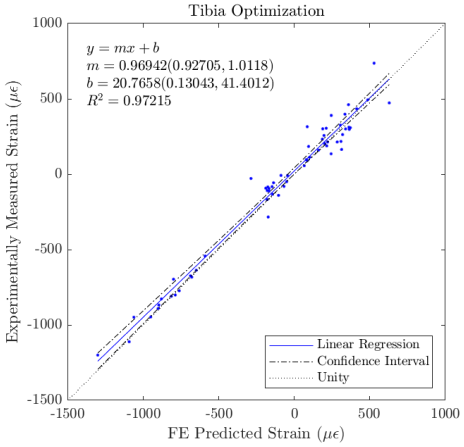

Figure 1: Linear regression between predicted and measured strain.

Conclusions

FE models for our *in vivo* mechanical testing device will be modeled with a force orientation of $\varphi = 195°$ and $\theta = 173°$. The bounded optimization will be used to quantify expected strain variance across the probable force orientations. By understanding the strain sensitivity to force orientations, our work further serves to highlight inaccuracies in previous *in vivo* FE modeling and strain calibration approaches [2].

Acknowledgments

This work was funded in part by a CIHR Project Grant and NSERC CGS Master's Award.

References

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