EFFECT OF STRAIN GAUGE SIZE AND PLACEMENT DURING THE MOUSE AXIAL ULNAR LOADING PROTOCOL CALIBRATION

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INTRODUCTION

Understanding the mechanisms of bone mechanobiology has benefitted from the use of animal models in which controlled loading protocols can be used to test bone adaptation hypotheses in-vivo. In particular, the axial ulnar loading protocol is a popular model [1,2]. The axial ulna loading protocol facilitates the direct manipulation of applied force magnitude, duration, and frequency. A key initial step in any study utilizing this protocol is a load-strain calibration experiment using a uniaxial strain gauge attached at the medial diaphysis, typically using five sacrificed animals and loading those limbs in the same manner as will be done in live animals. Some of these calibration experiments in the literature show significant variability in the strain values among animals. Two questions that have not been adequately examined are 1) how sensitive is the measured strain to small differences (e.g., 250 microns) in the placement of the strain gauge, and 2) what is the effect of gauge size on the magnitude of measurable strain?

METHODS

The methods used here were similar to those described previously [3]. Briefly, the left forelimb of a C57BL/6 strain mouse was scanned with a Scanco vivaCT 40 microCT scanner. The voxels in the model were down sampled by a factor of two, resulting in 21.0 μm voxels. A direct voxel to hex element conversion was performed to create the FE model and was solved using the Scanco FE software (v1.15b). The elastic modulus and Poisson's ratio of the bone elements were 13.3 GPa and 0.3, respectively. The ulna model had 1,166,563 nodes and 1,063,357 elements and was subjected to a 1 Newton axially oriented force (Figure 1).

Uniaxial strain along the longitudinal axis was calculated for each node. The nodal strains along the ulna surface can be interpreted as an 'idealized' gauge strain with a gauge size equal to the element size of the FE model (0.021 mm x 0.021mm). In a second model, an active gauge area of 0.51 x 0.38 mm^2 (Figure 1), which represents the size of a commonly used uniaxial strain gauge (EA-06-015DJ-120, Vishay), was used [2]. The equivalent 'Vishay' gauge strain was calculated by averaging the surface nodal strains within the active gauge area. A similar investigation was performed with a smaller active gauge area of 0.1524 x 1.27 mm^2, corresponding to the gauge size of a semiconductor bar gauge (SS-080-050-500P-S1, Micron Instruments) and is referred to here as the 'semiconductor' model.

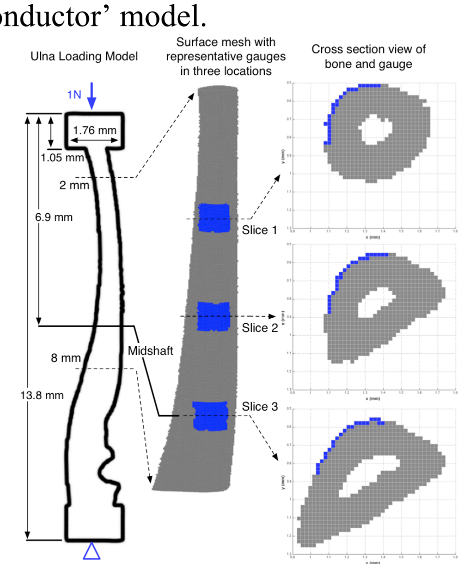

Figure 1: Ulna model and active gauge area for the Vishay gauge at three axial slice locations.

RESULTS AND DISCUSSION

Uniaxial nodal strain for three representative axial slice locations is presented for three unique strain gauge sizes. Additionally, to simulate a small error in gauge placement, we present the results of an analysis in which the Vishay gauge location corresponding to the location of peak strain for the axial slices (Fig. 1) was perturbed in four directions: distal, proximal, circumferential clockwise (CW), and counterclockwise (CCW). All perturbations in gauge placement were 250 microns in magnitude (e.g. approximately half of the Vishay gauge active width or about 2.5 times the thickness of standard printer paper) and calculated as the distance along the bone surface.

The effect of gauge size on peak strain measurement for the three selected axial slices is presented in Table 1. The Vishay and semiconductor gauges underestimated the idealized peak strain by an average of 25% and 16%, respectively. The results of the perturbation analysis for the Vishay gauge size are presented in Table 2. Perturbations of the gauge position along the longitudinal axis resulted in a maximum decrease of 116 με at slice 2 for a perturbation in the proximal direction. The counter-clockwise circumferential perturbations resulted in the largest deviation from the unperturbed Vishay model with the smallest absolute change of 737 με occurring for slice 3 and the largest magnitude change of 1046 με occurring for slice 2.

Table 1: Peak strains at three representative axial slices for the different gauge models (Fig. 1).

	Ideal (με)	Vishay (με / % of ideal)	Semiconductor (με / % of ideal)
Slice 1	-3526	-2624 / 74.4%	-3040 / 86.2%
Slice 2	-3642	-2806 / 77.0%	-3079 / 84.5%
Slice 3	-3122	-2334 / 74.8%	-2530 / 81.0%

The purpose of this study was to quantify the sensitivity in peak longitudinal strain associated with direct measurement limitations related to strain gauge size and placement position for the axial ulnar loading technique of the mouse forelimb. The relative importance of the results presented here may be best interpreted in the context of reported bone formation and response to induced strain. Lee et al. [1] reported an approximate increase in the periosteal bone formation rate ($\mu m^2/\mu m$ per day) from 0.5 to 2.8 for CD1 mice resulting from a change in induced peak strain from 2000 με to 3000 με. Lee et al. also observed a change from a lamellar to a mixed woven/lamellar response with the same increase of induced peak strain indicating a potential damage response. In the results presented here, a relatively small change in circumferential gauge placement (250 microns Counter-CW) resulted in a strain gauge reading nearly 40% lower than the true, peak strain value at certain slice locations. In the context of the induced strains used by Lee et al., such a perturbation would result in a larger change in peak strain than the 1000 με increase reported to induce a change from a lamellar to a mixed woven/lamellar response.

Considering the sensitivity of bone response (magnitude and response type) to strain magnitude, accurately quantifying the induced strain during the calibration procedure is critical to interpreting the results of the axial ulnar loading protocol and to better understanding the mechanisms driving a particular mechanistic response. The results presented here, particularly the underestimation of peak strain associated with available strain gauges and the high degree of sensitivity of measured strain to gauge placement circumferentially about the longitudinal axis, suggest that additional consideration must be afforded how specimens are reliably calibrated such that the desired strain level at a particular location of interest is accurately interpreted.

REFERENCES

1. Lee KCL, et al. *Bone* **31**, 562-569, 2002.
2. Robling AG, et al. *Bone* **31**, 407-412, 2002.
3. Wagner DW, et al. *Proceedings of ORS 2011,* Long Beach, CA, USA, 2011.

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Table 2: Vishay model perturbations for the peak strain locations of three representative axial slices (Fig. 1).

	No Perturbation (με)	Distal* (με / % diff.)	Proximal (με / % diff.)	Clockwise (CW) (με / % diff.)	Counter-CW (με / % diff.)
Slice 1	-2621	-2664 / 2%	-2615 / 0%	-1959 / -25%	-1626 / -38%
Slice 2	-2806	-2881 / 3%	-2690 / -4%	-1987 / -29%	-1760 / -37%
Slice 3 (Midshaft)	-2334	-2392 / 2%	-2220 / -5%	-1841 / -21%	-1597 / -32%

*All perturbations result in a 250 micron change in position of the Vishay gauge along the direction listed.