2004 ASME International Mechanical Engineering Congress and Exposition
November 13-20, 2004, Anaheim, California USA

IMECE2004-61934

EFFECT OF INTEROSSEOUS MEMBRANE ON LOAD TRANSFER IN RAT FORELIMB USING FINITE ELEMENT ANALYSIS

Tami A E
1) Orthopaedic Research Center, The Cleveland Clinic Foundation, Cleveland, OH
2) Dept. of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, OH

Suresh G
3) Dept. of Biomedical Engineering
Case Western Reserve University, Cleveland, OH

Patel R B
3) Dept. of Biomedical Engineering
Case Western Reserve University, Cleveland, OH

Knothe Tate M L
1) Orthopaedic Research Center, The Cleveland Clinic Foundation, Cleveland, OH
3) Dept. of Biomedical Engineering
Case Western Reserve University, Cleveland, OH

ABSTRACT

Due to the curvature of the ulna and the complex geometry of the ulna and radius as well and their interaction with and possible transfer of load through the interosseous membrane that joins them, an understanding of the loading situation is not trivial. The IOM might counteract the bending effect resulting from the curvature of the ulna, therefore stabilizing the lateral displacement of the ulna and decreasing the ratio between bending and compression.

Thus, in order to understand the mechanisms underlying effects of the mechanical stimulation applied using the end-loading model of the ulna, it is necessary to have a fundamental understanding of the loading mechanics and strain distribution. Hence, the goals of this study were: i) to develop a three dimensional finite element mesh of a mature rat ulna, ii) to measure experimental surface strain values of rat forelimbs with intact and non-intact interosseous membranes, iii) to compare experimental and computational strain distribution data, and iv) to analyze for the first time the effect of the radius and interosseous membrane on axial load distribution through the ulna.

keywords: finite element, bone, strain gauge, interosseous membrane, load transfer

INTRODUCTION

In order to elucidate mechanisms of mechanotransduction and functional adaptation in musculoskeletal tissues, it is necessary to develop experimental models in which controlled loads can be applied to the tissue with minimal artifactual compromise to tissue physiology. Less than a decade ago, a ulnar compression model was developed [1] that applies an exogenous load to the proximal or distal end of the rat forelimb, imparting a compressive load between the olecranon and the flexed carpus and allowing for study of adaptive changes in the ulna and radius. Compared to previous experiments with exogenous loads, the axial loading of the rat ulna offers many advantages. First, the model is noninvasive in that it requires no surgical intervention. Secondly, axial loading of the curved ulna mimics the loads occurring during normal activity. In the past five years, this model has been used to study (the effect of) strain magnitude, rate, frequency, distribution, and range, as well as the effect of number of loading cycles on growth, modeling and remodeling processes in bone of skeletally immature and mature rats [2-7]. Recently the ulna compression model has been successfully extended to recreate a consistent and reproducible fracture following fatigue [6] and to study mechanical loading effects in ligament [5], thus expanding the range of applications for this animal model. Although this model has been widely applied to study a variety of research questions, the mechanics of loading are poorly understood. Hence, the goal of this study was to elucidate the mechanical behavior of the model system by analyzing for the first time the effect of the radius and interosseous membrane (IOM) on axial load distribution through the ulna.

METHODS

Experimental Strain Measurement Methods

Forelimb tissue of a 10-week-old mature male Lewis Rat was obtained courtesy of the Microsurgery Group at the Cleveland Clinic Foundation. The surrounding skin and muscular tissue around the forelimbs was removed and the head of the ulnae was dislocated from the elbow joint. To measure surface strain on the rat forelimb, 4 strain gauges (EA-06-015-DJ, Measurements Group, Raleigh, NC) were placed along the circumference of the mid-diaphaysis (fig. 2).

The circuit used to obtain our measurements is shown in Figure 1. The intact forelimbs were loaded with a 14 N compressive load; surface strain, total displacement, and load was measured using the Enduratec Machine. Measurements were made with all four strain gauges with first an intact forelimb and then again after slicing the interosseous membrane in half to negate its effect on load transfer.

Finite Element Methods

The limb of a skeletally mature (250-300 g) male Lewis rat was imaged in a high-resolution computer tomograph (mCT 40, Scanco Medical, Bassersdorf). Digitized contours of the cross sections served as input file for the solid mesh that was created with ABAQUS (ABAQUS 6.1, HKS Inc, Pawtucket). In the first stage of the study a stress analysis was performed. Stress and strain were calculated after applying a 14 N load to impose a single static deformation at the ulnar extremities corresponding to values of experimental strain gauge measurements [1,6]. The tissue was modeled as a continuum; however, to account for the anisotropy of the bone matrix, elasticity material parameters describing transverse isotropy were applied.

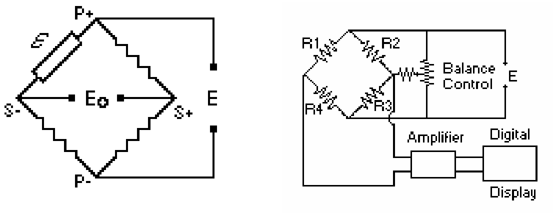

Figure 1. Quarter wheatstone bridge circuit with one active element used to measure strain (left). Full circuit diagram of our strain measurement setup (right).

RESULTS

The strain values for cases including intact interosseous membrane and severed interosseous membrane are displayed in Table 1. Based on these measurements, there is compressive stress on the lateral region of the ulnae and a tensile stress on the medial region of the radius. The opposite regions of both bones are mostly along the neutral axis and show minimal strain values under load. When the interosseous membrane was severed longitudinally and strain measurements were retaken, a complete loss of load transfer to the radius resulted. The ulna carried all the load, with the lateral region once again under compression and the medial region under tension.

	intact ligament	cut ligament
	microstrain	microstrain
ulnae lateral	-1249.88	-833.32
ulnae medial	204.8	3749.94
radius lateral	-204.6	0
radius medial	416.66	0

Table 1. From our strain measurements it is shown that slicing interosseous ligament eliminates load transfer between ulna and radius bones.

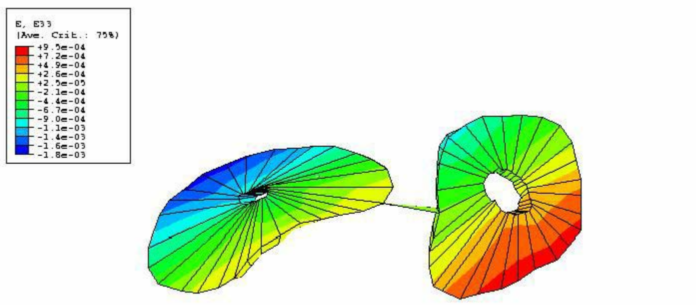

Figure 2. Finite Element model of intact forelimb. Load transfer between radius and ulna occurs with the radius bending in compression and the ulna in tension.

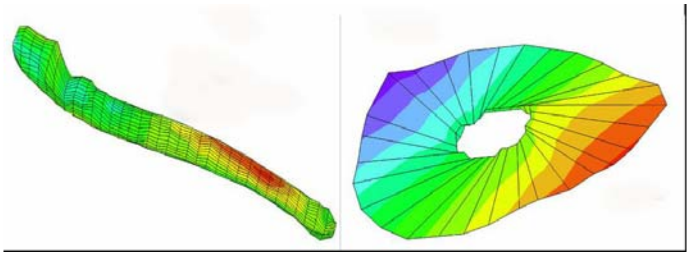

Figure 3. When ligament was cut ulna bore the whole load. The lateral region of the ulna was under compressive strain while the medial region was under a tensile strain.

DISCUSSION

For all cases studied, the radius and IOM reduced stress and strain in the ulna by structurally stiffening the forelimb construct. Compared to the ulna alone, the location of maximal deformation was almost identical and the distribution of compressive and tensile strain was similar. The lowest deformation in the ulna was observed for the case where the load was applied homogeneously, distributed over the radius and ulna, when the radius was not allowed to displace. The highest ulnar deformation was induced when the load was applied only on the ulna and the radius was free to move proximally.

The three-dimensional FE model of the rat forelimb confirms the influence of ulnar curvature on its deformation and underscores the influence of the radius and IOM on strain distribution through the ulna. The mode of strain, i.e. compression or tension, and strain distribution along the diaphysis correspond to those measured experimentally in vivo [1,2,4,6]. When the radius and, indirectly, the membrane were loaded, the deformation shifted centrally with respect to the diaphysis (Figure 2).

This finite element analysis of the ulnar compression model provides new insight into mechanical loading behavior of the ulna-radius-interosseous membrane construct.

REFERENCES

[1] Torrance AG et al., 1994, Calcif Tissue Int, 54:241-247 [2] Hsieh YF and Turner CH, 2001, J Bone Miner Res, 16:918-24
[3] Lanyon LE and Rubin CT, 1984, J Biomech, 17:897-905.
[4] Mosley JR et al., 1997, Bone, 20:191-198[5] Netrebko P et al., 2002, *Trans ORS 2002*, *583* [6] Tami AE et al., 2002, *Trans ORS 2002*, *335* [7] Tami AE et al., 2002, *J Bone Miner Res*, 17:2030-7