

Determination of Physiological External Loading Conditions Based On Bone Morphology

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Introduction

It is generally accepted that bone density and microarchitecture are the result of a load-adaptive bone remodeling process in which bone strives for homogeneous tissue loading ('Wolff's law'). This implies that, in turn, it would be possible to obtain information about the bone loading history by finding the set of external forces that result in homogeneous tissue loading. Such a procedure for the determination of bone loading history on the basis of bone density and architecture would be of great importance to derive estimates of bone loading conditions for bone remodeling studies.

In earlier studies, this concept was explored with the use of continuum finite element models that account for the bone density distribution only. Most of these studies, however, were limited to 2D analyses and were not able to predict complex physiological loading. With the development of micro-FE models that can account for the actual trabecular architecture, it is now possible to extend this procedure to the bone micro-level, which is the aim of the present study.

The purpose of the present study was, first, to investigate if realistic estimates of bone loading conditions are found based on optimal homogeneous bone tissue loading and, second, to investigate to what extent homogeneity of bone tissue loading can be achieved with a limited set of plausible external forces.

Materials and methods

Micro-FE models of artificially created grid structures and mouse tail vertebrae based on micro-CT scans were generated (Figure 1), where three-month-old female C57BL/6 mice underwent loading of the sixth caudal vertebra at 0N (Group A; n=8) or 8N (Group B; n=8) for 3000 cycles at 10 Hz three times per week for four weeks (Figure 2). The micro-FE models were used to calculate the tissue loading conditions, quantified as strain energy density (SED), for unit load cases representing compression (F_{xx}), shear (F_{yx} , F_{zx}), torque (T_{xx}) and bending moments (M_{yx} , M_{zx}). An optimization algorithm was then used to calculate the magnitude for each load case such that a bone tissue SED closest to a target value of 0.003 MPa was obtained when results for all scaled load cases were added.

To quantify the homogeneity of the final SED distribution, its coefficient of variation (CV) was calculated.

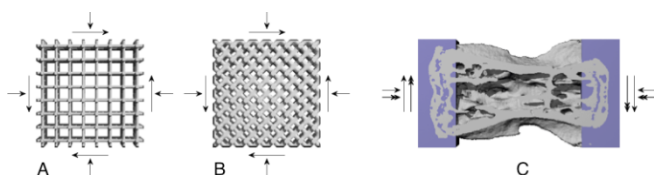


Figure 1: Micro-FE models and their boundary conditions of the regular grid structure (A), the rotated grid structure (B), and the mouse vertebrae structure (C).

Results

Forces in the direction of the grid struts were predicted as the dominant loading directions and little remaining variation was found (CV<20%) in both grid structures.

For the vertebrae, the algorithm predicted compression as the main loading case (Table 1). However, the compressive force predicted for the group that had the vertebrae loaded was much higher than that predicted for the unloaded vertebrae (p<0.01). For both cases, considerable inhomogeneity in tissue SED remained with CV values of about 100% (Figure 2).

Table 1: Predicted force/moment magnitude for vertebrae that were loaded with 0N (A) and 8N (B) respectively.

Group	Forces [N]			Moments [Nm]		
	F_{xx}	F_{yx}	F_{zx}	T_{xx}	M_{yx}	M_{zx}
A; n=8	4.62	0.02	0.04	0.90	0.66	0.67
B; n=8	10.3	0.04	0.07	1.01	0.47	0.43

Discussion and conclusions

The approach introduced here successfully predicted the expected external forces for both grid models. It also well predicted the difference in loading history to which the mouse vertebrae were adapted. The remaining inhomogeneity in tissue SED could indicate that a larger set of external forces should be considered or could indicate a 'lazy zone' in bone cell mechanosensitivity of around 100%. Although more analyses will be needed to establish the reliability and accuracy of the approach, we conclude that the results obtained here are encouraging.

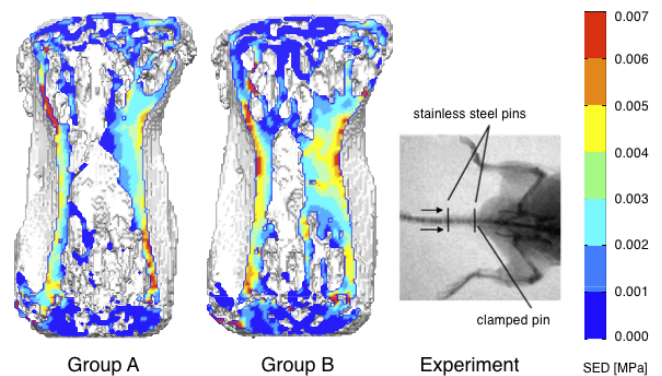


Figure 2: SED distribution for the vertebrae bone structure that were loaded with 0N (A) and 8N (B) respectively. The experimental procedure entails pushing pins in two adjacent vertebrae and cyclic loading of these pins.

Acknowledgments

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