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Adaptations of Trabecular Bone to Low Magnitude Vibrations Result in More Uniform Stress and Strain Under Load

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Abstract—Extremely low magnitude mechanical stimuli (<10 microstrain) induced at high frequencies are anabolic to trabecular bone. Here, we used finite element (FE) modeling to investigate the mechanical implications of a one year mechanical intervention. Adult female sheep stood with their hindlimbs either on a vibrating plate (30 Hz, 0.3 g) for 20 min/d, 5 d/wk or on an inactive plate. Microcomputed tomography data of 1 cm bone cubes extracted from the medial femoral condyles were transformed into FE meshes. Simulated compressive loads applied to the trabecular meshes in the three orthogonal directions indicated that the low level mechanical intervention significantly increased the apparent trabecular tissue stiffness of the femoral condyle in the longitudinal (+17%, $p<0.02$), anterior–posterior (+29%, $p<0.01$), and medial-lateral (+37%, $p<0.01$) direction, thus reducing apparent strain magnitudes for a given applied load. For a given apparent input strain (or stress), the resultant stresses and strains within trabeculae were more uniformly distributed in the off-axis loading directions in cubes of mechanically loaded sheep. These data suggest that trabecular bone responds to low level mechanical loads with intricate adaptations beyond a simple reduction in apparent strain magnitude, producing a structure that is stiffer and less prone to fracture for a given load. © *2003 Biomedical Engineering Society.* [DOI: 10.1114/1.1535414]

Keywords—Bone adaptation, Mechanical stimuli, Mechanical strain and stress, Mechanical properties, Finite element modeling, Bone formation, Osteoporosis, Noninvasive.

INTRODUCTION

Mechanical parameters believed to guide bones' adaptive process to mechanical stimuli, such as strain magnitude,[16,25] strain rate,[10,19] strain energy density,[3] or strain gradients,[4,9] have been associated with large magnitude mechanical signals. More recently, however, we have shown that extremely small magnitude mechanical stimuli, inducing strains of less than 10 microstrain ($\mu\varepsilon$) in the bone matrix, will increase bone formation when applied at high frequencies (>20 Hz).[21,24] In contrast to many high-impact physical exercise interventions that are unsuitable for patients with fragile bones, the clinical potential of these high-frequency mechanical stimuli to treat and prevent osteoporosis is promising because of their extremely small magnitudes. For any anabolic intervention to be relevant to the clinic, however, it is important to demonstrate its ability to improve the mechanical outcome of the treatment, as it has been learned that an increase in bone quantity does not necessarily lead to a mechanically more competent bone structure.[20,28] Using mechanical compression tests, we have recently verified that a one-year mechanical intervention involving a low magnitude mechanical stimulus, applied for 20 min per day, will increase trabecular bone stiffness in the femoral condyles of sheep.[23] The mechanism by which the bone achieved this increase in stiffness, however, was not immediately clear.

In the study reported here, we used finite element (FE) modeling to more completely characterize the manner in which morphological adaptations of trabecular bone to mechanical vibration influence the resultant strain and stress environment of the trabeculae under load. Specifically, we tested whether simulated FE testing of trabecular bone cubes from vibrated and control animals produces similar increases in apparent stiffness as previously collected from mechanical testing and asked how strain and stress magnitudes within the trabeculae are affected by the adaptations of bone volume and architecture.

MATERIALS AND METHODS

Experimental Design

Adult female sheep (Warhill, intact ewes, 60–80 kg), 6–8 years of age, were randomized into experimental

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