PREDICTION OF RESONANCE CHARACTERISTICS OF THE HUMAN FOREARM BONES USING FINITE ELEMENT ANALYSIS

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INTRODUCTION

The resonance characteristics of a structure predispose its response to dynamic loading. Modal analysis is a method to determine the resonance characteristics in terms of natural frequencies and mode shapes of a structure. It is often used as a diagnostic tool for osteoporosis, fracture healing, and dental treatment monitoring due to its non-destructive nature of testing. Experimental modal analysis techniques require application of a known sinusoidal or impact force on an anatomic site and measurement of the subsequent acceleration or displacement near the site. However, such application of an input force and measurement of the acceleration or displacement is only limited to an anatomic structure, where the measurement site are superficially accessible. Therefore, little is known about the resonance characteristics of the radius, while much is known about the ulna from previous in vivo modal testing.

As an alternative way to in vivo modal testing, finite element (FE) analysis has been used to estimate the resonance characteristics of a structure having irregular geometry and variability of the material properties inside [1]. Thus, having precise geometry and material property is a key to FE modal analysis. In this study, we obtain the geometric models of the human forearm bones from the Visible Human Project (VHP) datasets through color image segmentation and 3D reconstruction techniques. Subsequently, the geometric models of the forearm bones were exported to create FE models and the resonance characteristics of the radius and ulna were estimated using FE modal analysis.

METHODS

The VHP datasets consist of anatomical color slice images of a representative male and female cadavers at an average of one or 1/3-millimeter intervals, respectively. The Visible Human Male dataset was used for our model construction. Image segmentation, a process of dividing an image into different homogeneous anatomical regions, was conducted in the RGB pattern space to detect the boundaries of each different anatomical region by means of a minimum distance classifier, while each class prototype was obtained using a fuzzy c-mean clustering method [2]. Computational implementation of the above algorithms was done using custom MATLAB programs and the image processing toolbox (The MathWorks, Inc, Natick, MA).

The detected boundary points in each slice were fitted to a spline curve and re-sampled to generate boundary curves of each anatomical structure in the forearm. Then, all the boundary curves in the transverse planes along the longitudinal axis were lofted in a commercial CAD system (SolidWorks, Inc, Concord, MA) to generate the 3D surface and solid models of the radius, ulna, and surrounding soft tissue of the forearm. According to different mechanical properties of the tissues [3], the geometries of the forearm bones were reconstructed into four different anatomical structures, including bone marrow, diaphysis (cortical), and distal and proximal metaphyses (cancellous). The proximal and distal metaphyses were reconstructed with the cross-sectional boundary curves at 7 mm intervals, while the diaphysis and bone marrow was reconstructed at 12 and 8 mm intervals, respectively.

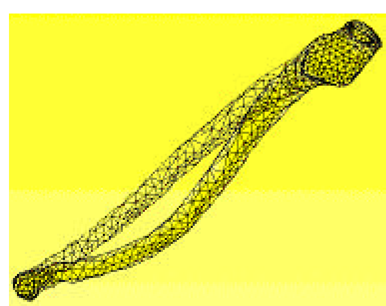

Figure 1. Fundamental mode shape of the human ulna

An FE model of the ulna with 10,864 of 10-noded tetrahedral solid elements was created using the imported geometry in ANSYS 6.1 (ANSYS, Inc, Canonsburg, PA) (Fig. 1). In a similar fashion, an

FE model of the radius with 15,033 of 10-noded tetrahedral solid elements was created. A total of nine material parameters should be assigned to the FE model, which included the Young's moduli, Poisson's ratios, and densities of the cortical and cancellous bones and bone marrow. Typically, the Young's modulus and Poisson's ratio of the bone marrow are assumed to be zero. Nominal values of the Poisson's ratios of the cortical and cancellous bones, 0.33 and 0.25, respectively, were used based on our initial observations on their insensitivity to the resonance characteristics. In this study, a reported Young's modulus of the radius, 18.9 GPa [4], was used as the Young's modulus of the cortical bone, and subsequently its density was calculated as 1,947 kg/m^3 by using an empirical equation [5]. Then the material properties of the cancellous bone and bone marrow should be optimized within the reported ranges of the literatures through FE modal analysis of the ulna and thereby the simulation results should be validated with the literature data from the experimental modal analysis studies [6]. As for the boundary conditions, both ends of the ulna were rigidly fixed around the articular surfaces of the distal and proximal ends, representing the ligamentous attachments and joint contacts.

RESULTS

A series of FE modal analysis was conducted in the reported ranges of the material parameters to understand the sensitivities of each parameter to the first resonant frequency of the ulna. The densities of the cancellous bone and bone marrow showed a little effect, less than 0.5% error relative to the nominal value of 400 Hz within the ranges, 300-1,000 and 1,000-1,227 kg/m^3, respectively. However, the Young's modulus of the cancellous bone within the range between 0.1 and 1.5 GPa had a significant effect on the estimated fundamental resonant frequency of the ulna, ranging between 251 and 493 Hz. Therefore, the parametric optimization could be done mostly by varying the Young's modulus of the cancellous bone. From the parametric optimization, the densities of the cancellous bone and bone marrow of the forearm were determined as 800 and 1,227 kg/m^3. The Young's modulus of the cancellous bone was 0.6 GPa. These "calibrated" material properties were used in further FE modal analysis of the radius.

Table 1. Estimated natural frequencies and vibration modes

		1	2	3	4	5	6
Ulna	Frequency [Hz]	400	465	1079	1205	1762	1959
	Vibration Mode	M-L (I)	A-P (I)	A-P (II)	M-L (II)	A	T
Radius	Frequency [Hz]	411	464	1240	1400	1787	1949
	Vibration Mode	A-P (I)	M-L (I)	A-P (II)	M-L (II)	A	T

(M-L: bending mode in the medio-lateral direction, A-P: bending mode in the anterior-posterior direction, A: axial mode, T: torsional mode, I, II: first and second modes, respectively)

For both bones, there were four vibration modes, two bending modes in the medio-lateral and anterior-posterior directions, one axial mode, and one torsional mode. The corresponding first resonant frequencies were summarized in Table 1. The axial and torsional modes had relatively higher corresponding resonant frequencies, exceeding 1,700 Hz, while the first four resonant frequencies were bending modes. The ulna had the first resonance frequency in bending mode along the M-L direction (Fig. 1), while the radius in bending mode along the anterior-posterior direction.

The mass of the bone marrow has often been neglected for the sake of simplicity in mathematical modeling [7]. The effect of the bone marrow was easily evaluated in this study by omitting the finite elements of the bone marrow. The resonance frequencies of the ulna without bone marrow were +3.7 ~ +9.0% higher than with the bone marrow. The resonant frequency for the axial mode had the largest increase by 374 Hz. The bone marrow of the radius also showed similar effects (+3.5 ~ +8.5%). The mass of the bone marrow of the ulna comprised at least more than 12% of the total mass of the ulna as estimated from the solid volumes in the CAD model. Thus, its mass and inertia should not be neglected in any dynamic analysis for the forearm bones.

DISCUSSION

Modal analysis methods have been used in the biomechanics area for identifying vibration modes of long bones and determining the bone stiffness, since they are non-invasive and nondestructive techniques without any risk to the subjects. However, in vivo or in vitro estimation of the resonance frequencies of a bone without easy superficial access such as the radius, has not been feasible. We developed biofidelic geometric models of the human forearm bones using color images from the VHP dataset and used the reconstructed geometric models to create meshes for further FE modal analysis. Though linear isotropic material models were used, different material properties were assigned to the four different structures of the forearm bones to improve the biofidelity.

It was demonstrated in this study that the resonance frequency characteristics of the radius were similar to those of the ulna. The two long bones seemed to have higher axial and torsional rigidities compared to the bending stiffness so that flexural vibrations would be predominat dynamic responses to transient loading. The radius has smaller flexural rigidity in the A-P direction due to its smaller cross-sectional area moment of inertia, resulting in its fundamental mode in this direction. As denoted by the sensitivity of the bone marrow to the resonant frequency of the bone, the surrounding soft tissues such as muscles, ligaments, and tendons should take into account for accurate estimation of the resonance characteristics of the forearm complex.

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