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Relationship between the shape and density distribution of the femur and its natural frequencies of vibration

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ABSTRACT

It has been recently suggested that mechanical loads applied at frequencies close to the natural frequencies of bone could enhance bone apposition due to the resonance phenomenon. Other applications of bone modal analysis are also suggested. For the above-mentioned applications, it is important to understand how patient-specific bone shape and density distribution influence the natural frequencies of bones. We used finite element models to study the effects of bone shape and density distribution on the natural frequencies of the femur in free boundary conditions. A statistical shape and appearance model that describes shape and density distribution independently was created, based on a training set of 27 femora. The natural frequencies were then calculated for different shape modes varied around the mean shape while keeping the mean density distribution, for different appearance modes around the mean density distribution while keeping the mean bone shape, and for the 27 training femora. Single shape or appearance modes could cause up to 15% variations in the natural frequencies with certain modes having the greatest impact. For the actual femora, shape and density distribution changed the natural frequencies by up to 38%. First appearance mode that describes the general cortical bone thickness and trabecular bone density had one of the strongest impacts. The first appearance mode could therefore provide a sensitive measure of general bone health and disease progression. Since shape and density could cause large variations in the calculated natural frequencies, patient-specific FE models are needed for accurate estimation of bone natural frequencies.

1. Introduction

It is well established that bone apposition and resorption are partially controlled by the mechanical loading that bone experiences (Campoli et al., 2012; Carter, 1984, 1987; Grimston et al., 1993; Pearson and Lieberman, 2004; Price et al., 2011; Sugiyama et al., 2010; Turner et al., 1994; Zadpoor et al., 2013). The characteristics of mechanical loading including the frequency and amplitude of dynamic mechanical loads are found to be particularly important for regulation of bone turnover (Hsieh and Turner, 2001; Rubin et al., 2002; Turner, 1998; Werner et al., 2009). It has been recently (Zhao et al., 2014) suggested that dynamic mechanical loads with a frequency close to the bone resonance frequencies could enhance bone apposition. This finding has potentially important practical implications. For example, the exercise regimes (Kerr et al., 1996; Wallace and Cumming, 2000; Wolff et al., 1999) or vibration therapies (Cardinale and Rittweger, 2006; Flieger et al., 1998) designed to increase bone mass and/or to prevent bone mass loss could be optimized such that the musculoskeletal system is loaded with a frequency close to the natural frequencies of the targeted bone. Furthermore, the exercise regimes could be made subject-specific taking account of the natural frequencies of every specific subject. It is therefore important to understand the effects of bone shape and density distribution on the natural frequencies of bones.

In addition to regulating the bone regeneration process, modal analysis of bones could be useful in several other applications. It has been shown that the natural frequencies of long bones such as tibia and femur are correlated with their mechanical properties including stiffness and strength (Arpinar et al., 2005; Christensen et al., 1986; Cornelissen et al., 1986, 1987; Lowet et al., 1993; Van der Perre and Lowet, 1996). This correlation has been used for

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several purposes including assessment of the stiffness of bones and monitoring of fracture healing (Alizad et al., 2004; Benirschke et al., 1993; Nakatsuchi et al., 1996a, 1996b; Tower et al., 1993; Wong et al., 2013). In a different line of research, the vibration properties of bones such as natural frequencies and natural modes are used for characterizing the orthotropic properties of long bones such as the femur (Taylor et al., 2002) and validating density–elasticity relationships used in finite element modeling of bones (Scholz et al., 2013). Another application of modal analysis of bones is detection of the loosening of fixation plates (Bull et al., 1991) and measuring/monitoring the structural features of the spine (Van Engelen et al., 2011, 2012). In all above-mentioned applications, knowledge about the effects of anatomical variations on natural frequencies could be useful particularly to maximize the accuracy of the proposed technique through integration of patient-specific aspects. Introduction of patient-specific aspects could, for example, be performed using patient-specific finite element models (Poelert et al., 2013).

In this study, we examine the effects of shape and density distribution on the natural frequencies of the human femur. A statistical shape and appearance model (SSAM) (Sarkalkan et al., 2014) of the femur is created first. This model consists of the mean femur shape and density as well as their modes of variations found in the training set of 27 CT images. The independent effects of shape and density on the natural frequencies are then studied using the main modes of variation in shape and density and finite element (FE) models. In addition, the combined effects of bone shape and density are studied based on CT images of the femurs used for building the SSAM.

2. Methodology

2.1. SSAM

SSAM of the femur was generated according to (Baka et al., 2011; Cootes and Taylor, 2004a, 2004b) using 27 CT scans of the lower extremity. These scans were acquired as a part of a clinical CT angiography routine performed in Leiden University Medical Center. The population included 5 women and 22 men in their fifties or sixties. First, a point distribution model (PDM) of the bony surfaces was constructed. For this, the femora were semi-automatically segmented with the support of a 2D snake algorithm. After segmentation, a triangulated mesh represented each training shape such that the mesh points (in total 1687) were in correspondence throughout the shapes. Correspondence was achieved by registering the distance transform of all shapes to the distance transform of a reference shape using B-spline non-rigid transformation and the advanced mean squares distance metric available in the Elastix toolkit (Klein et al., 2010). A subject with a relatively high resolution CT [0.686 mm × 0.686 mm × 0.8 mm], about mid-range age (56), and no obvious pathology was chosen as the reference subject. The triangulation and landmark positions of this reference shape were then transformed back to each training shape. The shapes were subsequently aligned using Procrustes analysis (translation, rotation and isotropic scaling) to eliminate pose variations from the model. Each shape was then represented as a vector of its concatenated landmark coordinates:

$$s_i = [x_1^i,\ y_1^i,\ z_1^i, x_2^i, y_2^i, \ldots,\ z_n^i]^T \quad (1)$$

We modeled the point cloud with a Gaussian distribution and calculated the mean shape through averaging and the variance using principal component analysis (PCA).

This resulted in a model of the form:

$$s = \bar{s} + \Phi b \quad (2)$$

where s denotes a shape vector, $\bar{s}$ is the mean shape, Φ is a $[3nxn_p]$ matrix containing the directions of largest variance in its columns, and b is the $[n_p x1]$ shape parameter vector. The number of parameters n_p (26) was defined such that the model contained 99% of the total variance.

For the appearance model, the femur shape differences were eliminated in the training set by deforming all CT images to match the reference femur. The above-mentioned deformation field was used together with a b-spline interpolator for the required image resampling. Grid sampling of all voxels inside the femur was performed to create the intensity vectors from all femora. PCA was then applied to create the intensity model. The retained variance for the model creation was set to the value of 99% and required 25 modes.

The generated SSAM models were evaluated for compactness, normality, and generalization ability. We performed an Anderson–Darling test to assess normality of the modes (Anderson and Darling, 1954). The leave-one-out test was used to estimate the generalization capability of the SSAM. Compactness requires that most variability present in the population be described by the first few modes of variation.

2.2. FE models

Numerical methods such as FE models are often used for calculating the natural frequencies of structures (Azrar et al., 2002; Daya and Potier-Ferry, 2001; Taher et al., 2006). Three types of FE models were created to study the effects of shape and density distribution both separately and in combination with each other. In the first series of FE models, the average density distribution was used for all FE models and only the shape modes were varied around the average shape by up to three standard deviations. Secondly, the average shape was used and the density distribution was varied around the average density distribution by up to three standard deviations. Thirdly, FE models were created for the 27 femora that were used for generation of the SSAM. ZIBAmira 2012.30 (Zuse Institute Berlin (ZIB), Berlin, Germany) was used for generating the geometries and density distributions as well as for mapping the material properties. Tetrahedral elements with linear integration (element type C3D4 in Simulia Abaqus v6.10, Dassault Systèmes) were adopted for all the models generated and analyzed in this study.

The 'effective density' of the bone was defined such that the minimum Hounsfield Unit (HU) within the bone area corresponded to water mass density, i.e. 1000 kg/m^3, and the maximum HU corresponded to the mass density of cortical bone, i.e. 1952 kg/m^3 (Snyder and Schneider, 1991). For calculating the 'apparent density' of bone, the apparent density corresponding to the minimum HU was considered to equal 0, while the apparent density corresponding to the maximum HU minimum was considered to equal the apparent density of cortical bone. The 'apparent density' of bone was related to the elastic modulus of bone using the well-established density–modulus relationship proposed by Morgan et al. (2003). This relationships is shown to be an accurate density–modulus relationship (Schileo et al., 2007) in general and for modal analysis of the femur in particular (Scholz et al., 2013):

$$E = 6.85\rho_{app}^{1.49} \quad (3)$$

where E is Young's modulus (GPa) and ρ_{app} is the apparent density of the bone (g/cm^3). Poisson's ratio was assumed to be 0.3 (Turner et al., 1999; Ulrich et al., 1999; Zysset et al., 1999) throughout the bone. A sensitivity analysis showed that the natural frequency in the vast majority of cases changes by less than 1% when Poisson's ratio is varied between 0.2 and 0.4. Finite element modal analysis was then performed based on the Lanczos method within Abaqus to predict the natural frequencies of the femur. Free boundary conditions were used. The convergence of the FE solutions was examined using the mean bone shape and mean density distribution that was discretized at five different level. The choice of the discretization level was based on the ZIB Amira re-meshing module options (Zachow et al., 2007; Zilske et al., 2008). This approach attempts at isotropic vertex placement, and allows for adjusting the percentage of the original surface mesh size that must contain high quality triangles. Once the surface triangulation was completed, volumetric tetrahedral elements were generated using the of ABAQUS element types. Table 1 lists the re-meshing percentage levels as well as the corresponding number of nodes, degrees of freedoms, and elements and distorted elements (in absolute values and percentage on the total amount of elements). The first 10 natural frequencies were then calculated and compared with each other.

3. Results

3.1. SSAM

The covariance matrix of the training set is a diagonal matrix with decreasing values. Fig. 1a shows these diagonal values

Table 1
Convergence study: re-meshing discretization level, number of tetrahedral elements (type C3D4), number of nodes, number of global Degrees of Freedom (DoF), number of distorted elements, and the percentage of distorted elements.

Discretization level ZIB AMIRA %	Elements (C3D4) Nr.	Nodes Nr.	Degrees of Freedom Nr.	Distorted elements Nr.	Distorted elements %
1	13,285	3234	9702	238	1.79
5	118,878	24,185	72,555	802	0.67
10	288,365	56,361	169,083	1601	0.56
20	681,309	129,151	387,453	3793	0.56
30	1,124,628	209,972	629,916	6107	0.54