A Theoretical Analysis of Vibrational Modes Aimed at Their Use as Measures of Bone Damage

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Abstract—Extended exposure to microgravity reduces bone mass and degrades mechanical properties of bone tissue; its most damaging consequence is the loss of bone strength. Unfortunately, the first signature of bone loss is the occurrence of a non-traumatic fracture. Such events can be reduced if there were a reliable and routinely available non-invasive diagnostic for bone strength. Bone density scans, the most routinely used clinical tool, are not sufficiently accurate for the purpose. We propose the use of vibrational assessment and the development of a conceptual framework to implement it as a diagnostic for bone strength.

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REDUCTION IN BONE MASS with the resulting skeletal damage is one serious consequence of extended exposure to microgravity.[1-3] Moreover, bone damage in microgravity is expected to be vastly different from that caused by aging; hence, traditional diagnostics such as bone density scans and ultrasonic assessment may not provide reliable estimates for bone damage during space travel. The principal issue of interest is whether damage incurred during flight is permanent. If not, bone degradation can be reversed using rigorous exercise regimens following return to Earth. On the other hand, if the damage is irreversible, it is necessary to take steps during flight to reduce bone loss, such as the use of new powerful therapies. However, care must be taken in using such medications because of adverse side-effects caused by their indiscriminate use.[4] Hence, accurate methods for obtaining a comprehensive biomechanical profile of the skeleton are a pre-requisite for extended space travel including the proposed manned missions to Mars.

Our research program is aimed at developing a prediction model for a comprehensive profile of biomechanical properties of bone using vibrational assessment. It will address one of the critical issues for the success of the program. Its completion will justify our approach and allow us to initiate experimental and *in-vivo* human studies.

Structure of Bone

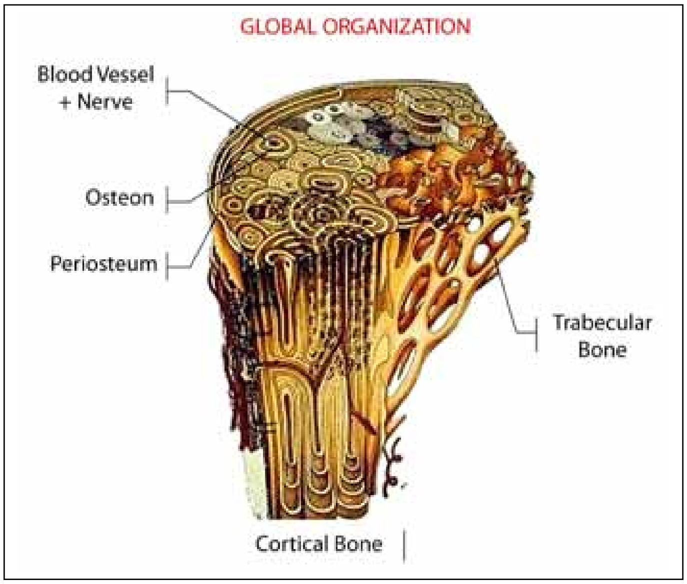

Figure 1. Schematic of a Large Bone

Large bones consist of an outer solid segment (cortex) and an inner porous region (trabecular architecture), as seen in Fig. 1. The tissue forming bone is a composite consisting of “needles” of calcium phosphate and fibers of collagen.[5] Although the cortex is the principal load carrier in children and young adults, it becomes brittle with aging because of the accumulation of long micro-fractures. Consequently, its load carrying ability is severely compromised. Extended exposure to microgravity is expected to make the trabecular elements thinner, and, occasionally, to perforate them. These perforations are most alarming since lost connections are never regenerated naturally. In terrestrial environments, damage to trabecular bone is less than that on cortical bone; both trabecular and cortical segments of

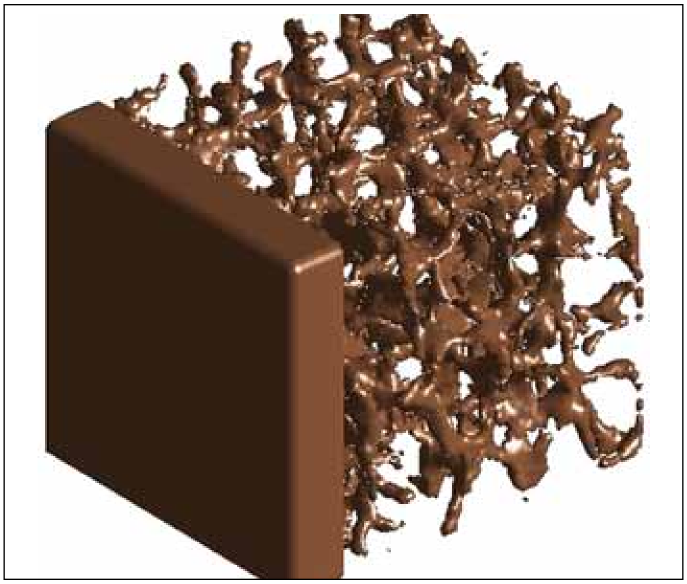

Figure 2. Model Specimen of Bone on Which Computations Are Performed

bone make important contributions to the strength of bone in middle-aged adults.

The most commonly used surrogate for bone strength is the bone density, which is estimated using dual energy x-ray absorptiometry (DEXA). The fact that the much lighter trabecular bone plays a significant role in strength suggests that DEXA cannot provide reliable estimates for bone strength. Ultrasonic scans are also used to determine the need for therapy. However, scans cannot identify architectural changes because the velocity of ultrasound is unchanged unless material properties of bone tissue are modified. These measures cannot provide a comprehensive profile of the many different types of damage that can weaken bone. Such an assessment is critical during space travel because damage modalities are vastly different from natural aging; the latter is the only scenario where surrogates have been tested and indexed.

Vibrational Assessment

We propose to develop vibrational assessment as a method to determine the need for therapeutic intervention to reduce the damage from bone loss. Sonic and ultrasonic techniques have found application in damage assessment in a wide range of structures including bridges and airplane components. Additional problems arise in structural analysis of bones: (1) bone has multiple components (cortical and trabecular segments) that are important in load transmission, (2) non-invasive tests can only be conducted on the whole bone, and (3) soft tissue such as skin and muscle degrade the ultrasonic signal used to evaluate the response of bone.

Goals of the Project

The project has four overall goals: (1) Devise an algorithm to use vibrational response of the whole bone to estimate those of the cortical and trabecular bone. This will be done using advanced signal processing techniques. (2) Determine a scheme to estimate the strength of a specimen of trabecular bone from its response. (3) Develop a method to estimate the strength of a specimen of cortical bone from its linear response function. (4) Construct a portable instrument to capture the linear response functions of bone *in-vivo*. The instrument has been constructed by Prof. Michael Liebschner, Department of Bioengineering at Rice University, in collaboration with UH researchers.

In addition, we expect to compare the reliability and ease of application of vibrational techniques with those currently in use, including bone density scans and the use of micro-computed tomography.

Methodology

Computational techniques will be developed using the simplified bone model shown in Fig. 2. The model consists of a porous segment (which is a digitized image of a specimen of human skeletal bone) and a solid component. Its rear end is fixed and the outer boundary is subjected to vibrations at a fixed frequency Ω. The force $F(\Omega)$ needed to implement the motion $A\sin(\Omega t)$ of the outer boundary is obtained from an integration of the appropriate set of ordinary differential equations, and the linear response function $\chi(\Omega)$ is evaluated. This process is implemented for a frequency sweep. Part (1) of the goals is to extract the linear response functions of the solid and the porous segments from $\chi(\Omega)$ using techniques from inverse scattering, in particular the Lippman-Schwinger expansion.[6] In order to solve this inverse problem, we will assume that the model can be represented by a two-phase medium; i.e., we assume that the porous region can be represented by an "effective" uniform medium. Further, we assume that $\chi(\Omega)$ is a smooth function of Ω and use a suitable basis expansion for interpolation. We expect that with this constraint, we will obtain the (otherwise under-determined) solution to the inverse problem; the proposed calculation will give the linear response functions $\chi_C(\Omega)$ and $\chi_T(\Omega)$ for cortical and trabecular components.

The next step is to estimate the strength of the trabecular bone specimen from $\chi_T(\Omega)$. We note that, as a bone decays, it is only able to use a progressively smaller part of itself for stress transmission. The cause of this inefficiency is the presence of (occasional) long fractures; they prevent large regions of the remaining trabecular network (in particular those immediately above and below the fracture) from taking part in load transmission.[7] Analyses of model systems show that this inefficiency is the leading cause of reductions in bone strength. It is thus natural to assert that the strength of the trabecular bone is related to the fraction of elements belonging to the stress-carrying-backbone.

We used this observation to introduce a new surrogate Γ for the strength of trabecular bone. It is the ratio of the elastic modulus of the specimen to its linear response function at resonance; it can be obtained from $\chi_T(\Omega)$. We have shown[7,8] that the fractional reduction of strength τ (i.e., the ratio of current strength to peak strength during young adulthood) is related to Γ by

$$\tau = A\,\Gamma + h(\Gamma),$$

where the constant A depends on very general properties of the specimen (e.g., its length, the fact that it is a cubic network, etc.)

and $h(\Gamma)$ is a nonlinear function that depends on more detailed (and subject dependent) characteristics of the specimen. We have shown how this relationship can be used to estimate the strength of a sample of trabecular bone; the conclusions have been confirmed in computer models.[9] Figure 3 shows the relationship for computer models constructed from two samples of cadaveric bone. As they become weaker (the case of interest), the curves are seen to coincide, as predicted theoretically.

We propose to use a similar method to estimate the strength of the cortical segment of the bone from $\chi_C(\Omega)$. Preliminary analysis has shown that our propositions are valid for this case.[10]

Results

We introduced a simple struts-and-nodes model to conduct preliminary studies of trabecular bone and to identify non-destructive measures that are appropriate to estimate the strength. This work is published in a series of papers.[8,7] The analysis showed that the ratio Γ is a reliable estimate for the loss of strength of trabecular bone. The conclusions were validated using computations on several models that were constructed from digitized images of human trabecular bone obtained by micro-computer tomography.[11,9]

Like trabecular bone, the cortex experiences fractures due to daily activity. Typically, smaller fractures formed in the cortex are repaired on a time scale of about one to two months, while the longer (and deeper) ones are not. The principal mode of damage in cortical bone is the accumulation of long fractures. We conjectured that the ratio Γ reliably estimates loss of strength due to such fractures. These findings were recently validated in a model system.[10]

Discussions and Conclusions

Extended exposure to microgravity reduces bone mass and degrades mechanical properties of bone tissue; its most damaging consequence is the loss of bone strength. Unfortunately, the first signature of loss of bone mass is the occurrence of a non-traumatic fracture. Such events can be reduced if there were a reliable and routinely available non-invasive diagnostic for bone strength. We propose that vibrational response be used for this purpose. The work proposed develops the conceptual framework to determine how vibrational methods can be used to reliably estimate bone strength. Successful completion of the tasks will provide a basis for experimental and clinical studies to provide the final validation prior to using the tools in clinical and low gravity settings.

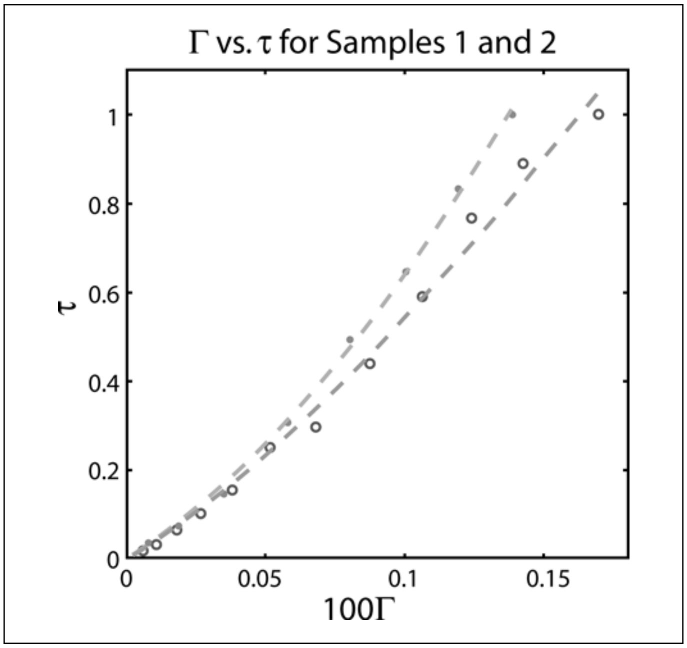

Figure 3. The Relationship between τ and Γ for Two Models

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(Continued on page 126.)

A Theoretical Analysis of Vibrational Modes Aimed at their use as Measures of Bone Damage

(Continued from page 107.)

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Collaborators

Graduate student Chamith Rajapakse received his Ph.D. in 2005. He currently serves in the Department of Radiology, University of Pennsylvania as a post-doctoral researcher.