Determination of macroscopic biological material properties by dynamic, in-vivo testing
by Edward Roger Garner

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Mechanical Engineering
Montana State University

Abstract:
The intent of this research was to develop analytical-experimental techniques to quantitatively determine the "in-vivo macroscopic biological material properties" of biological structures. The complexity of biological structures requires that a new definition of material properties be developed for analytical modeling of in-vivo biological structures. It was assumed that all soft tissues (flesh) in the human forearm can be modeled by a common set of "in-vivo macroscopic biological material properties", and that all calcified tissues (bones) can be modeled by another common set of "in-vivo macroscopic biological material properties".

The human forearm was modeled analytically by using the finite element technique. Two types of finite elements were incorporated in the model. The bones were modeled with three-dimensional bending elements, and the flesh was modeled with constant stress tetrahedron elements. The deviatoric stress-strain rheological models for the "in-vivo macroscopic biological material properties" of bone and flesh were represented by two different three parameter solids. Both bone and flesh were assumed to be hydrostatically elastic. The solution of the finite element model equations was simplified by using approximations that were appropriate because of the limited frequency band over which the solution was required. These approximations reduced the number of simultaneous equations from 602 to 25, thus dramatically reducing the computer storage requirements and solution times.

The dynamic response of the human forearm to a steady-state harmonic excitation in the 100 to 1000 Hertz band was determined analytically from the finite element model and experimentally from a living forearm of a 34 year old male. The bone stiffness parameters were adjusted until the peak response amplitude in the 100 to 1000 Hertz band occurred at the same frequency as it did in the experimental response. The flesh damping was then adjusted until the sum of the squares of the difference between the analytical response and the experimental response at 50 frequencies in the 100 to 1000 Hertz band was a minimum. Thus, numerical values were obtained for the "in-vivo macroscopic biological material properties" representing bone stiffness and flesh damping.

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August, 1973

ACKNOWLEDGMENTS

The author wishes to thank Dr. D. O. Blackketter for his assistance, guidance and understanding. Dr. Blackketter spent many hours helping define and solve the problems that developed during this research effort. This research could not have been accomplished without the rapport that existed between the author and Dr. Blackketter.

The author would also like to thank the Montana State University Computer Center staff, particularly Allen Porter, for their assistance with the computer during this research.

The patience and understanding of both the author's family and friends was also of great assistance during the past three years.

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ABSTRACT

The intent of this research was to develop analytical-experimental techniques to quantitatively determine the "in-vivo macroscopic biological material properties" of biological structures. The complexity of biological structures requires that a new definition of material properties be developed for analytical modeling of in-vivo biological structures. It was assumed that all soft tissues (flesh) in the human forearm can be modeled by a common set of "in-vivo macroscopic biological material properties", and that all calcified tissues (bones) can be modeled by another common set of "in-vivo macroscopic biological material properties".

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INTRODUCTION

The intent of this research was to develop analytical-experimental techniques to quantitatively determine the "in-vivo macroscopic biological material properties" of biological structures. Numerical values were obtained for the "in-vivo macroscopic biological material properties" representing bone stiffness and flesh damping.

The experimental-analytical technique for determining the "in-vivo macroscopic biological material properties" utilized the steady state response of the human forearm to a harmonic excitation in the 100 to 1000 Hertz band. The forearm was analytically modeled by using the finite element technique. The complexity of the solution of the finite element model was reduced by using approximations that were valid because of the narrow (100 to 1000 Hertz) band over which the solution was needed.

The "in-vivo macroscopic biological material properties" were determined by adjusting the material properties of the anlytical model until there was a minimum of difference between the response of the analytical model and the response found experimentally in the 100 to 1000 Hertz band. Thus, the properties used in an analytical model which cause the response of the analytical model to a harmonic excitation to be similar to the response found experimentally are the "in-vivo macroscopic biological material properties".

Chapter 1

LITERATURE REVIEW

The object of this chapter is to review the literature on mechanical properties of biological materials. Most of the work in this field deals with "in-vitro" properties and experiments. The relationship of "in-vivo" properties to "in-vitro" properties is not presently known. The need for "in-vivo macroscopic biological material properties" is evident in much of the recent literature.

The literature on engineering properties is divided into two parts: first is the study of calcified tissues (bones) mostly conducted by orthopedic surgeons, and second, the study of soft tissues. These two parts are each subdivided into "in-vitro" and "in-vivo" work.

Bones--"in-vitro"

Early testing of bones was performed by Wertheim about 120 years ago. From that time until the mid 1960's most of the effort dealt with the determination of an approximate modulus of elasticity and the non-linear properties associated with large strain values. Little attention was paid to changes in proerties due to death and storage techniques after death. In 1965 a comprehensive study by

Sedlin (1) was published in Copenhagen. This seventy-five page document describes in detail the effects of storage techniques, testing methods, etc. on the "in-vitro" material properties of cortical bone. Sedlin presents very substantial evidence that bones are linear viscoelastic for small deformations and also verifies that the rheological model (Figure 1) he chose is the best possible model for his "in-vitro" experiments. Although Sedlin's experiments were carried out on very small sections of the femur, the properties he describes are more macroscopic in nature than those of other recent authors. Unfortunately, he gives no numerical results.

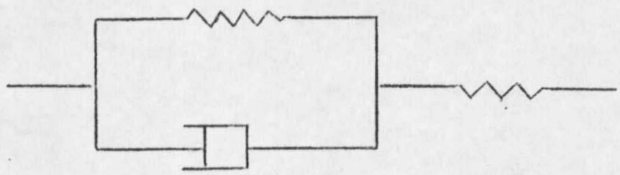

Figure 1

Sedlin's Rheological Model

Katz (2) discusses bone as a two-phase material and uses the Voigt rheological model, a slightly less complex model than Sedlin's. It may be that such a two-phase model will help explain, from a diagnostic point of view, why certain macroscopic changes occur. Consideration of bones as a two-phase material would be necessary if modeling of wave propagation in the bone medium was the diagnostic technique being considered.

McElhaney and Byars (3) have reported rheological models and data from which parameters for these models can be computed. Amazingly enough this is one of the few papers that reports actual numerical results. Their study considered strain rates up to 4000 in/in/sec. in human bone, bovine bone, and bovine muscle tissue. Their experiments were "in-vitro" and the samples were embalmed. Sedlin (1) and McElhaney (3) demonstrated that embalming will change the material properties. Evans (4) considered bone to be viscoelastic and yet still determines a modulus of elasticity and claims that embalming does not affect the modulus of elasticity.

A group at Stanford has measured bending vibration "in-vitro" of bare dog radii (5,6). They have also analyzed a viscoelastic beam. Their method of analysis is not applicable to the more complex nature of a total biological structure. The experimental techniques used in this study are such that estimation of "in-vivo" properties from their data is not reasonable.

Chamay (7) performed fatigue tests "in-vitro" on fresh dog ulnas and was able to reproduce some of the forms of failure seen in clinical orthopedic work. This paper does not discuss the viscoelastic nature of bone materials.

Hirsch and Sonnerup (8) have used the models developed by Sedlin and others to discuss the loading in femoral cortical bone and lumbar annulus fibrosis. They have indicated that a better understanding of the engineering properties has a direct clinical application to orthopedics. They also emphasize the need for three-dimensional stress analysis in this area.

Tennyson, Ewert and Niranjan (9) describe the changes in bone properties as a function of post-mortem age. They used the split-Hopkinson bar test in their experiments and modeled the bone with the Voigt rheological model.

Bones--"in-vivo"

There are some examples of "in-vivo" testing in the literature. Seireg and Kempke (10) have tested rat tibias "in-vivo" under low load cyclic loading. Their main interest was the description of the fatique properties of bones. Their tests were destructive in nature. It is interesting to note that they obtained typical s-n diagrams with the knee of the s-n diagram at about 4000 cycles. The endurance limit was at approximately 42% of the static fracture load.

Curry (11) has shown that bone engineering properties (he specifically discusses a modulus of elasticity) are a function of mineral content. Since it is known that bone mineral content changes drastically with certain diseases, for example, osteoporosis, a means of inexpensive "in-vivo" tesing for mineral content of bone as is suggested in the current study has definite potential as a new medical diagnostic technique.

Nowinski and Davis (12) have modeled bone as a two-phase porous substance in order to study wave propagation in bone. Their goal was to determine "in-vivo" material properties from wave propagation data. Nowinski (13) also used a poroelastic model in studying "in-vivo" contact stress at joints. Our initial experiments and Martin's (14) work indicated that wave propagation studies will probably have to be carried out "in-vitro", because of the large energy absorption capability of bone and flesh.

Basset (15) discusses some of the fascinating microscopic engineering properties of bone. It is now speculated that mechanical loading causes a piezo-electric effect which changes the alignment of collagen fibers to better accept the load. Such a feedback system within the bone itself would verify the need to study the physical properties "in-vivo" while the feedback system is still intact.

McElhaney, Alem, and Roberts (16) used a porous block model and assumed that the mechanical response was proportional to load density raised to some power. They also assumed that the microscopic properties were constant and that the differences observed were due to geometric structural differences. Wood (17) compared the structural composition of the skull to that of modern engineering sandwich construction. He also showed that the skull's response is sensitive to strain rate, thus verifying the viscoelastic nature of bone.

Liu (18) has developed a lumped mass multi-degree of freedom model for the dynamic response of the spine. It is interesting to note that Liu chose the three parameter solid as his viscoelastic model for the discs. It might be possible to obtain a more accurate model of the spine by using the finite element technique.

First bending resonance in the ulna of humans has been studied "in-vivo" by Jurist (19). His work has led to possible new techniques for detection of diseases. Because of his purely medical goal, he has not reported analysis of total response plots obtained from bending excitation. Thus, diagnostic information that may be available from response plot characteristics other than the first bending resonance of the ulna are not being utilized. It would appear that a careful analytical study of the dynamic response of the forearm would aid in the medical diagnostic interpretation of dynamic response data.

Matz, Blackketter, et al. (20) used an experimental procedure similar to Jurist's. The forearms of a large sample of humans were vibrated transversely by a small amplitude, low-frequency harmonic input. The correlation between the first resonant frequency and four easily measured parameters was determined by a 2^n factoral experiment. The four parameters were fleshiness, bone size, arm length and muscle development. It was shown that all four of these factors were important in determining the first resonant frequency.

Blackketter and Garner (21) used the finite element method to model the human forearm. The analysis of the two-dimensional, viscoelastic, finite element model was performed in the Laplace domain. The steady-state response of the model to a harmonic forcing function was obtained. The model had a maximum amplitude response in the first bending mode near the same frequency found experimentally by Matz. The model also demonstrated that rigid body motion of the bones was present.

Kraus' paper (22) is a comprehensive review of bone properties, and he discusses Sedlin's rheological model. Kraus states strongly the need for continued work in this area, 1) to fill in the gaps in mechanical properties, 2) to formulate three-dimensional constitutive equations for compact bone, 3) to determine relationships between "in-vitro" properties and "in-vivo" properties, and 4) to collect data on diseased bones. The last part of Kraus' paper is quoted here because it so clearly defines the need for the research effort described in this thesis. "An alternative goal would be the invention of instruments for the determination of the mechanical properties and behavior of bone 'in-vivo'. It is anticipated that non-destructive tests for the determination of all properties except strength will eventually be devised, however, a non-destructive test for the determination of strength is inherently impossible, as is one for the determination of fatigue life.

Since various diseases such as osteoporosis, and osteopetrosis have strong influence upon the ability of bone to support loads, the studies suggested in the preceding discussion must be carried out for various categories of diseased bone. Indeed, no examination of the mechanical properties or behavior of any diseased bones have, to the author's knowledge, been carried out as yet.

The investigation of the foregoing areas represents an exquisite challenge to the bioengineer and promises a rewarding career to those who wish to take it up. It has been our goal here to provide the necessary introduction to such work."

Flesh--"in-vitro"

In general, the literature does not contain as much information on mechanical properties of soft tissue as it does for bones. Most of the soft tissue mechanical properties reported are for large strain, well beyond the linear region. Bennedict, Walker and Harris (23) performed some very interesting experiments on human tendons. They demonstrated that embalming tendons affects their stiffness, thus again verifying the need for a method of "in-vivo" testing. They also fixed their strain rates because of the viscoelastic properties of tendons found by Van Brocklin and Ellis (24). Van Brocklin and Ellis found non-elastic response of the human tendon at loading rates above 22psi/sec.

There are a number of papers (25,26) that attempt to develop strain energy functions to match the large strain non-linear properties of flesh. Although this is of no direct interest in the current research, it is a related area that needs a considerable amount of work if large stresses and strains are to be accurately modeled.

Research of Viidik (27), as well as that by Jamison, Marangon, and Glasur (28), indicate specific rheological models for soft tissue. Viidik's work with rabbit anterior cruciate ligaments determined a qualitative rheological model which is non-linear (Figure 2). Note, however, that at low strain levels this model reverts back to the standard three parameter solid used by Sedlin. Jamison reports both a rheological model (Figure 3) and values for the parameters for guinea pig skin. The scatter in his data