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THE MECHANICAL PROPERTIES OF TRABECULAR BONE: DEPENDENCE ON ANATOMIC LOCATION AND FUNCTION

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Abstract—In 1961, Evans and King documented the mechanical properties of trabecular bone from multiple locations in the proximal human femur. Since this time, many investigators have cataloged the distribution of trabecular bone material properties from multiple locations within the human skeleton to include femur, tibia, humerus, radius, vertebral bodies, and iliac crest. The results of these studies have revealed tremendous variations in material properties and anisotropy. These variations have been attributed to functional remodeling as dictated by Wolff's Law. Both linear and power functions have been found to explain the relationship between trabecular bone density and material properties. Recent studies have re-emphasized the need to accurately quantify trabecular bone architecture proposing several algorithms capable of determining the anisotropy, connectivity and morphology of the bone. These past studies, as well as continuing work, have significantly increased the accuracy of analytical and experimental models investigating bone, and bone implant interfaces as well as enhanced our perspective towards understanding the factors which may influence bone formation or resorption.

INTRODUCTION

Investigating the mechanical properties of trabecular bone and its adaptation to alterations in its physiologic and mechanical environment remains one of the most important arenas in musculoskeletal research. Characterizing its response to metabolic diseases and treatments, fractures, degenerative joint disease, and total joint arthroplasty is inherent to clinical success. Although the physical properties of bone have been investigated for over 100 years, detailed studies on the distribution for trabecular bone material properties have been documented more recently. In 1961, F. Gaynor Evans published a study designed to catalog the regional differences in the physical properties of human trabecular bone from the proximal and distal femoral metaphyses. This study was one of the first to document the tremendous variability of physical properties of trabecular bone. This paper, which was typical of the pioneering work in bone biomechanics published by Dr Evans, was one of the first to statistically analyze the physical properties of cancellous bone as a function of anatomic location.

The purpose of this paper is to present a review of studies on the physical properties of trabecular bone. The evolution of experiments designed to characterize trabecular bone has moved from material and densitometry studies at a continuum level, to macroscopic properties of trabecular tissue. Morphologic and architectural observations continue to be made as a means of assessing clinical conditions. Technological advances in both experimental and analytical techniques promise to direct future studies towards more accurate predictions of fracture risks, a detailed understanding of bone's reponse to its mechanical environment, and perhaps elucidating the fundamental mechanisms controlling bone resorption or formation.

COMPRESSIVE PROPERTIES

Historically, the interest in characterizing the physical properties of trabecular bone centered around the need to evaluate the risk of fracture; epidemiologically recognized to be a consequence of age or metabolic disease. As early as 1876, Rauber determined the specific gravity of fresh specimens of human spongy bone as well as its compressive strengths. More extensive studies of the mechanical behavior of trabecular bone were reported by Gocke (1925, 1928), Hardinge (1949), Yokoo (1952), and Knese (1956, 1958).

Evans and King (1961) published one of the first studies designed to investigate the compressive properties of trabecular bone as a function of position within the human femur and loading direction. Their study, which was performed on cubic and rectangular specimens from embalmed femurs, provided the first statistical evidence of the great variation in material properties of trabecular bone as a function of anatomic position. Since this time, many investigators have reported on the mechanical properties of trabecular bone from the major metaphyseal regions of the human body. Perhaps the greatest impetus for these

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studies was the advent of prosthetic joint replacement and the need to understand the bone implant interface.

A summary of published data on the compressive properties of trabecular bone is presented in Table 1. These studies demonstate that trabecular bone acts similarly to porous engineering materials due to its cellular structure and energy absorption capabilities. Its stress/strain response is characterized by a somewhat linear region followed by yield at an extended plastic region maintaining constant stress due to collapse within the cellular framework. As the cellular pores continue to collapse, the stiffness may again increase.

One of the most striking features of this data is the huge variation in modulus and strength reported. These variations have been shown to be a function of anatomic position, loading direction, methods of storage and testing conditions. Some of the most important findings from this large body of work can be summarized as follows:

(1) The most significant and consistent result from these studies was the correlation between the variation in material properties and the function of the bony region tested. These findings support the generally accepted hypothesis that function directly influences the structure and strength of metaphyseal bone, a relationship known as Wolff's Law (Wolff, 1892).

(2) In general, a linear relationship was found between the elastic modulus and strength of trabecular bone. While the coefficients of this relationship varied among the various authors, the correlations were consistently high.

(3) The strength of the bone was found to be proportional to the strain rate raised to the 0.06 power (Carter and Hayes, 1977) and viscous stiffening due to *in situ* marrow was only significant at very high strain rates (Carter and Hayes, 1977).

(4) Environmental and testing conditions contributed significantly to the variation of data among the cited studies. Temperature, moisture content and storage conditions are important and make it difficult to compare the absolute values of data from the many laboratories and investigators. Recent work has suggested that preconditioning factors may have also played a major role in measurement stability (Linde and Hvid, 1987).

TENSILE AND SHEAR PROPERTIES

Compared to the extensive studies on the compressive properties of trabecular bone, only a few studies have attempted to characterize the tensile and shear properties of trabecular bone. Due to its porous, lattice-like structure, the experimental methodologies are demanding and may have contributed to these limited efforts.

One of the earliest studies was performed by Sonoda in 1962 using trabecular bone from the thoracic and lumbar vertebrae of seven individuals. The results of this study suggested that the tensile strength is significantly less than the compressive strength of trabecular bone. Later studies by Carter *et al.* (1980) and Neil *et al.* (1983) in human bone and Bensusan *et al.* (1983) in bovine trabecular bone, have reported no significant difference between tensile and compressive properties. Finally, in a study by Kaplan *et al.* (1985) using trabecular bone from fresh bovine humeri, it was demonstrated that the bone was significantly less stiff in tension then in compression and supported an earlier analytical prediction of tensile properties by the same group (Stone *et al.*, 1983).

Shear properties of trabecular bone have also only received limited attention, perhaps due to experimental and conceptual difficulties encountered when testing the highly anisotropic porous structures. Melvin *et al.* (1970) reported a mean shear strength of approximately 20.7 MPa from cylindrical specimens extracted from human skulls. Halawa *et al.* (1978) investigated the shear properties of trabecular bone as a function of location within the proximal and distal human femur. Their results demonstrated a range of shear strengths from approximately 1 to 17 MPa. The trabecular bone demonstrating the greatest shear strength was found closest to the cortical cancellous junction, but was also dependent on the shear plane chosen relative to the anatomic position of the bone. Saha and Gorman (1981) studying human femoral trabecular bone and Stone *et al.* (1983) using bovine humeri, found average shear strengths in the range of 5–7 MPa.

RELATIONSHIP OF MODULUS AND STRENGTH TO BONE DENSITY

Although many factors may influence the mechanical properties of trabecular bone, most investigators have attempted to determine the correlation between density measures and the stiffness or strength. The attractiveness of these correlations lies in the fact that these measures are relatively easy and may relate to similar noninvasive techniques enabling the characterization of bone properties to be carried out *in vivo*. Weaver and Chalmers (1966) and Bartley *et al.* (1966) found positive correlations between human trabecular bone compressive strengths and apparent densities or ash content. Since this time, many studies have documented similar correlations as noted in Table 2. While most investigators demonstrated significant correlations, the unexplained variance and the order of the corresponding relationships between the mechanical properties and the density measures have been quite variable. As noted in Table 2, the relationships have been expressed as a function of linear regressions and power functions.

Current sentiment among investigators tends to favor the power formulations described by Carter and Hayes (1976, 1977) due to the similarity of trabecular bone to porous engineering materials. Studies by Patel

Table 1. A survey of published mechanical properties of human trabecular bone is presented as a function of anatomic location

Region	Storage method	Specimen configuration	Comments	Properties
Proximal tibia				
Behrens *et al.* (1974)	Fresh frozen	5 mm slabs	0.785 cm^2 indenter	Strength 1.8–63.6 MPa
Lindahl (1976)	Dried defatted	0 mm × 14 mm × 9 mm	Uniaxial stress	Strength 0.2–6.7 MPa Modulus 1.4–79 MPa
Carter and Hayes (1977)	Fresh frozen	10.3 mm dia. 5 mm length	Uniaxial strain Variable strain rate	Strength 1.5–45 MPa Modulus 10–500 MPa
Williams and Lewis (1982)	Dried defatted	5–6 mm cubes	Rewetted Orthogonal preyield Uniaxial stress	Strength 1.5–6.7 MPa Modulus 8–457 MPa
Goldstein *et al.* (1983)	Fresh frozen	7 mm diameter 10 mm length	Uniaxial Stress	Strength 1–13 MPa Modulus 4–430 MPa
Hvid and Hansen (1985)	Fresh frozen	5 mm slabs	2.5 mm needle indenter	Strength 13.8–116.4 MPa
Ciarelli *et al.* (1986)	Fresh frozen	8 mm cubes	Orthogonal preyield Uniaxial stress	Strength 0.52–11 MPa Modulus 5–552 MPa
Distal femur				
Pugh *et al.* (1973)	Fresh frozen	9.5 mm diameter 5 mm length	Uniaxial stress Elastic and viscoelastic	Modulus 413–1516 MPa
Behrens *et al.* (1974)	Fresh frozen	5 mm slab	0.785 cm^2 indenter	Strength 2.25–66.2 MPa
Ducheyne *et al.* (1977)	Fresh frozen	5 mm diameter 8 mm length	Uniaxial stress Variable strain rate	Strength 0.98–22.5 MPa Modulus 58.8–2942 MPa
Ciarelli *et al.* (1986)	Fresh frozen	8 mm cubes	Orthogonal preyield Uniaxial stress	Strength 0.56%18.6 MPa Modulus 7.6–800 MPa
Proximal femur				
Hardinge (1949)	Fresh	0.25 inch diameter 0.25 inch length	Crushing test	Failure 105–382 lb
Evans and King (1961)	Embalmed	2.5 × 0.79 cm prisms 0.79 cm cubes	Uniaxial stress	Stength 0.21–14.82 MPa Modulus 20.68–965 MPa
Schoenfeld *et al.* (1974)	Fresh	4.8 mm diameter 9.5 mm length	Uniaxial stress 37°C	Strength 0.15–13.5 MPa Modulus (ave.) 344.7 MPa
Brown and Ferguson (1980)	Fresh frozen	5 mm cubes	Orthogonal preyield Uniaxial stress	Strength 120–310 MPa Modulus 1000–9800 MPa
Martens *et al.* (1983)	Fresh frozen	8 mm diameter 10 mm length	Uniaxial stress	Strength 0.45–15.6 MPa Modulus 58–2248 MPa
Ciarelli *et al.* (1986)	Fresh frozen	8 mm cubes	Orthogonal preyield Uniaxial stress	Strength 2.1–16.2 MPa Modulus 49–572 MPa
Vertebral bodies				
Weaver and Chalmers (1966)	Fresh frozen	1 cm cube	Uniaxial stress	Strength 0.34–7.72 MPa
Galante *et al.* (1970)	Fresh	7,10 mm diameter 10 mm length	Uniaxial stress Two strain rates	Strength 0.39–5.98 MPa
McElhaney *et al.* (1970)	Fresh	Variable	Uniaxial stress	Ave. strength 4.13 MPa Ave. modulus 151.7 MPa
Lindahl (1976)	Dried defatted	10 × 9 × 14 mm	Uniaxial stress	Strength 0.3–7.0 MPa Modulus 1.1–139 MPa
Struhl *et al.* (1987)	Fresh frozen	8 and 6 mm cubes	Orthogonal preyield Uniaxial stress	Strength 0.06–15 MPa Modulus 10–428 MPa
Ashman *et al.* (1986)	Fresh	5 mm diameter 10–15 mm length	Ultrasound	Ave. elastic modulus 158–378 MPa Ave. shear modulus 58–89 MPa
Keller *et al.* (1987)	Fresh frozen	1 cm cubes	Uniaxial stress	Modulus 15–30 MPa

Table 1. (*Contd.*)

Region	Storage method	Specimen configuration	Comments	Properties
Patella				
Townsend *et al.* (1975)	Fresh	5.5–10 mm cubes	Orthogonal moduli	Moduli 121.3–580 MPa
			Uniaxial stress	
Distal tibia and talus				
Hvid and Hansen (1985)	Fresh frozen	5 mm slabs	2.5 mm diameter indenter	Strength 5–65 MPa
Calcaneus				
Weaver and Chalmers (1966)	Fresh frozen	1 cm cubes	Uniaxial stress	Strength 0.34–10.34 MPa
Humerus, distal radius				
Ciarelli *et al.* (1986)	Fresh frozen	8 mm cubes	Orthogonal preyield	Strength 0.03–6.3 MPa
			Uniaxial stress	Modulus 1.1–448 MPa
Iliac crest				
Struhl *et al.* (1987)	Fresh frozen	6 or 8 mm cubes	Orthogonal preyield	Strength 0.12–8.2 MPa
			Uniaxial stress	Modulus 5–282 MPa

Table 2.

Investigators	Region	Relationship	Density measures
Weaver and Chalmers (1966)	Vertebral Calcaneal	Linear	Ash weight
Galante *et al.* (1970)	Vertebral	Linear	Real density Apparent density
McElhaney *et al.* (1970)	Cranial bone	Power	Apparent density
Behrens *et al.* (1974)	Distal femur Proximal tibia	Linear	Bulk density
Schoenfeld *et al.* (1974)	Proximal femur	Linear	Apparent density
Hayes and Carter (1976)	Bovine distal femur	Power	Apparent density
Lindahl (1976)	Vertebral	Linear	Apparent density
Carter and Hayes (1977)	Tibial plateau	Power	
Ducheyne *et al.* (1977)	Distal femur	Linear	Wet and dry Bulk density
Carter *et al.* (1980)	Proximal/distal femur	Power	Apparent density
Martens *et al.* (1983)	Proximal femur	Linear	Bulk density Bone mineral content
Stone *et al.* (1983)	Bovine humeri	Power	Apparent density
Kaplan *et al.* (1985)	Bovine humeri	Power	Apparent density
Ciarelli *et al.* (1986)	Distal femur Proximal femur Proximal tibia Proximal humerus Distal radius	Linear	Apparent density Ash weight

The relationship between the mechanical properties and density of trabecular bone have been evaluated in many investigations. Although the order of these correlations varied, each explained significant proportions of the variance in the data.

(1969) in rigid, cellular plastics, Gibson *et al.* (1981) in cellular materials, and Gibson (1985) in trabecular bone, support the concept of these power relationships relating to deformation patterns in the cellular substructure.

Despite these analytical arguments, the inconsistency in experimental results provides strong evidence of the importance of factors other than density contributing to the mechanical properties of trabecular bone. As with any anisotropic material, the organization of the material components may be more important than the absolute amount of the material present. This obvious dependence of material properties on the architecture of trabecular bone has been noted by virtually all investigators involved in trabecular bone research. The difficulty in characterizing its complex, three-dimensional architecture has severely limited the development of algorithms relating this architecture to its subsequent material properties.

ARCHITECTURAL MEASURES OF TRABECULAR BONE

Most of the earlier work on quantifying the architecture of trabecular bone was summarized in a paper by Hayes and Snyder (1981). Hayes and Snyder, as well as most current investigators, have advanced these earlier techniques through the use of digital analysis algorithms and refined imaging processes.

The emphasis of present investigations is to correlate the influence of morphologic and architectural measures on the material properties of trabecular bone. These correlations are becoming increasingly important as investigators proceed with studies designed to document architectural changes associated with adaptations of bone as a consequence of degenerative joint diseases, total joint arthroplasty, metabolic diseases and treatments, and fractures. It is assumed by most investigators that the architecture of trabecular bone exists as a physiologic optimization maintaining mechanical integrity while minimizing bone mass. Determining the relative contributions of the architectural components to the overall structural properties may provide support for hypotheses relating to the optimization criteria and perhaps the mechanisms fundamental to bone resorption or formation.

Studies by Raux *et al.* (1975), Pugh *et al.* (1973), and Townsend *et al.* (1975) began to investigate the effects of anisotropy, connectivity, as well as morphologic measures (trabecular plate thickness, trabecular plate separation) on the structural properties of trabecular bone. Harrigan and Mann (1984) drawing on the fundamentals of stereology demonstrated that the microstructural anisotropy of orthotropic materials (trabecular bone) could be characterized by a second rank tensor. In subsequent studies, the second rank tensor expression was found to be a good measure of the structural anistropy of trabecular bone and preliminary correlations to elastic properties were formulated (Harrigan and Mann, 1984; Cassidy and Davy, 1985; Cowin, 1985). Predictions of elastic moduli from two-dimensional stereologic techniques (Henshaw *et al.*, 1986) are continuing. In addition, algorithms using morphologic, connectivity and anisotropy measures from three-dimensional digitizations of trabecular bone are also being evaluated (Goldstein *et al.*, 1986).

TRABECULAR TISSUE PROPERTIES

As our sophistication in experimental and analytical techniques investigating the physiologic and mechanical behaviour of trabecular bone as a continuum material increases, the properties of trabecular tissue at a microstructural level are becoming increasingly important. Many investigators utilizing structural models to describe the mechanical behavior of trabecular bone assumed that the trabecular tissue possessed the same physical properties as cortical bone (Beaupre and Hayes, 1985; McElhaney, *et al.*, 1970; Pugh *et al.*, 1973; Townsend *et al.*, 1975). Although the predictive accuracy of these models may depend heavily on inclusion of appropriate tissue material properties, few data were available to support or refute this assumption. Townsend *et al.* (1975) experimentally demonstrated in a buckling study of single human trabeculi, that the modulus of trabecular tissue was very near that of cortical bone. Contradictory evidence has also been reported which suggests that trabecular tissue modulus is considerably less than cortical tissue modulus (Gong *et al.*, 1964; Williams and Lewis, 1982). Ryan and Williams (1986) reported experimental modulus values an order of magnitude less than cortical tissue. Two recent studies have attempted to address this unresolved subject. Mente and Lewis (1987) described a combined analytical and experimental methodology utilizing irregularly shaped trabeculi to determine the elastic modulus. Ku *et al.* (1987) described an experimental protocol utilizing micromachined beams of trabecular bone to determine the mechanical properties of trabecular tissue. Both studies demonstrated a similar range of moduli between 3 and 5 GPa, 0.2–0.5 the values reported for cortical bone.

SUMMARY

It is clear that our understanding of the mechanical behavior of trabecular bone significantly increased during the past two decades, paralleling the growth of the field of bone biomechanics and orthopaedic science. The clinical and technological advances in artificial joint replacement both benefited from and inspired the intense effort in characterizing the bone architecturally and mechanically. These past studies, as well as continuing work, have significantly increased the accuracy of analytical and experimental models investigating the effects of metabolic and degenerative diseases and their treatments as well as enhanced our perspective towards understanding the factors which may influence bone formation or resorption.

Many of us are indebted to the pioneering studies of early investigators. I personally have had the great privilege and honor of learning from and working with F. Gaynor Evans, during his tenure at the University of Michigan. It is the dedication, perceptiveness and originality of individuals such as Dr Evans that shape the personality of the investigators and the investigations that follow.

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