ELSEVIER

Journal of Biomechanics 33 (2000) 1325–1330

JOURNAL
OF
BIOMECHANICS

www.elsevier.com/locate/jbiomech

Technical note

Critical evaluation of known bone material properties to realize anisotropic FE-simulation of the proximal femur

Dieter Christian Wirtz[a],*, Norbert Schiffers[a], Thomas Pandorf[b], Klaus Radermacher[c], Dieter Weichert[b], Raimund Forst[a]

[a]*Department of Orthopaedic Surgery, University of Technology Aachen, Paulwelsstr 30, 52074 Aachen, Germany*
[b]*Institute of Mechanics, University of Technology Aachen, Germany*
[c]*Helmholtz-Institute of Biomedical Engineering at the University of Technology Aachen, Germany*

Accepted 6 March 2000

Abstract

Purpose: In a meta-analysis of the literature we evaluated the present knowledge of the material properties of cortical and cancellous bone to answer the question whether the available data are sufficient to realize anisotropic finite element (FE)-models of the proximal femur. *Material and method*: All studies that met the following criteria were analyzed: Young's modulus, tensile, compressive and torsional strengths, Poisson's ratio, the shear modulus and the viscoelastic properties had to be determined experimentally. The experiments had to be carried out in a moist environment and at room temperature with freshly removed and untreated human cadaverous femurs. All material properties had to be determined in defined load directions (axial, transverse) and should have been correlated to apparent density (g/cm^3), reflecting the individually variable and age-dependent changes of bone material properties. *Results*: Differences in Young's modulus of cortical [cancellous] bone at a rate of between 33% (58%) (at low apparent density) and 62% (80%) (at high apparent density), are higher in the axial than in the transverse load direction. Similar results have been seen for the compressive strength of femoral bone. For the tensile and torsional strengths, Poisson's ratio and the shear modulus, only ultimate values have been found without a correlation to apparent density. For the viscoelastic behaviour of bone only data of cortical bone and in axial load direction have been described up to now. *Conclusions*: Anisotropic FE-models of the femur could be realized for most part with the summarized material properties of bone if characterized by apparent density and load directions. Because several mechanical properties have not been correlated to these main criteria, further experimental investigations will be necessary in future. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Bone material properties; Bone density; Proximal femur; Orthotropy; Finite element model

1. Introduction

In order to simulate the reactions of bone to physiological and non-physiological load conditions multiple computer-aided finite element models of the proximal femur have been generated since the mid-1970s (Andriacchi et al., 1976; Svensson et al., 1977; Rohlmann et al., 1980,1982,1983; Huiskes et al., 1989). Although many previous studies had clearly demonstrated the anisotropic behaviour of bone (Dempster and Liddicoat, 1952; Bargren et al., 1974; Martens et al., 1983; Goulet et al., 1994), all FE-simulations that have been developed so far have assumed isotropic material properties without exception.

Besides the numerical problems of anisotropic simulation of bone remodelling (Beaupré et al., 1990; Jacobs et al., 1997), the main reason for this exclusive assumption of isotropic conditions in bony FE-models has been the lack of a comprehensive data bank incorporating the material properties of bone as a function of the orthotropic load directions.

Therefore, it was the aim of this study to summarize the present knowledge in the literature about the direction-dependent material properties of cortical and cancellous femoral bone. In addition, we tried to answer the question whether these data are sufficient to develop and feed anisotropic FE-models of the proximal femur.

2. Materials and methods

A survey of more than 300 published studies which investigated experimentally the following material

---

*Corresponding author. Tel.: +49-241-8089410; fax: +49-241-8888453.

PII: S0021-9290(00)00069-5

properties of human cadaverous femurs were analyzed:

1. Young's modulus
2. Compressive strength, tensile strength and torsional strength
3. Shear modulus
4. Poisson's ratio
5. Viscoelastic behaviour

As inclusion criteria of this evaluation all investigations had to be carried out on freshly extracted cadaverous femurs, in a moist environment and at body temperature. Additionally, studies were also accepted where femurs had been frozen at a minimum of $-20°C$ directly after removal and had been investigated at room temperature (causing no alteration of material properties (Sedlin and Hirsch, 1966; Linde and Sorensen, 1993)).

Since a definite correlation has been found between changes of material properties, bone density and age of cortical and cancellous femoral bone (Schmitt, 1968; Burstein et al., 1976; Viano et al., 1976; Knauβ, 1981a), the assumption is justified, that the individually variable and age-dependent changes of bone are largely characterized by bone density. Therefore, all studies included in our analysis referred their reported material properties to bone density measurements made by quantitative computertomography (QCT), weight or volumetric determinations.

Bone densities measured via CT-scan and weight were converted into volumetric bone densities (g/cm^3) by the method of Lotz et al. (1990). Thus, all given details about bone density were defined as apparent density (mass of mineralized bone divided by bulk volume including porous surface).

To account for the orthotropy of bone, all analyzed experiments had to be carried out in defined load directions. The axial direction had to be defined according to the Haversian osteons of the cortical bone and according to the spatial main direction of the trabecular structures within the samples of cancellous bone. In addition, the transverse axis had to be positioned perpendicular to this anatomically well-defined axial direction.

On the basis of these data the average values of the analyzed material properties were calculated in correlation with apparent density and separated for cortical and cancellous bone. The mean value plots were approximated by power-law-type functions, which might be used in any numerical application.

3. Results

3.1. Young's modulus

The Young's modulus of cortical bone is a function of density. For this reason, cortical bone must be considered an inhomogeneous material (Rauber, 1896; Knese et al., 1956; Schmitt, 1968). Fig. 1 shows differences of Young's modulus of cortical bone between 33% (at low apparent densities; 1.5 g/cm^3) and 62% (at high apparent densities; 2 g/cm^3) higher in the axial than in the transverse load directions.

Similar results have been found in the case of cancellous bone (Fig. 2). Here, apparent density-related Young's modulus in the transverse direction differs by between 58 and 80% below the average values of the corresponding axial direction.

In order to be able to predict changes in the relationship between Young's modulus and apparent density as a function of the load direction between the axial and transverse orthotropic axes, the decrease of the relative values of Young's modulus is shown versus load direction between 0° (axial) and 90° (transversal) (Fig. 3). The graphs exhibit an almost linear decrease of the relative values of Young's modulus of about 55% for the axial relative to the transverse load direction.

3.2. Compressive strength, tensile strength and torsional strength

The compressive strength of cortical and cancellous bone rises with increased apparent density (Fig. 4). At low apparent densities (0.1–0.3 g/cm^3), the average values of compressive strength of cancellous bone in the transverse direction exceed the corresponding values in the axial load direction. This is probably because at these low apparent densities measurements might be more inaccurate and orientation among the trabeculae less measurable.

Data concerning the tensile and torsional strength of cortical bone have not been correlated with bone density (tensile strength: ~ 150 MPa; torsional strength: 49–68 MPa) (Lindahl and Lindgren, 1967a,b; Simkin et al., 1971; Vinz, 1972; Wall et al., 1972; Reilly et al., 1974; Saito, 1983). In the case of cancellous bone, Carter et al. (1980) found a linear correlation between apparent density and the tensile strength (0.2 $g/cm^3 \sim 3$ MPa; 0.5 $g/cm^3 \sim 15$ MPa). Although these data do not exactly fit the criteria for inclusion in our study (experiments were performed with dried and rewetted specimens of cancellous bone from proximal and distal femora), it seems to be justified to mention these important experimental findings. In contrast, details about the torsional strength of cancellous bone are not available in the literature.

3.3. Shear modulus

According to experiments by Martens et al. (1981/1983), the shear modulus of cortical femoral bone is assumed to be between 2840 and 4040 MPa (average: 3280 MPa). These results were confirmed by Reilly and

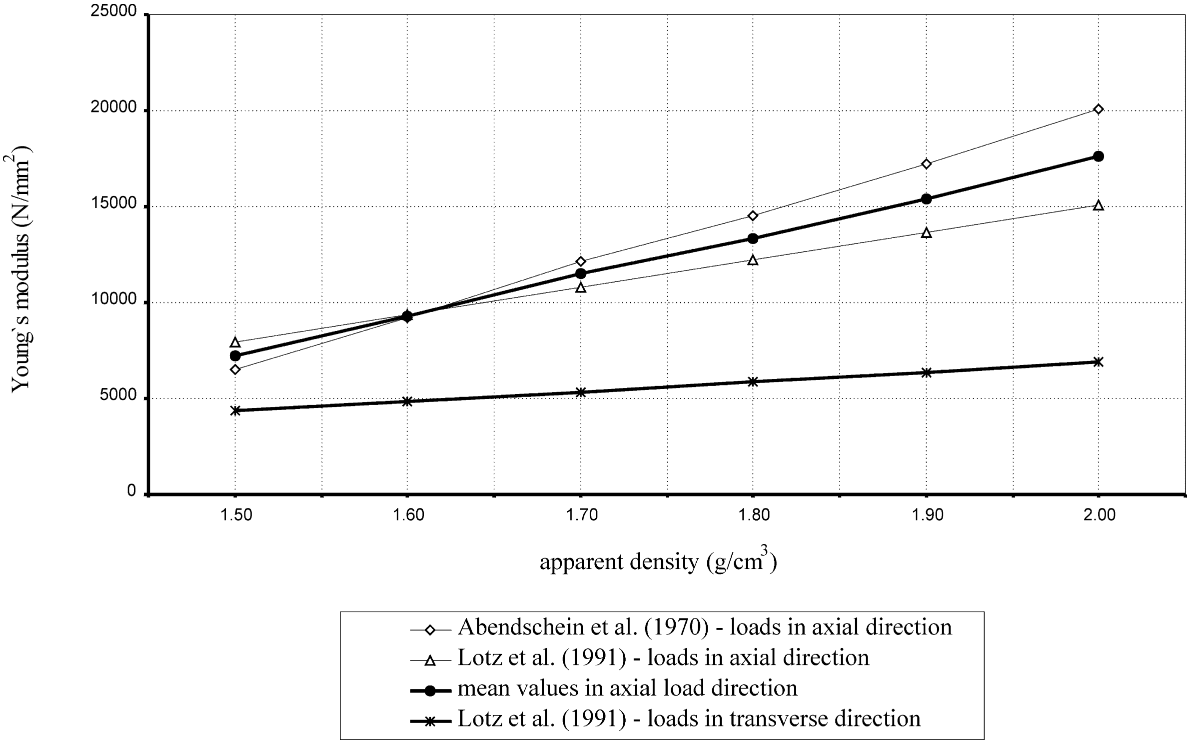

Fig. 1. Young's modulus-apparent density-relationship of cortical femoral bone in the axial and the transverse load directions. Only one literature reference (Lotz et al., 1991) considered and precisely quantified the dependence on apparent density in transverse load direction. The functional relations are approximated by $E = 2065\rho^{3.09}$ in the axial load direction, $E = 2314\rho^{1.57}$ in the transverse load direction.

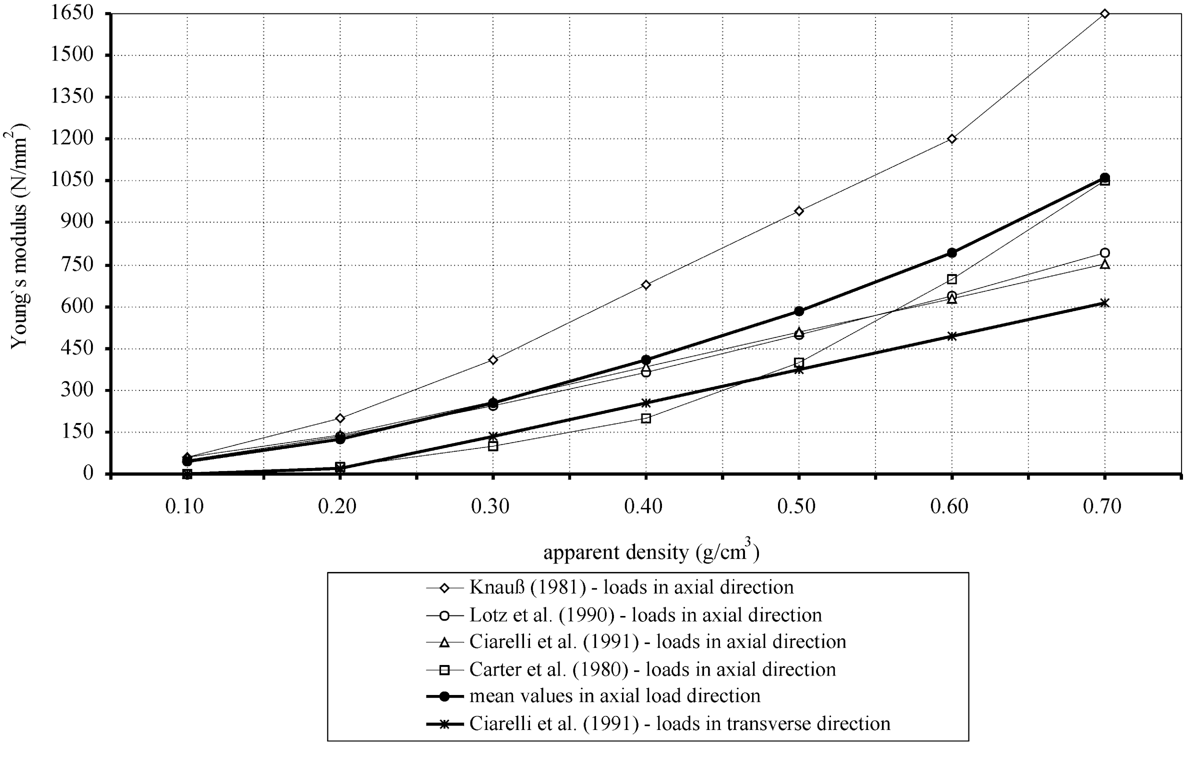

Fig. 2. Young's modulus–apparent density relationship of cancellous femoral bone in the axial and the transverse load directions. The functional relations are approximated by $E = 1904\rho^{1.64}$ in the axial load direction, $E = 1157\rho^{1.78}$ in the transverse load direction.

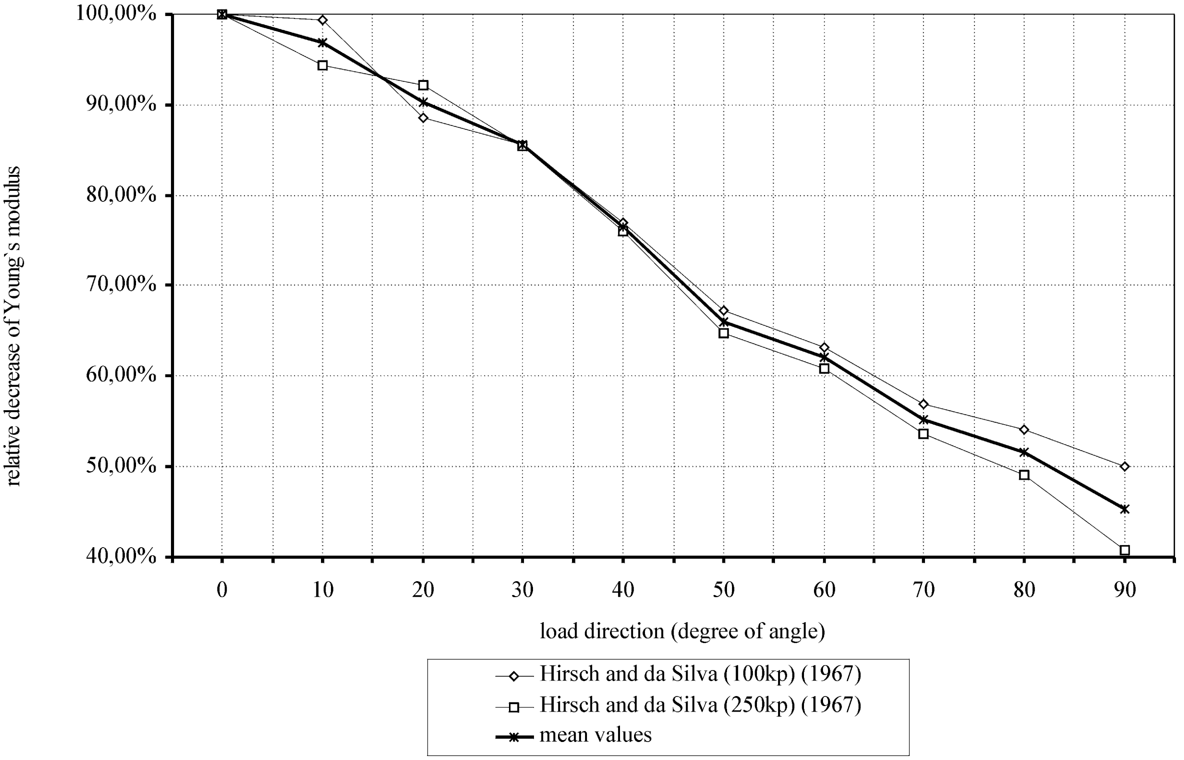

Fig. 3. Young's modulus of cortical femoral bone in relation to loads between the axial and the transverse directions. Hirsch and da Silva (1967) measured changes of Young's modulus with two different loads (100, 250 kp) between the axial (0°) and the transverse (90°) direction on human cadaverous femurs.

Burstein (1974) giving an average value of 3300 MPa. Data on different bone densities influencing the shear modulus have not been detected for cortical structures.

In contrast, shear modulus correlations with apparent density in cancellous bone were studied mainly by Knauβ (1981a). Although the measured values varied over a wide range, the shear modulus has to be assumed between 8 and 40 MPa for apparent densities between 0.1 and 0.8 g/cm^3. Taking the regression analysis of Knauβ (1981b) as a basis, the shear modulus is about 10–20% lower in the transverse plane than in the axial plane.

3.4. Poisson's ratio

Concerning Poisson's ratio of cortical and cancellous bone quite different data are presented in the literature. The cited values are between 0.2 and 0.5 (average: 0.3) for cortical bone and between 0.01 and 0.35 (average: 0.12) for cancellous bone depending on the prevailing study (Knauβ, 1981b; Reilly and Burstein, 1974; Ashman et al., 1984/1988). No details have been given about any correlation to bone density.

3.5. Viscoelasticity

Smith and Walmsley (1959) have already shown that human bone behaves in a viscoelastic way. This material behaviour of bone as a function of strain rate ε (1/s) and the apparent density ρ (g/cm^3) was quantified by Carter and Hayes (1976) using the formula

$$\sigma_b = 68\varepsilon^{0.06}\rho^2.$$

Here, σ_b describes the ultimate compressive strength. According to Carter and Hayes (1976), this mathematical relation is applicable for cortical as well as for cancellous bone. A distinction between the axial and the transverse load directions is not available in the literature so far.

4. Discussion

Although over the last 25 years multiple investigations were performed to determine the material properties of the proximal femur, definitive statements about the real in vivo behaviour of cortical and cancellous femoral bone are still impossible. This is mainly due to restrictions in ascertaining in vivo conditions in experimental work.

For constructing finite element models of bony structures, the apparent density-dependent characterization of material properties appears to be the most suitable way to consider individual and local variations as well as the dependence of bone on age. However, only for Young's modulus and the compressive strength of cortical and cancellous bone are sufficient apparent density-related

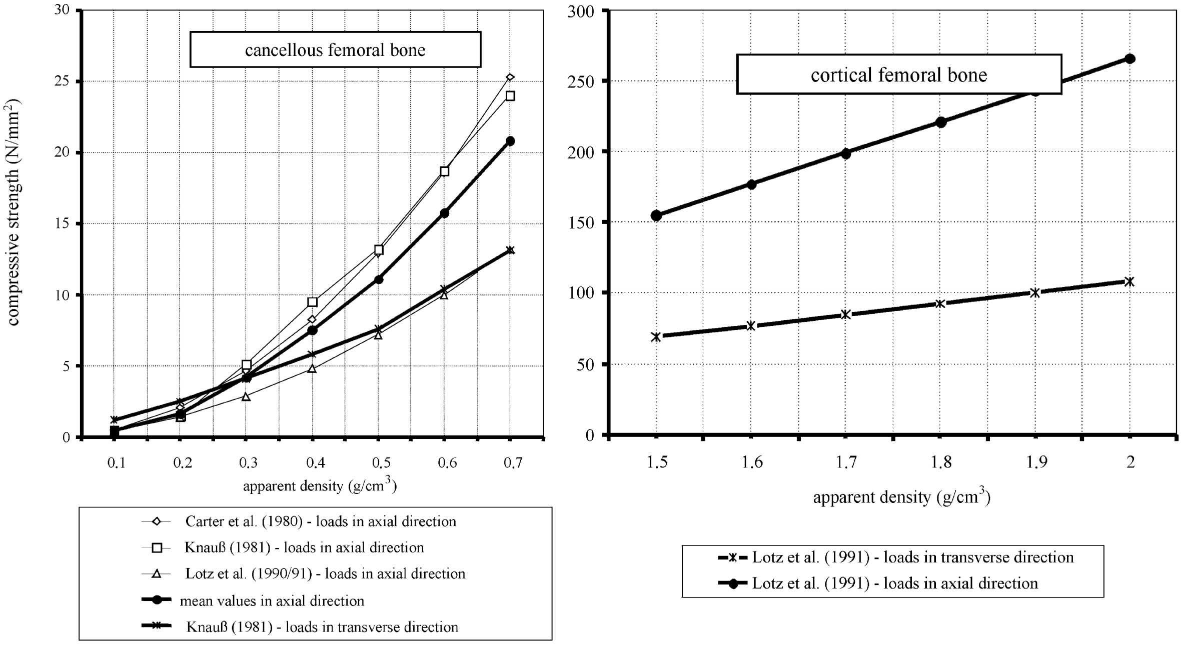

Fig. 4. Compressive strength–apparent density relationship of cortical and cancellous femoral bone in the axial and transverse load directions. Out of all studies only Lotz et al. (1991) reported about the compressive strength of cortical femoral bone in the axial and transverse load directions dependent on apparent density. For cortical femoral bone the functional relations are approximated by $\sigma_b = 72.4\rho^{1.88}$ in the axial load direction, $\sigma_b = 37\rho^{1.51}$ in the transverse load direction. For cancellous femoral bone the functional relations are approximated by $\sigma_b = 40.8\rho^{1.89}$ in the axial load direction, $\sigma_b = 21.4\rho^{1.37}$ in the transverse load direction.

data available in the literature. No correlation with bone density has been found for Poisson's ratio, the shear modulus and the torsional and tensile strength. Therefore, further investigations will be necessary in the future to give a comprehensive apparent density-dependent characterization of the bony material.

For anisotropic FE-modelling, the determination of bone material properties as a function of direction is the essential requirement (Besdo and Handel, 1994). In the literature, the mechanical behaviour of the bone has been sufficiently characterized in the axial as well as the transverse load directions. However, it is not possible to define predominant orientations for cortical nor for cancellous bone in the transverse plane. At least for the moment, this problem could be ignored by assuming transverse isotropy (Reilly and Burstein, 1974,1975; Katz and Meunier, 1987).

In conclusion, the development of an anisotropic finite element model of the proximal femur seems to be feasible on the basis of the present knowledge of bone material properties although there are limitations as mentioned above. Each finite element might be characterized by its apparent density (derived from QCT), its apparent density-dependent material properties (derived from this meta-analysis) and the privileged directions of its orthotropic axes (derived from the spatial orientation of trabeculae and the haversian osteons). Such a mathematical model has the potential to assist in the study of clinical questions, for example for the optimized planning of proximal femur osteotomies or for the evaluation of different types of total joint replacement systems.

References

Andriacchi, T.P., Galante, J.O., Belytschko, T.B., Hampton, S., 1976. A stress analysis of the femoral stem in total hip prosthesis. Journal of Bone and Joint Surgery 58-A, 618–624.

Ashman, R.B., Cowin, S.C., Van Buskirk, W.C., Rice, J.C., 1984. A continuous wave technique for the measurement of the elastic properties of cortical bone. Journal of Biomechanics 17, 349–361.

Ashman, R.B., Rho, J.Y., 1988. Elastic modulus of trabecular bone material. Journal of Biomechanics 21, 177–181.

Bargren, J.H., Andrew, C., Bassett, L., Gjelsvik, A., 1974. Mechanical properties of hydrated cortical bone. Journal of Biomechanics 7, 239–245.

Beaupré, G.S., Orr, T.E., Carter, D.R., 1990. An approach for time-dependent bone modeling and remodeling — theoretical development. Journal of Orthpaedic Research 8, 651–661.

Besdo, D., Handel, M., 1994. Numerical treatment of bone as anisotropic material. Biomedical Technology 39, 293–298.

Burstein, A.H., Reilly, D.T., Martens, M., 1976. Aging of bone tissue: mechanical properties. Journal of Bone and Joint Surgery 58-A, 82–86.

Carter, D.R., Hayes, W.C., 1976. Bone compressive strengh: the influence of density and strain rate. Science 194, 1174–1175.

Carter, D.R., Schwab, G.H., Spengler, D.M., 1980. Tensile fracture of cancellous bone. Acta Orthopaedica Scandinavica 51, 733–741.

Dempster, W.T., Liddicoat, R.T., 1952. Compact bone as a non-isotropic material. American Journal of Anatomy 91, 331–362.

Goulet, R.W., Goldstein, S.A., Ciarelli, M.J., Kuhn, J.L., Brown, M.B., Feldkamp, L.A., 1994. The relationship between the structural and orthogonal compressive properties of trabecular bone. Journal of Biomechanics 27, 375–389.

Hirsch, C., da Silva, O., 1967. The effect of orientation on some mechanical properties of femoral cortical bone specimens. Acta Orthopaedica Scandinavica 38, 45–56.

Huiskes, R., Weinans, H., Dalstra, M., 1989. Adaptive bone remodeling and biomechanical design considerations. Orthopedics 12, 1255–1267.

Jacobs, C.R., Simo, J.C., Beaupré, G.S., Carter, D.S., 1997. Adaptive bone remodeling incorporating simultaneous density and anisotropy considerations. Journal of Biomechanics 30, 603–613.

Katz, J.L., Meunier, A., 1987. The elastic anisotropy of bone. Journal of Biomechanics 20, 1063–1070.

Knauβ, P., 1981a. Material properties and strength behaviour of spongy bone tissue at the coxal human femur. Biomedical Technology 26, 200–210.

Knauβ, P., 1981b. Material properties and strength behaviour of the compact bone tissue at the coxal human femur. Biomedical Technology 26, 311–315.

Knese, K.H., Hahne, O.H., Biermann, H., 1956. Festigkeitsuntersuchungen am menschlichen Extremitätenknochen. Gegenbaurs Morphologisches Jahrbuch 96, 141–209.

Lindahl, O., Lindgren, A., 1967a. Cortical bone in man, I. Variation of the amount and density with age and sex. Acta Orthopaedica Scandinavica 38, 133–140.

Lindahl, O., Lindgren, A.G., 1967b. Cortical bone in man, II. Variation in tensile strengh with age and sex. Acta Orthopaedica Scandinavica 38, 141–147.

Linde, F., Sorensen, H.C., 1993. The effect of different storage methods on the mechanical properties of trabecular bone. Journal of Biomechanics 26, 1249–1252.

Lotz, J.C., Gerhart, T.N., Hayes, W.C., 1990. Mechanical properties of trabecular bone from the proximal femur: a quantitative CT study. Journal of Computer Assisted Tomography 14, 107–114.

Lotz, J.C., Gerhart, T.N., Hayes, W.C., 1991. Mechanical properties of metaphyseal bone in the proximal femur. Journal of Biomechanics 24, 317–329.

Martens, M., vanAudekercke, R., DeMeester, P., Mulier, J.C., 1981. The geometrical properties of human femur and tibia and their importance for the mechanical behaviour of these bone-structures. Archives of Orthopaedics and Trauma Surgery 98, 113–120.

Martens, R., Van Audekercke, R., Delport, P., DeMeester, P., Mulier, J.C., 1983. The mechanical characteristics of cancellous bone at the upper femoral region. Journal of Biomechanics 16, 971–983.

Rauber, A., 1896. Elastizität und Festigkeit der Knochen. Engelmann Press, Leipzig.

Reilly, D.T., Burstein, A.H., 1974. The mechanical properties of cortical bone. Journal Bone and Joint Surgery 56-A, 1001–1022.

Reilly, D.T., Burstein, A.H., Frankel, V.H., 1974. The elastic modulus for bone. Journal of Biomechanics 7, 271–275.

Reilly, D.T., Burstein, A.H., 1975. The elastic and ultimate properties of compact bone tissue. Journal of Biomechanics 8, 393–405.

Rohlmann, A., Bergmann, R., Kölbel, R., 1980. Finite element analysis, its limitations and the relevance of its results to orthopedic surgery as shown by simultaneous experimental measurements. Zeitschrift fuer Orthopadie 118, 122–131.

Rohlmann, A., Mössner, U., Bergmann, G., Kölbel, R., 1982. Finite-element-analysis and experimental investigation of stress in a femur. Journal of Biomedical Engineering 4, 241–246.

Rohlmann, A., Mössner, U., Bergmann, G., 1983. Finite-element-analysis and experimental investigation in a femur with hip endoprosthesis. Journal of Biomechanics 16, 727–742.

Saito, S., 1983. Distribution of density, pressure and tensile strength of the human femoral shaft. Anatomischer Anzeiger 154, 365–376.

Schmitt, H.P., 1968. On the relationship between density and strength of bone; examination of human femora. Zeistschrift fuer Anatomie und Entwicklungsgeschichte 127, 1–24.

Sedlin, E.D., Hirsch, H., 1966. Factors affecting the determination of the physical properties of femoral cortical bone. Acta Orthopaedica Scandinavica 37, 29–48.

Simkin, A., Makin, M., Menczel, J., Gordon, R., Naor, E., 1971. The mechanical properties and the porosity of femoral cortical bone in patients with fractured neck of femur. Israel Journal of Medical Science 7, 448–451.

Smith, J.W., Walmsley, R., 1959. Factors affecting the elasticity of bone. Journal of Anatomy 93, 503–523.

Svensson, N.L., Valliappan, S., Wood, R.D., 1977. Stress analysis of human femur with implanted Charnley prosthesis. Journal of Biomechanics 10, 581–588.

Viano, D., Helfenstein, U., Anliker, M., Rüegsegger, P., 1976. Elastic properties of cortical bone in female human femurs. Journal of Biomechanics 9, 703–710.

Vinz, H., 1972. Firmness of pure bone substance. Approximation method for the determination of bone tissue firmness related to the cavity-free cross section. Gegenbaurs Morphologisches Jahrbuch 117, 453–460.

Wall, J.C., Chatterji, S., Jeffery, J.W., 1972. Human femoral cortical bone: a preliminary report on the relationship between strength and density. Medical and Biological Engineering 10, 673–676.