Geometrical and mechanical properties of the human femur

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Several investigations on stress analyses of the intact human femur have been published in the literature (Koch, 1917; Brekelmans et al., 1972; Olofsson, 1975; Scholten, 1975; Valliapan et al., 1977; Rohlmann et al., 1979). Besides finite element methods, either two- or three-dimensional linear beam theory was applied.

It was the purpose of this paper to give some examples of the accuracy by which linear beam theory applies to the femur. The answer to this question is of importance for stress analyses of intramedullary bone-prosthesis structures (Huiskes, 1979).

METHODS

The right femur of a 52-yr-old male cadaver was embedded in acrylic and carefully cut in 27 slices. The slices of the diaphysis region were accurately measured. For each cross-section, the area, the principal axes of inertia, the principal moments of inertia and the polar (torsional) moment of interia were calculated. By using these data, stresses on the outside surface of the femur were calculated (using three-dimensional beam theory and assuming the bone material to be homogeneous) on loading of the femoral head with forces in three directions and couples in three planes. The results were compared to those of strain-gauge measurements on the left femur of the same cadaver (Huiskes et al., 1977). On the outside surface of the femur 112 rosette strain gauges were attached. Forces on the head in three directions and moments in three planes were applied in turn. The strain values were calculated to principal strains, principal stresses and equivalent stresses, assuming isotropy, homogeneity and linear elasticity

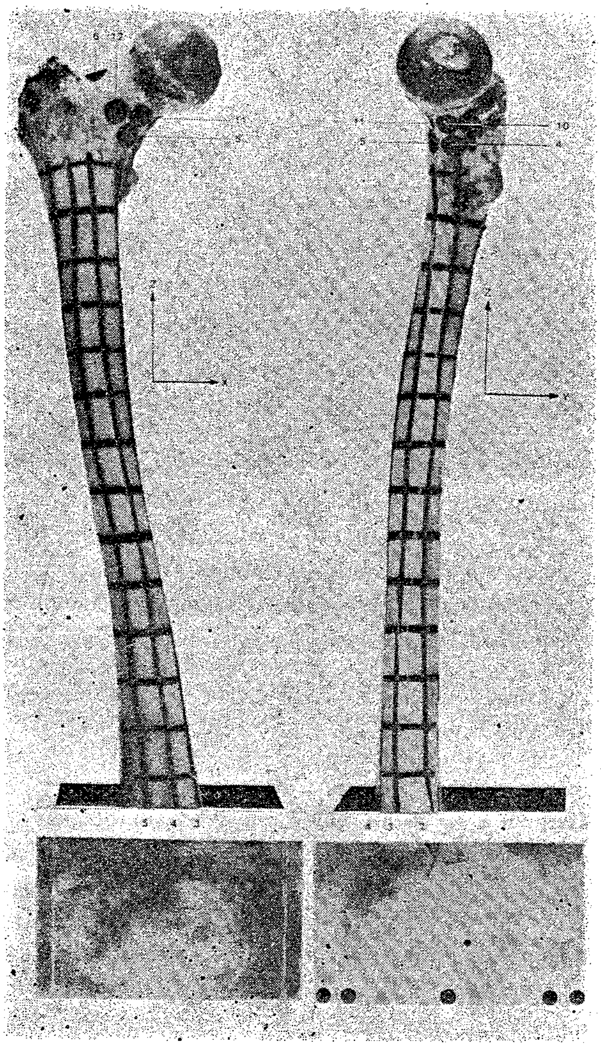

Figure 1. The (right) femur of the cadaver in anterior and medial view, respectively. The coordinate system is shown. The crossings of the black lines indicate where the strain-gauges (at the left femur) were applied. Strain gauges were applied at the neck also, but this has no relevance in this article.

(Young's modulus: 20,000 N/mm²: Poisson's ratio: 0.37). The (right) femur is shown in Figure 1.

RESULTS

The cross-sectional mechanical properties of the diaphysis region as calculated from the sliced femur are shown in Figure 2.

In the strain-gauge experiments, some viscoelastic behavior of the bone was evident; $3^1/_2$ min. after application of the load, the strains stabilized to constant values. The bone material behaved linear elastic, which can be concluded from comparing results of pure couple loading in negative and

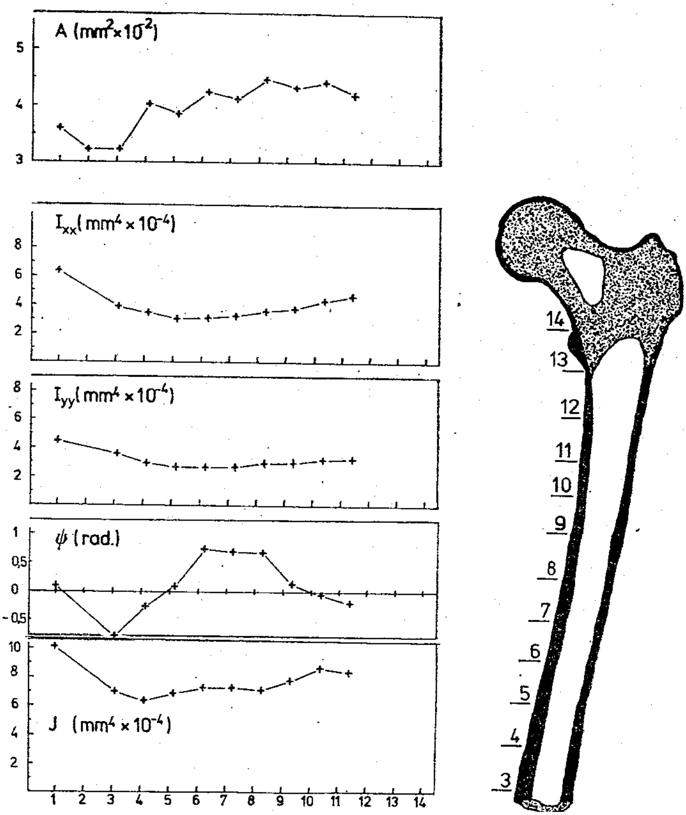

Figure 2. From top to bottom: Cross-sectional area (A), maximal principal moment of inertia (I_{xx}), minimal principal moment of inertia (I_{yy}), orientation of the principal inertia axes with respect to the *x-y* axes (ψ), polar moment of inertia (J), as calculated for the sliced femur.

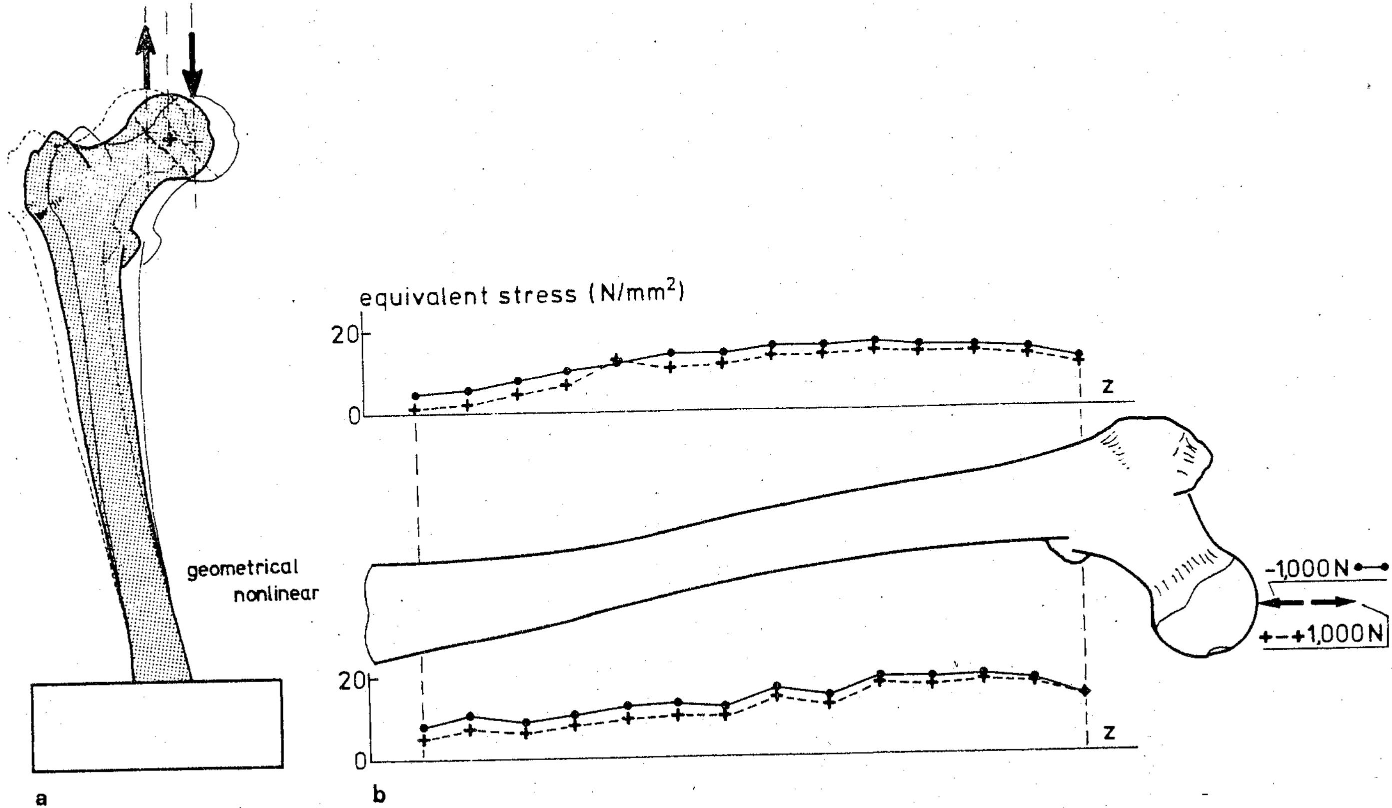

Figure 3. (a) Forces on the head in *z*-direction introduce an additional couple due to displacement of the head, resulting in geometrical nonlinearity. (b) Equivalent stresses at the lateral and the medial sides, as calculated from the strain-gauge measurements, on loading with a positive and a negative force in *z*-direction. Due to geometrical nonlinearity, the values are unequal.

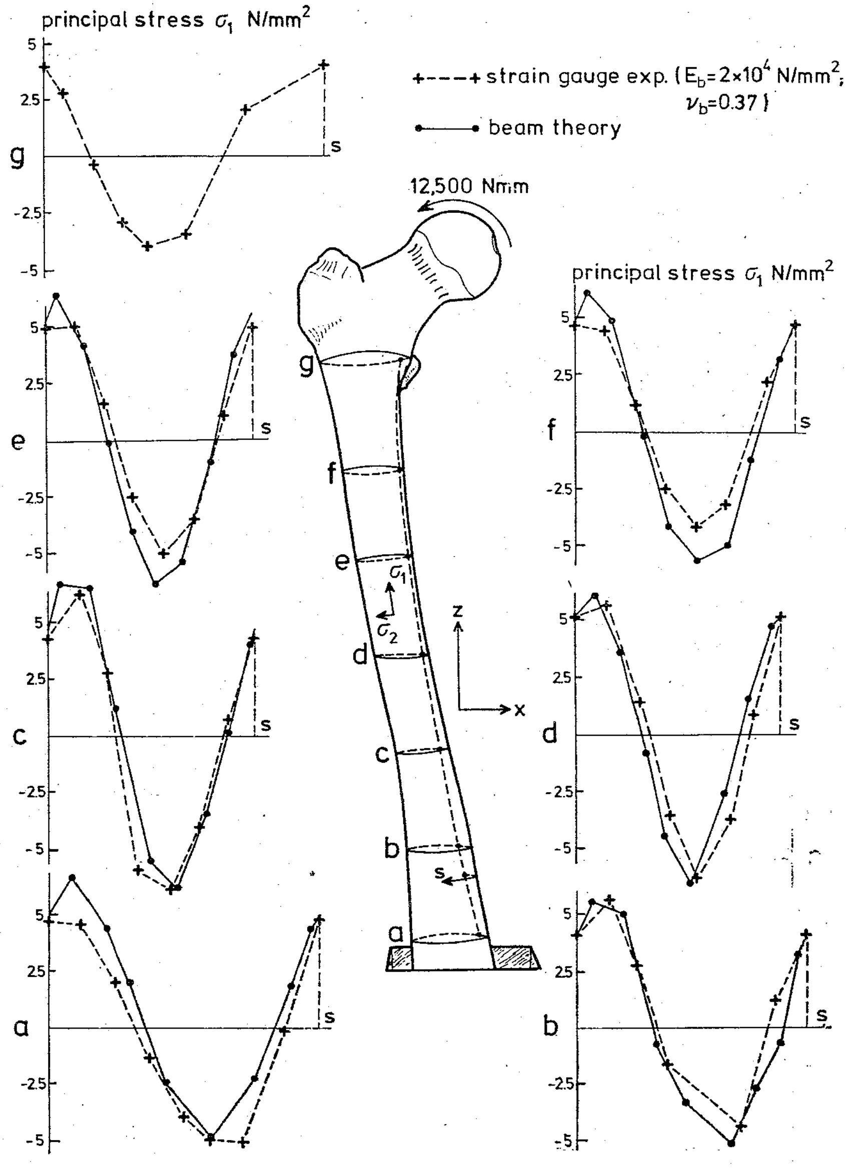

Figure 4. A comparison of maximal principal stresses on the outside of the femur, as calculated from the strain-gauge measurements (left cadaveric femur) and as calculated using beam theory on the basis of cross-sectional geometry data (right femur), on loading with a couple. The beam analysis did not extend further proximally than location f. The maximal principal stress direction is, with good approximation, in that of the femoral axis.

positive directions, which proved to be equal. On loading with a force in z-direction (Figure 3 a), an extra moment was introduced, due to a displacement of the point of application of the force (geometrical nonlinearity).

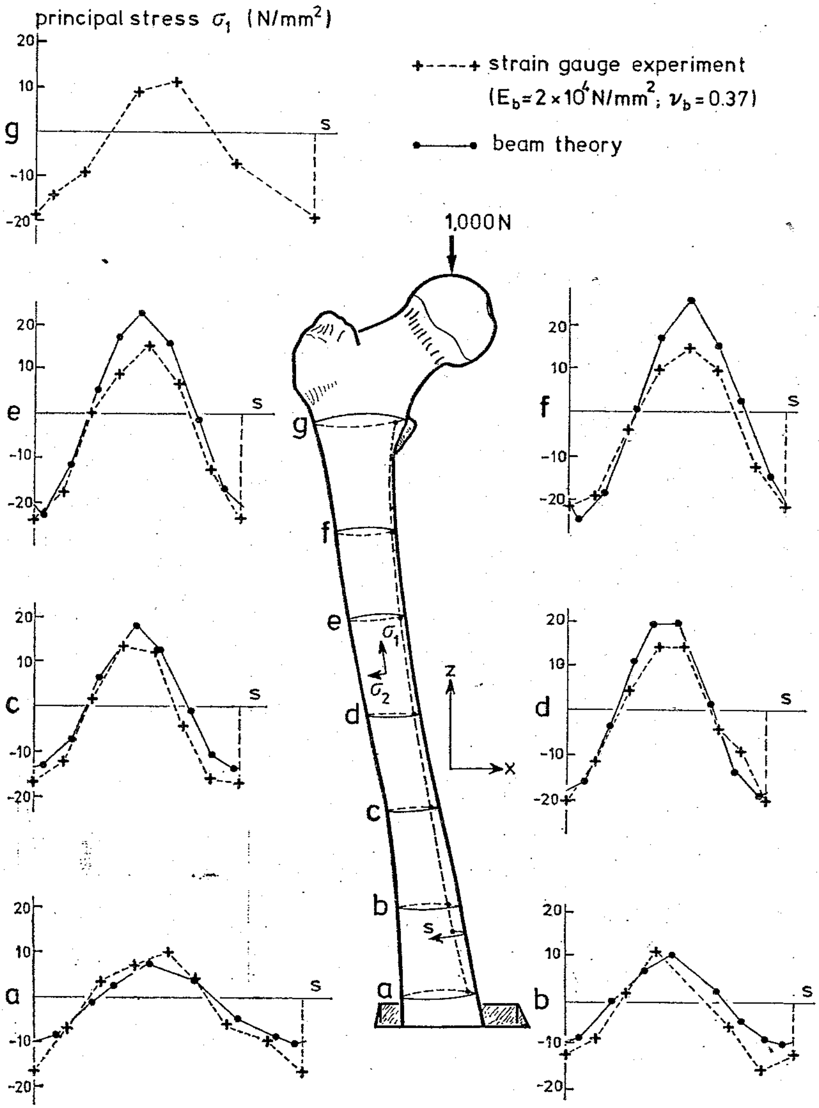

Figure 5. A comparison of maximal principal stresses, as calculated from the strain-gauge experiments and as calculated using beam theory, on loading with a force in negative z-direction.

Hence, stress (strain) values on loading with a force in the negative direction were not equal to those on opposite loading (Figure 3 b).

Figures 4 and 5 show comparisons of strain-gauge and beam-theory results, on loading with a moment and a force, respectively.

DISCUSSION

It is evident from Figures 4 and 5 that, at least for the diaphyseal region of the stem, linear beam theory is appropriate for the bone and gives a good approximation. The strain-gauge results in the proximal region suggest that here, too, beam theory could be used for reasonable approximations. It is remarkable, especially on loading with a pure couple, that although the cross-sectional area and the moment of inertia increased sharply in the metaphysis region, the strain values did not show a great variety over the length of the femur. This was due to the fact that the metaphysis region consists mainly of spongeous bone. These two phenomena combined result in a more-or-less homogeneous flexural stiffness over the entire length of the bone.

It should be noted that the assumed modulus of elasticity (20,000 N/mm^2) is only used for the experimental results, to calculate strains to stresses. The agreement between experimental and theoretical results hence reflects a good choice for this parameter.

ACKNOWLEDGMENTS

The experiments on which the results reported here are based were carried out between 1971 and 1974 at the Division of Applied Mechanics, Eindhoven University of Technology, The Netherlands, by various research fellows, technicians and students (F. v.d. Broek, P. v. Heugten, W. Laaper, J. Ijzermans and S. Zorge).

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