Stressanalysis of implanted knee joint prostheses with and without metal/cement bonding

H. J. GROOTENBOER
Twente University of Technology
Department of Mechanical Engineering

1 Introduction

In the last decennia the replacement of degenerated and infected joints by artificial ones has become a widely accepted treatment in orthopeadic surgery. In particular the replacement of the hip joint and the knee joint has gained wide application, and at this moment many different types of prostheses are offered by the industry.

The fixation of the artificial joint (prosthesis) to the bone is still one of the major problems in prosthesis design. Experience shows that 10–20 percent of the replaced joints are loosening in the first 5 years after implantation. In most of the cases this loosening is aseptic. This means that the loosening can not be ascribed to a bone or soft tissue infection but must be caused by a mechanical deterioration of the fixation. The fixation system of many joint prostheses consists of a stem which is anchored in the medullary canal by means of so-called bone cement (Fig. 1). This bone cement is made out of a powder of PMMA granules (poly methyl methacrylate) and a liquid monomer of MMA. After mixing, this cement is, when it is still viscous, introduced into the marrow cavity prior to the insertion of the prostheses. In about 10 minutes after mixing, the cement has fully cured. There is no chemical interaction between the metal of the prosthesis and the bone cement. Therefore the strength of the metal/cement interface is much lower than the strength of the individual materials. A de-bonding of the metal/cement connection is very likely to occur and can often be observed at reoperation and in autopsy specimen. When a metal/cement de-bonding takes place, the stress pattern in the configuration of prosthesis/cement/bone changes drastically.

The long term behaviour of an implanted prosthesis is greatly affected by the stresses in the surrounding bone. This is caused by the fact that bone as a living tissue adapts its density and strength to the load it has to carry. This functional adaptation or remodeling leads to an increased porosity (atrophy) in the case of an underloading and to an increased density (hypertrophy) in the case of overloading. The exact nature of the control parameters of this remodeling process are not yet fully known.

In this study the alteration of the stresses in the prosthesis/cement/bone configuration, when a de-bonding of the metal/cement interface takes place, is investigated.

The configurations considered are the tibial (shinbone) parts of a Sheehan knee joint prosthesis and of a GSB knee joint prosthesis (Fig. 2). The tibial part of both prostheses have a rather similar medullary stem, but a different design of the proximal part. This proximal part of the Sheehan prosthesis has the shape of a halve sphere while the proximal tibial part of the GSB prosthesis consists of a plate.

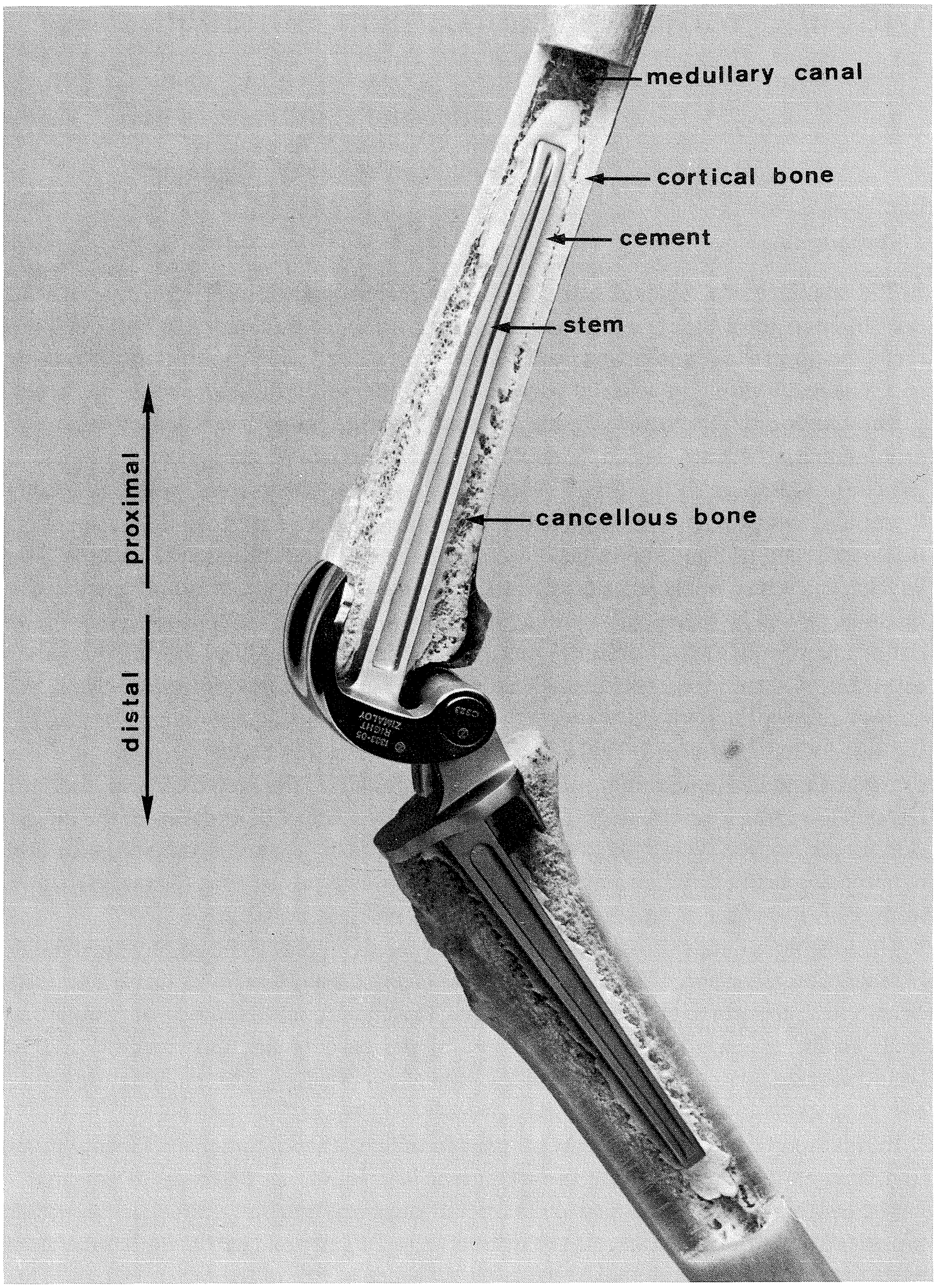

Fig. 1. Cutaway picture of a knee joint with prosthesis.

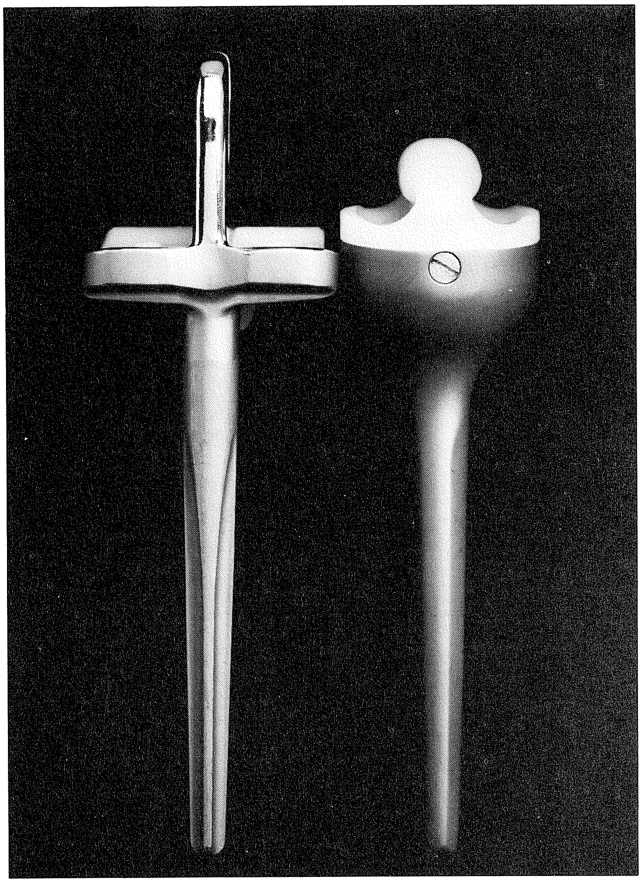

Fig. 2. Tibial part of a GSB (left) and of a Sheehan (right) knee joint prosthesis.

2 Analysis of the prosthesis/cement/bone complex

The stress analysis was done by a finite element discretisation. For this, the whole configuration was modelled as an axisymmetric form loaded by an axial force of 4000N on the proximal surface of the prosthesis. This corresponds to the results of several investigations, like Morrisson (1968, 1970) and Seireg and Arkivar (1975) who report for the maximum axial force in the knee joint at normal activities values between 4 and 7 times body weight. The solid ring elements used in the F.E.M. analysis were eight node isoparametric serendipity elements. Between the elements of the prosthesis and the elements of the bone cement special mixed type "contact elements" were placed. This element is capable of describing the various nonlinear and irreversible phenomena that can occur, such as adhesion fracture, gap opening and/or closing and sliding with Coulomb friction, including slip/stick effects at load reversal (see Klever 1984).

In Fig. 3 the finite element meshes for the tibial parts of the Sheehan and the GSB prosthesis are shown. Assuming full adhesion in the prosthesis/cement interface, Figs.

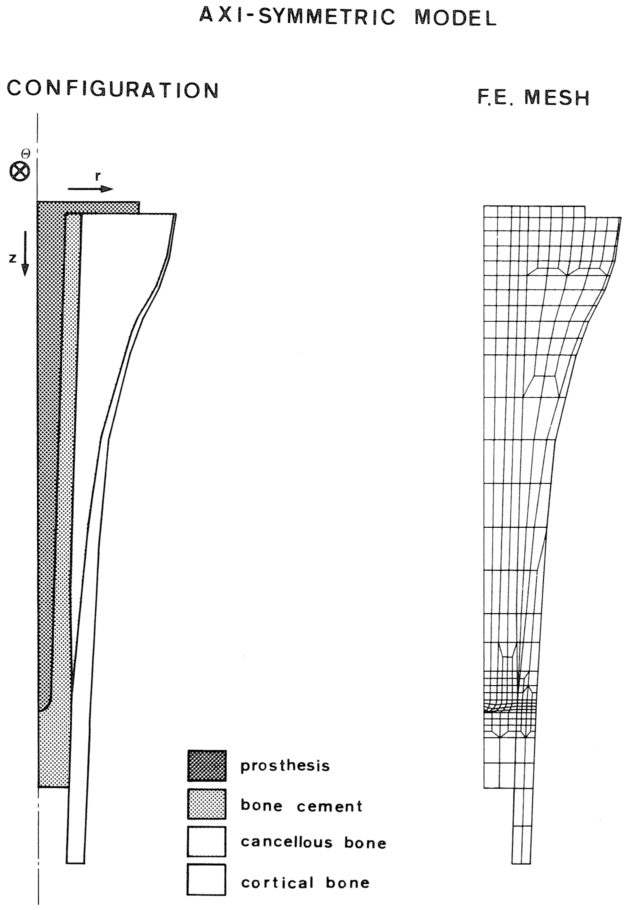

Fig. 3a. F.E. mesh Sheehan prosthesis.

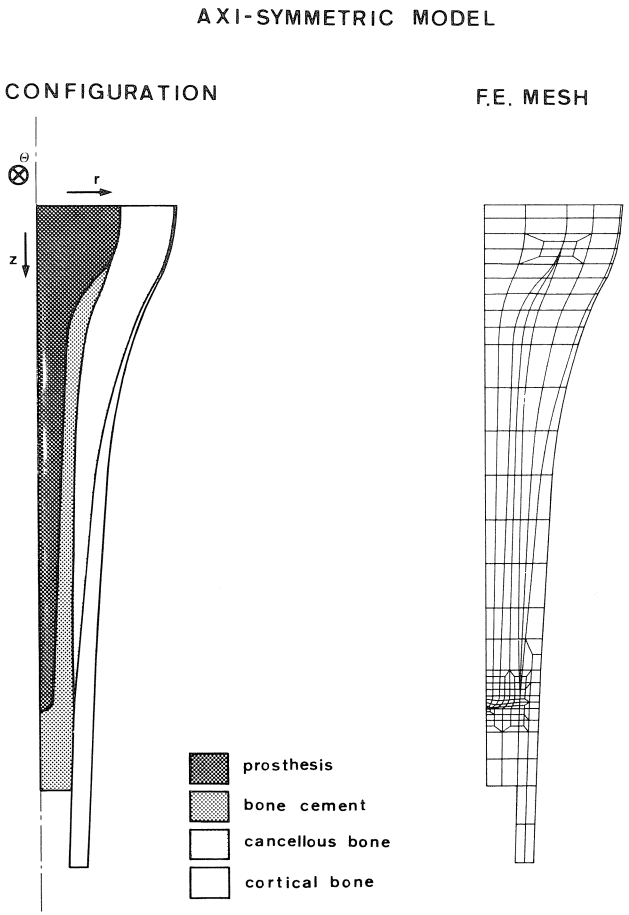

Fig. 3b. F.E. mesh GSB prosthesis.

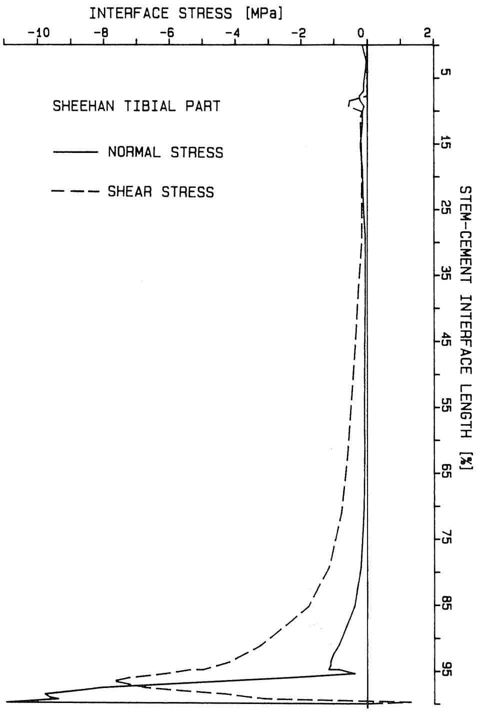

Fig. 4.

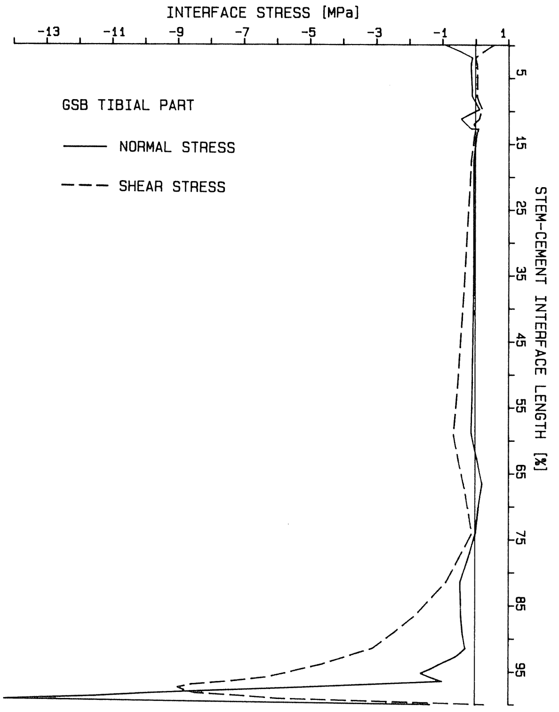

Fig. 5.

4 and 5 show the shear and normal stress in this interface for both prostheses. From these curves can be seen that the load transfer from the prosthesis to the surrounding cement for both prostheses mainly takes place in the distal part of the anchorage zone by means of shear stresses in the interface. The fact that the main part of the load is transferred by the prosthesis to the cement at the distal part of the prosthesis is illustrated by the percentage of the total axial load still present in the prosthesis stem at half length. This percentage is given in Table 1 and is for this bonded situation 75 and 70 percent. The shear stress at the prosthesis/cement interface reaches a maximum value

Table 1. LOAD TRANSFERRED BY THE LOWER HALF OF THE PROSTHESIS STEM

	PART OF THE LOAD	
INTERFACE CONDITION	SHEEHAN	GSB
BONDED	75 %	70 %
FRICTIONLESS	55	4
BONDED WITHOUT CEMENTPLUG	69	-
FRICTIONLESS WITHOUT CEMENTPLUG	4	-

of 7.7 resp. 9.0 MPa. These stresses are far above the shear strength of the metal/cement interface, which is about 2.5 MPa (Klumpert 1984). A shear fracture at this interface especially at the distal part of the prosthesis is therefore very likely to occur.

A de-bonding at the prosthesis/cement interface can also be seen at reoperations and in many autopsy specimen, accompanied by a thin layer of fibrous tissue between prosthesis and bone cement.

In order to examine the influence of such a de-bonding, both configurations were reanalysed with a model in which the contact zone between metal and cement was considered frictionless and only capable of transmitting contact pressure stresses (normal stresses). The distribution of these normal stresses in the prosthesis/cement interface in this frictionless case is depicted in Fig. 6. Now we can see a significant difference between the Sheehan and the GSB prosthesis. For the Sheehan, the normal stress at the distal end of the prosthesis is, compared to this stress for the bonded interface, ten times as large, while at that point for the GSB prosthesis the normal contact stress is for both situations approximately the same. This indicates that in the de-bonded situation the load transfer from the prosthesis to the surrounding material is essentially different for these two prostheses. This difference in load transfer can also be seen from Table 1. In the de-bonded situation, for the GSB prosthesis only a small percentage of the total load is transmitted at the distal part of the prosthesis to the surrounding material. The major-

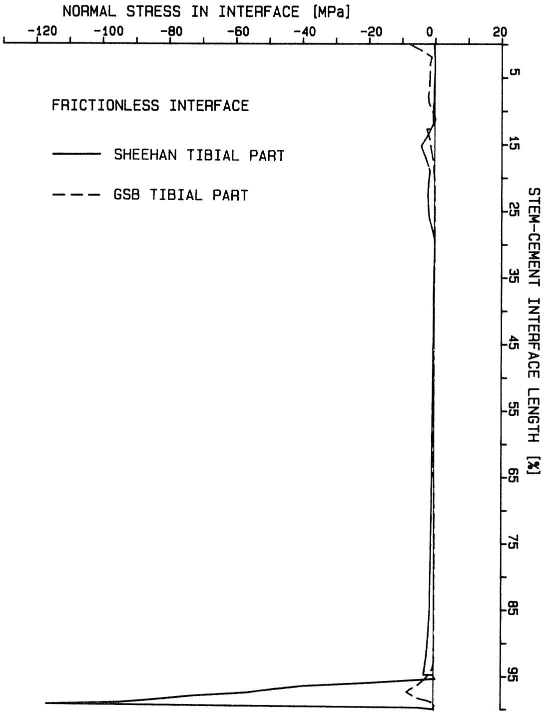

Fig. 6.

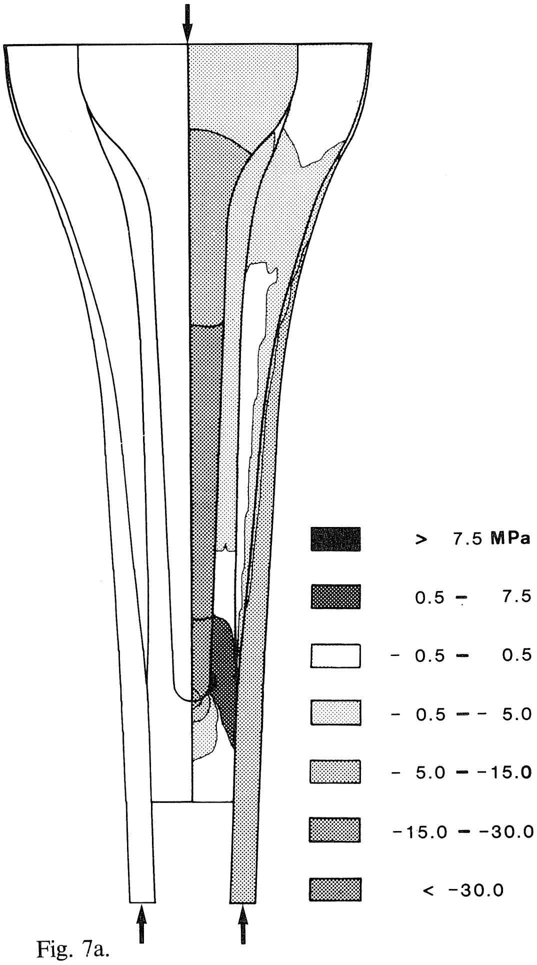

Fig. 7a.

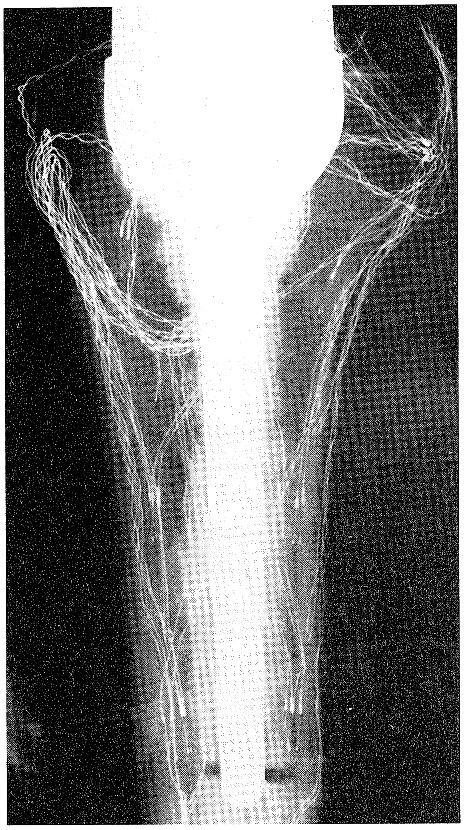

Fig. 7b.

Von Mises stresses in prosthesis-bone configuration.

ity of the load is now transferred by the proximal plate to the bone which gives a rather fysiological loading of the cancellous bone. The Sheehan prosthesis sinks into the cement and is mainly resting on the cementplug beneath the prosthesis.

This gives rise to high tensile stresses in the cement just above the tip of the prosthesis stem (Fig. 7a). These stresses can lead to cement fracture as can be seen on the X-ray picture in Fig. 7b. Would the cementplug beneath the Sheehan prosthesis stem be absent, then, after de-bonding of the metal/cement interface, the main part of the load is transferred from the prosthesis to the cement near the transition of the spherical part of the stem (Table 1).

3 Discussion

A perfect adhesion between prosthesis and cement for these types of prostheses is very unlikely and because of the unloading of the proximal bone perhaps also undesirable.

After a metal/cement de-bonding the Sheehan prosthesis gives much higher stresses in the cement than the GSB prosthesis, so cement fractures are more likely to occur. These fractures can lead to the fatal destruction of the anchorage system. The stresses in the proximal bone tissue of the tibia become very low after the implantation of a stem prosthesis. This can lead to serious bone atrophy. Only when the stem does not take part in the bearing of the axial load, this bone tissue is loaded in a way comparable with the situation in an untreated knee. For this case the GSB prosthesis leads to a more uniform loading of the cancellous bone while for the Sheehan prosthesis resting on its spherical tip the bone stresses are locally rather high (twice as high as before operation) which can lead to bone necrosis in that area. Although the process of bone remodelling is still not fully understood and prudence is ordered in the interpretation of histologic data and its relation to the results of a stress analysis, the study of the correspondence between the bone histology and the stresspatterns can contribute to our knowledge of the bone remodelling process due to the implantation of a joint endoprosthesis. To illustrate the remodelling around a prosthesis, the cross section of the proximal part of the left and right tibia of a person who had a guepar prosthesis for 1.5 years, are shown in Fig. 8. In Fig. 8a we see around the bonecement a zone of very low density cancellous bone and at the medial side a zone of high density cancellous bone acting as a strut between the prosthesis plate and the cortical bone of the tibia. This histological pattern corresponds very well with the Von Misses stress (calculated with a plane stress model) for this prosthesis with debonded stem-cement interface under axial load as shown in Fig. 9.

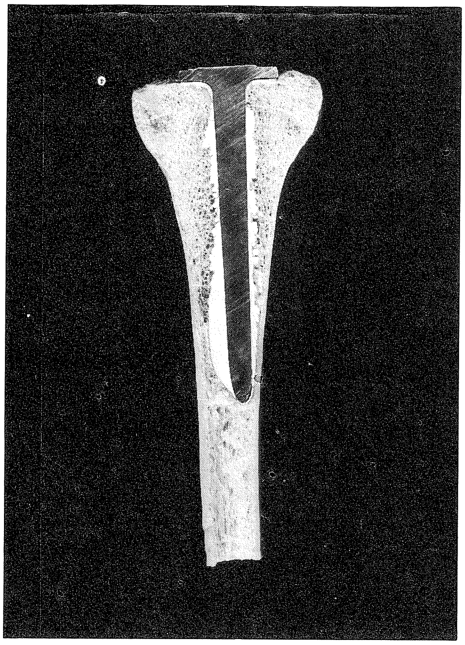

Fig. 8a.

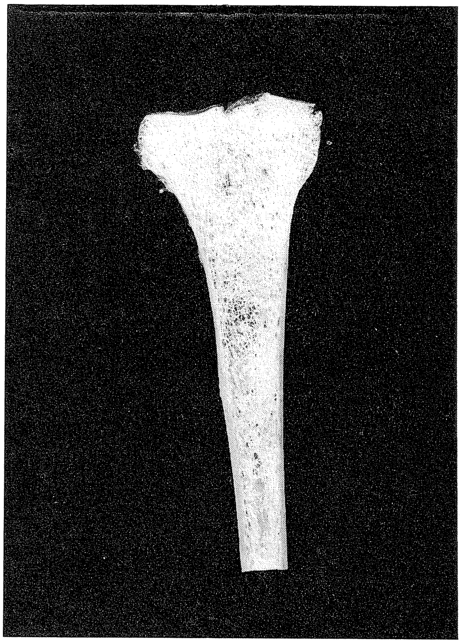

Fig. 8b.

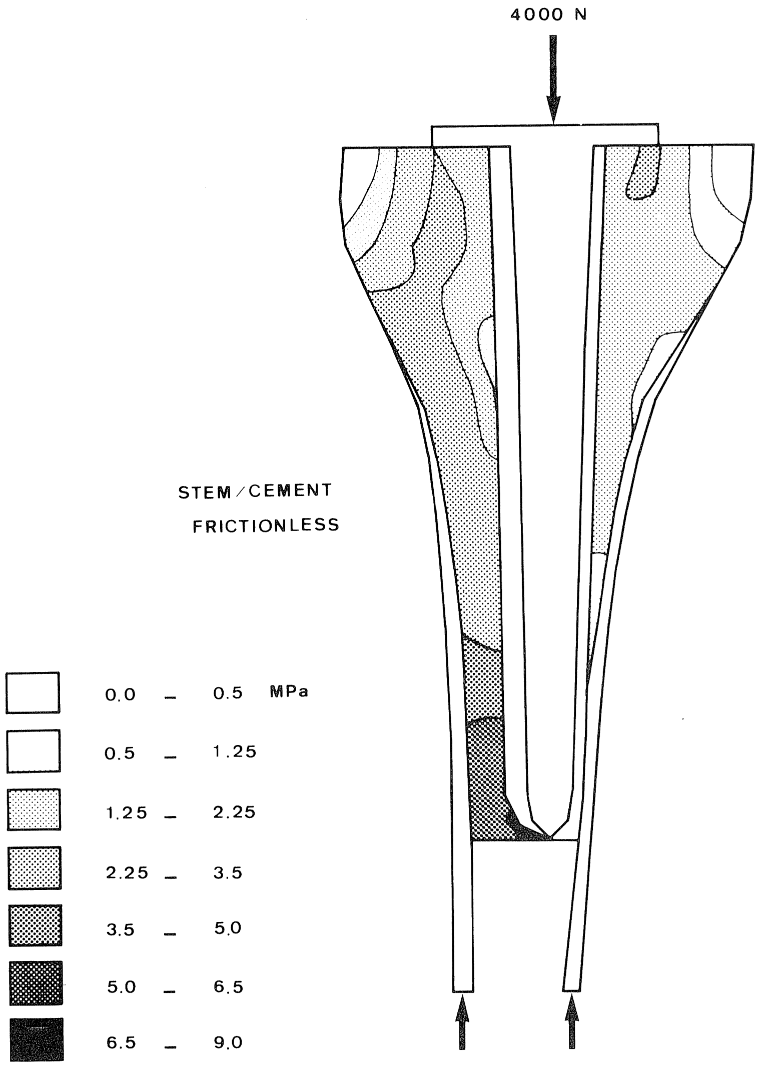

Fig. 9.

Acknowledgement

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