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An Axisymmetric Finite Element Analysis of the Mechanical Function of the Meniscus

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Introduction

According to the literature the function of the menisci of the knee has been studied almost only in laboratory experiments and clinical studies (Jaspers et al., 1980; Seedhom and Hargreaves, 1979; Krause et al., 1976; Walker and Erkman, 1975; Fairbank, 1948). The interindividual variations with respect to dimensions and mechanical properties of the distinct joint structures require quite large series of experiments in order to obtain definite quantitative results. Moreover, the experimental investigations are hampered by the poor accessibility of the meniscal structures, emanating from the complex anatomy of the knee joint and imposing heavy demands upon the measurement techniques used. Only De Lange et al. (1979) compared experimental results with the theoretical predictions of a phenomenological rheologic model of the menisci and found them to act as nonlinear springs. Although the menisci might have a joint stabilizing function as well (Minns and Muckle, 1982; Jaspers et al., 1980) the most important function of the menisci is constituted by their load carrying capacity. In this paper a simple theoretical model is presented that is expected to serve as a versatile tool for the exploration of the basic mechanisms and parameters governing the load transmitting function of the menisci.

Description of the model

The aim of the model is to obtain fundamental insight into the importance of the menisci for the load transmission from femur to tibia. As a starting-point served an axially loaded knee joint in full extension. The model is axisymmetric (Fig. 1) and comprises a plane tibial plateau, a spherical femoral condyle and a ring in between, representing the meniscus. In the unloaded situation the lower and upper surfaces of the ring match the respective tibial and femoral surface and there is direct femorotibial contact at the axis of symmetry. The model is based on a finite Element Method. This is a numerical approach, based on piecewise approximations to continuous fields. In using this method a structure is modeled as an assemblage of elementary building blocks, called elements, which are interconnected at a finite number of locations, called nodes. The distribution of elements that was actually used for the present analysis is shown in Fig. 2. The most important characteristic of this model is that it allows frictionless displacement of the meniscus with respect to the tibia and the femur. This is achieved by the use of especially developed gap elements. Both the bones and the meniscus are assumed isotropic and linearly elastic.

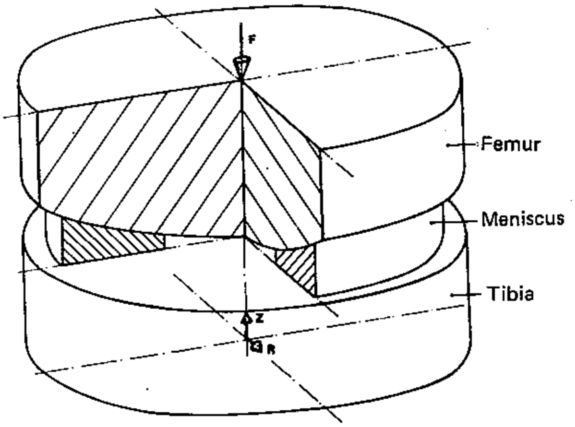

Fig. 1

Results

The analysis performed thus far comprised the following: On exertion of an axial load F (Figs. 1, 2) the axial compression of the joint and the radially outward displacement of the meniscus were computed. Attention was paid also to the contribution of the meniscus to load transmission. This was done for the three different combinations of material properties shown in Table 1. Moreover, for combination 1, which served as a reference, the joint behaviour was analyzed after omitting either the total meniscus or its outer half.

From Figs. 3 and 4 both the axial compression u and the radial displacement v can be seen to depend in a nonlinear way on F. A comparison of curves 1, 2, and 3 in Fig. 3 shows an increase of the Young's modulus of the bones (curve 2) or of both the bones and the meniscus (curve 3) to result in a decrease of the axial compression of the joint under the same axial joint load. Removal of the meniscus results in an increase of the axial compression (curve 5). Curves 1 and 4 show only a relatively slight increase of the axial compression after removal of solely the outer half of the meniscus. For the radially outward displacement of the meniscus in a qualitative sense the same results are found.

In Fig. 5 the percentage of the total axial load transmitted by the meniscus is given as a function of the total load. For the reference combination of material properties (curve 1) about 50% of the total joint load is transmitted by the meniscus. This percentage is diminished drastically by an increase of the Young's modulus of the bones (curve 2)

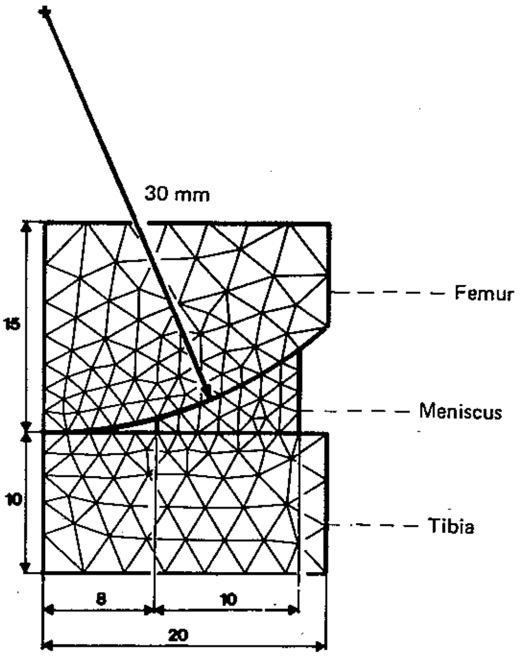

Fig. 2

Table 1 Combinations of Youngs' moduli (MPA)

Bone ($\nu = 0.2$)	Meniscus ($\nu = 0.3$)
500	20
5000	20
5000	200

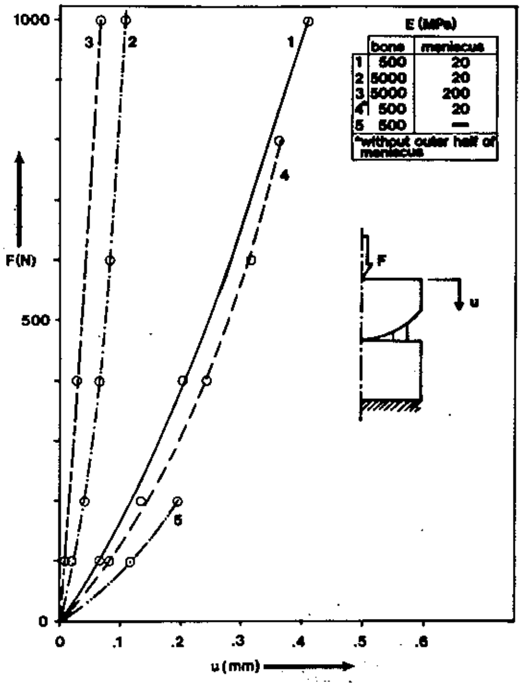

Fig. 3

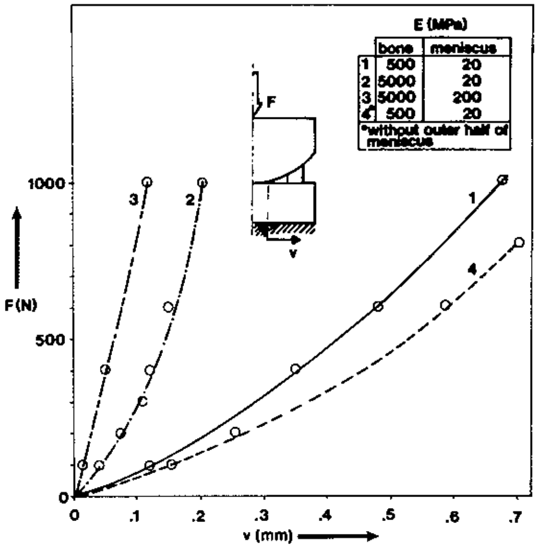

Fig. 4

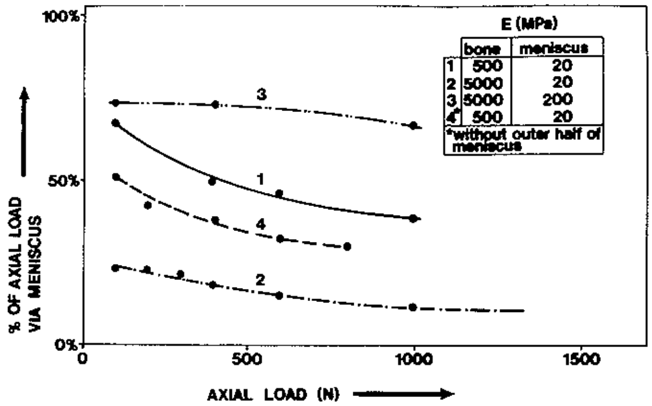

Fig. 5

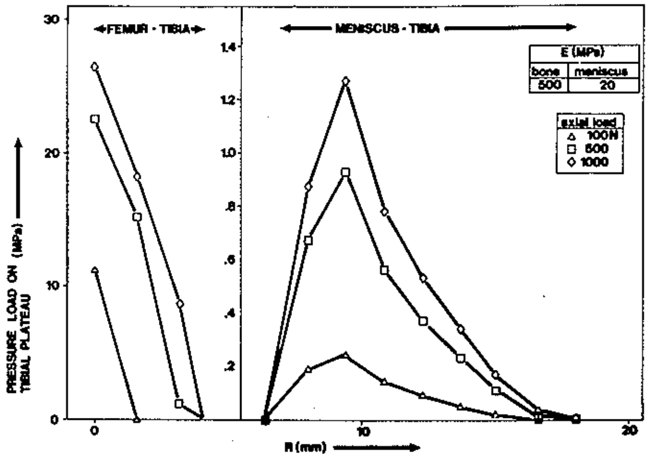

Fig. 6

whereas it increases after an increase of the Youngs moduli of both the bones and the meniscus. A half meniscus appears to contribute less to load transmission than a whole meniscus. However, the diminution of meniscal load transmission is less than would be expected from the decrease of the load carrying area (50%). The explanation of this finding is found in the load distribution on the tibial plateau (Fig. 6). From the load distribution in the meniscotibial contact area for a whole meniscus its inner half is seen to carry considerably more load than the outer half. Consequently, removal of the outer half of the meniscus will have a relatively slight effect on the meniscal share of load transmission. Fig. 6 shows the maximum pressure load on the tibial plateau in the femorotibial contact area to be about a factor of 20 higher than the maximum values in the meniscotibial contact zone.

Furthermore, the numerical results showed the highest stress values to occur in the bone at the site of femorotibial contact, while the stresses in the meniscus were about a factor of 10 smaller. Removal of the meniscus resulted in an increase of the former of about 40% whereas this increase amounted only 5 to 15% (depending on the total axial load) upon removal of the outer half of the meniscus.

Concluding Remarks

- From a simple axisymmetric finite element model the meniscus appears to contribute significantly to load transmission in the knee joint;
- The presence of a meniscal structure causes a considerable reduction of stresses in the femorotibial contact area;
- In the geometrical configuration, chosen in the present study, the inner half of the meniscus accounts for the major part of meniscal load transmission.
- The axial compression of the joint and the radially outward displacement of the meniscus depend nonlinearly on the axial joint load.
- The combination of material properties of bone and meniscal tissue is found to be more important for the amount of meniscal load transmission than the dimensions of the meniscus.

The results of this theoretical analysis support experimental findings reported in literature on the load-carrying function of the meniscus (Seedhom and Hargreaves, 1979; Walker and Erkman, 1975). However, extrapolation of these results towards biological reality would be unwarranted because of the gross simplifications made with regard to both geometry and material properties. By successive elimination of these simplifications it is possible to make a stepwise analysis of the importance of various parameters. Investigations on the importance of the geometry of the tibial plateau (e.q. slightly convex or concave instead of plane), the presence of articular cartilage layers on the bones as well as the actual anisotropic material properties of notably the meniscal tissues will be the logical continuation of this work. In this way we hope to obtain fundamental insight into some of the basic mechanisms that govern the mechanical function of the meniscus.

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