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Quantitative morphology of the subchondral plate of the tibial plateau

S. MILZ AND R. PUTZ

Anatomische Anstalt der Universität München, München, Germany

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ABSTRACT

The object of the present investigation was to measure the thickness distribution of the subchondral plate of the tibial plateau. The data were obtained by computerised image analysis of serial sections. The measured values revealed a marked difference in the thickness between the various regions of the joint surface. Thinner zones (100–300 μm) are found in the peripheral region near the margin of the tibial plateau. Thickness maxima (up to 1500 μm and more) are to be seen at the centres of the joint surfaces. The relationship between the thickness distribution of the subchondral plate and information about the stress distribution of this particular joint surface support the conclusion that the morphology of the subchondral plate of the tibial plateau is determined by the function of the joint.

Key words: Bone; knee joint.

INTRODUCTION

Early observations on the thickness of a 'pressure reception plate' in bones were made in the last century by Roux (1896), who investigated the differences between joints and between species. However, he did not allot his values according to measurements from particular regions of the joints, but merely recorded each maximum and minimum (e.g. tibial plateau, 0.1–1.0 mm). Both Roux and many later authors (amongst others Duncan et al. 1987; Clark & Huber, 1990) examined either macerated or decalcified paraffin sections. All previous research has revealed varying thicknesses of the subchondral plate, but the methods employed did not allow a map of the entire articular surface to be drawn. We therefore recorded the surface distribution of thickness of the subchondral plate (subchondral bone together with the overlying mineralised cartilage), using serial sections of block-embedded tibial plateaux. The values obtained were compared with theoretical concepts about the functional stress acting on the joint surfaces. Views on the stress and pressure distribution have been put forward by several investigators (Fukubayashi & Kurosawa, 1980; Ahmed & Burke, 1983; Spilker et al. 1992), most of whom supported a model in which about 50–60% of the load on the tibial plateau acts directly through the menisci, and particularly through those parts of the menisci which lie nearest to the centre of the plateau. The remainder is distributed over the more central region of the surface, where high contact pressure patterns can occur. This applies especially under dynamic load conditions, when the whole system reveals its capacity for impact absorption (Hoshino & Wallace, 1989).

MATERIAL

In total, 24 specimens of the human tibia which had been fixed for 6–12 months were investigated (Table 1). Before being dissected, the axial relations of knee joints were examined in the frontal plane, the external contours of the leg (while still attached to the body) being used to distinguish between a normal position and a valgus or varus deformity. The knee joints were removed and dissected free from adherent soft tissue, leaving only part of the capsule and menisci behind. The articular surfaces were examined for damaged cartilage and other signs of arthrosis, and those with extensive lesions discarded. Specimens were kept at −25 °C until required, none of them being stored for more than 8 months.

Correspondence to Dr S. Milz, Anatomische Anstalt der Universität München, Pettenkoferstrasse 11, D-80336, München, Germany.

Table 1. *Subjects investigated**

Subject	Sex	Age	Height (cm)
27/89	f	83	148
84/89	m	83	168
85/89	f	84	165
93/89	f	80	166
95/96	m	76	170
96/89	f	77	175
97/89	f	100	172
100/89	f	83	156
102/89	m	70	152
112/89	f	84	148
115/89	f	74	175
19/90	m	77	175

* Both knees examined: 19 tibial plateaux: sagittal sections; 5 tibial plateaux: frontal sections.

METHODS

Fine dissection and methyl methacrylate embedding

The specimens were thawed in the same solution with which the bodies had been embalmed (formalin and alcohol). The menisci, cruciate and collateral ligaments were removed, and the tibial head cut through with a band saw so as to leave the cartilage-covered joint surface, together with about 1–1.5 cm of the adjacent cancellous bone. The specimens were finally dehydrated in ascending concentrations of alcohol and the fat dissolved in acetone. After complete penetration with methyl methacrylate, controlled polymerisation was carried out in closed airtight glass vessels (Schenk, 1965; Romeis, 1980; Hutzschenreuter & Brümmer, 1984).

Cutting the methacrylate blocks

After they had set hard, single acrylate blocks were cut with a band saw in a plane passing through the circumference of the specimen. Most of the blocks (19) were divided in the median plane near the insertion of the cruciates, so that sagittal sections could be made of the medial and lateral tibial joint surfaces with a Leitz saw microtome. A few blocks (5) were cut in the frontal plane. A 300 μm loss of material (corresponding to the thickness of the saw blade) is unavoidable, and this was taken into account when deciding the distance to advance the saw between cuts.

Contact radiography and staining

In order to supplement and test the measurements obtained from the 500 μm sections, selected methyl methacrylate sections were used for contact radiography (Faxitron x-ray system Hewlett Packard) on Strukturix x-ray films (Agfa). This procedure made it possible to obtain a precise and well contrasted picture of the x-ray dense parts of the section, and thus to avoid the influence of air bubbles, which would impair light microscopy. The results were evaluated by a Vidas image analysis system.

The 100 μm undecalcified sections, still embedded in the methyl methacrylate, were stained with alizarin-toluidine blue, the action of which is mostly limited to the surface of the specimen.

Image analysis

Description of the method. A Leitz stereolupe connected to the Vidas image analysis system (Kontron) was used for the morphometry. This system consists of an IBM-compatible computer (CPU 80386), digitising hardware, a video camera and special software, including self-developed macros. Most of the 500 μm sections could be measured immediately after they had been cut, since uncalcified cartilage can easily be distinguished from the subchondral plate. The actual measuring was carried out by marking the distance on a screen which showed a digitised image of the section, the system being arranged to store the length of each marking automatically on a hard disc. The graphic visualisation was carried out by means of the PC version of Gnuplot, a software program originally designed as a Unix utility.

Measuring strategy. In order to assess and confirm the value of the information obtained, 3 tibial plateaux were measured at the highest resolution. For this purpose they were sawn in the sagittal plane. The sections were then numbered, and each was measured from before backwards, 3 mm being allowed between individual measuring points. About 550–600 of these points were found in each tibial plateau. Comparison between neighbouring points, and also those from different sections, made it possible to assess the accuracy of the method, as well as to ascertain the existence of any gradient.

This method of measuring the distribution of the thickness naturally ensures extreme accuracy, although the large number of measuring points and the expenditure of time involved do not make it suitable for investigating serial sections. For this reason, only every 3rd section was measured in 21 additional tibial plateaux, thus reducing the number of points for each tibia to between 250 and 300.

Starting from the articular surface, the distance was measured between the beginning of the calcified zone

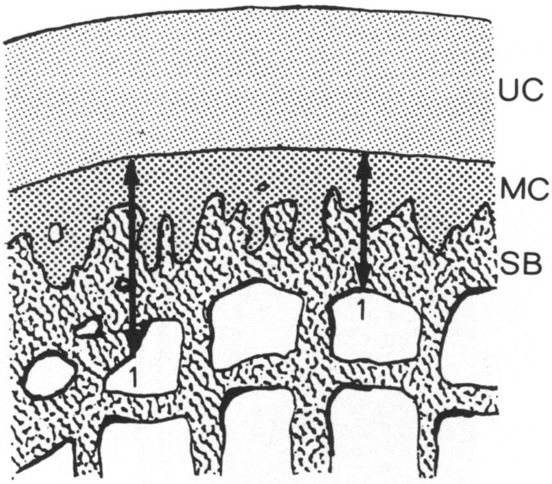

Fig. 1

Fig. 1. Diagram showing layers of articular surface. UC, uncalcified cartilage; MC, calcified cartilage; SB, subchondral bone; 1, thickness of subchondral plate.

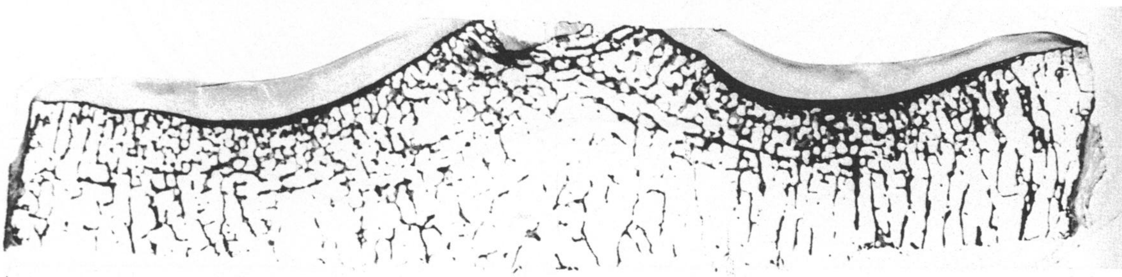

Fig. 2

Fig. 2. Frontal section through tibial plateau (alizarin–toluidine blue). The changes in the thickness of the subchondral plate are clearly seen.

of cartilage and the first clearly recognisable appearance of the marrow cavity of the spongiosa. These measurements were always made perpendicular to the articular surface (Fig. 1). Before beginning each series of measurements, the image analyser was initially calibrated with a graticule. In order to test the reproducibility of the system, test measurements were recorded (test length 5×100 μm, coefficient of variation 1.6%, minimum 4.92, maximum 5.09, mean 5.0, variance 0.0018, S.D. 0.0830).

Visualisation of the measurements. By interpolating between neighbouring points, contour lines representing the same thickness ('isocrassids') were obtained and entered on a map. The distance between adjacent isocrassids was chosen to represent a difference of 100 μm.

Summation of topographically corresponding values from each tibia produced a picture of the general distribution of thickness, by eliminating differences between the individual distribution patterns of the joints measured.

RESULTS

Thickness of the subchondral plate

Values obtained in 3 joints with a very fine grid showed that the transitions between the various grades of thickness do not run in steps. This was also clearly seen in a frontal section (Fig. 2). In general, the right and left tibial condyles of the same subject showed a clear symmetry of the thickness distributions of the subchondral plates. This applied not only to the shape, but also to the position of the maxima, allowance being made for a certain degree of variation.

If the individual distributions of the inclination of the curves from the periphery inwards was examined, the medial part of the plateau usually revealed a steeper increase in thickness than the lateral part. In 1 case with a valgus deviation, the thickness maximum in the medial part of the joint was significantly less, that of the lateral region being therefore considerably above the comparable average value.

Summation of the topographically corresponding values from all joints made it possible to calculate a pattern which, by averaging out the individual differences, represented the general distribution of the tibial plateau (Fig. 3). Thinner zones (100–300 μm)

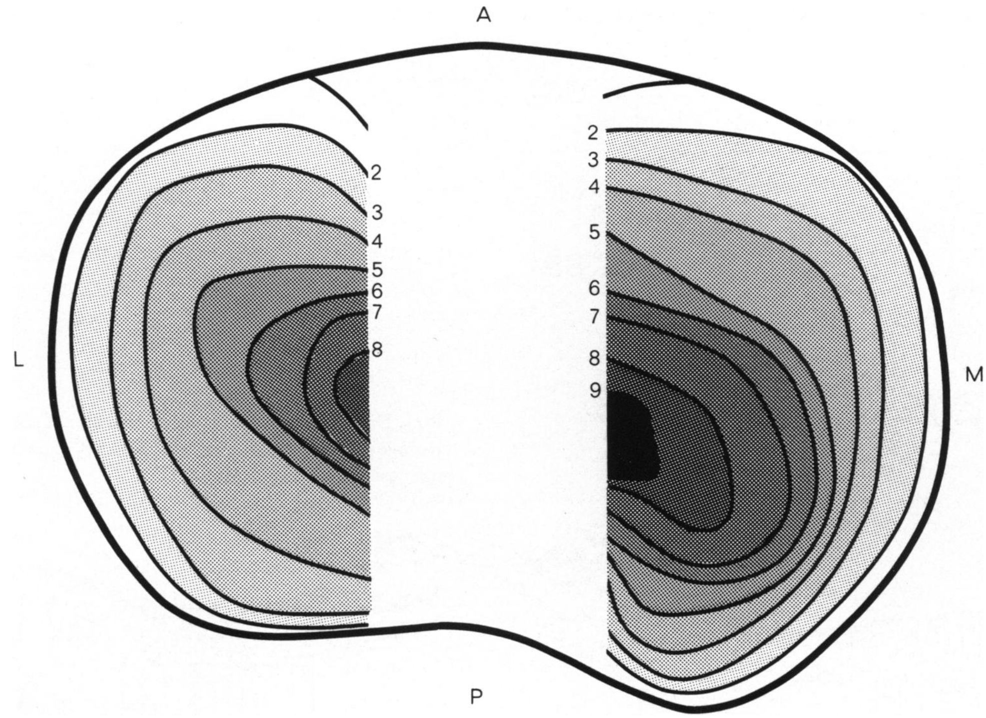

Fig.3

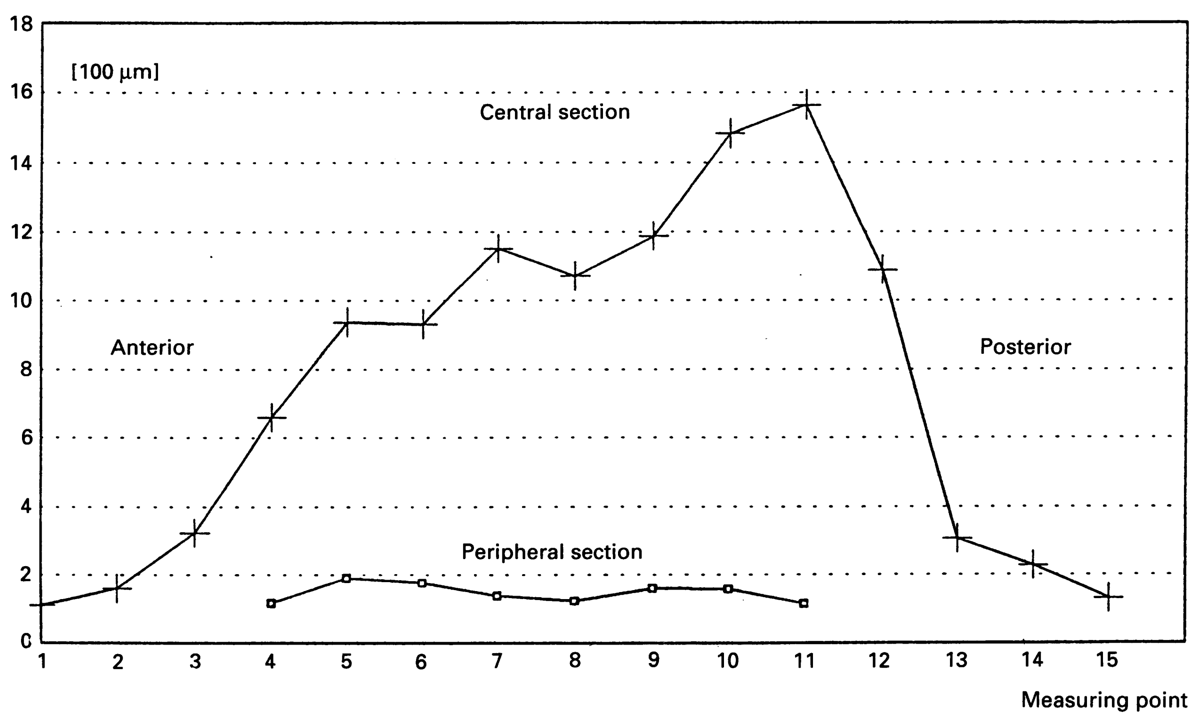

Fig.4

Fig. 3. Thickness distribution of the subchondral plate (summation picture) of the tibial plateau. The distance between the isolines (isocrassids) represents a difference of 100 μm. The isocrassids are marked with numbers (2, 200 μm; 3, 300 μm; 4, 400 μm; 5, 500 μm; 6, 600 μm; 7, 700 μm; 8, 800 μm; 9, 900 μm).

Fig. 4. Thickness of subchondral plate: typical values for central and peripheral sections.

were found in the peripheral region near the margin of the tibial plateau, whereas at the centres of the joint surfaces, zones of greater thickness were to be seen (Fig. 4). The transition from the thin to the thick zones was continuous, although to the naked eye it was particularly in the part of the joint not covered, or

Table 2. *Maximum values of thickness of subchondral plate**

	Right		Left	
	Lateral	Medial	Medial	Lateral
115/89	11.27	12.87	9.61	11.3
112/89	6.51	11.36	5.31	11.28
102/89	14.07	7.02	11.26	11.78
100/89	12.65	17.57	11.57	10.39
97/89	9.63	11.53	12.21	8.3
96/89	6.59	15.1	13.93	6.87
95/89	12.06	12.29	21.36	13.58
93/89	6.54	7.27	7.15	8.37
85/99	10.3	12.56	8.73	10.54
84/89	14.05	15.65	16.4	16.26
27/89	6.55	8.03	5.79	10.47
19/90	6.35	14.48	18.11	10.81

* Units: 100 µm.

Table 3. *Minimum values of thickness of subchondral plate**

	Right		Left	
	Lateral	Medial	Medial	Lateral
115/89	0.97	1.08	0.62	0.82
112/89	0.43	0.65	0.21	0.37
102/89	0.87	0.91	0.91	0.93
100/89	1.03	1.09	0.87	0.91
97/89	0.93	0.74	0.91	1.11
96/89	0.86	1.02	0.83	0.93
95/89	1.24	1.17	1.13	1.24
93/89	1.09	1.04	0.85	1.05
85/89	0.71	0.9	0.85	1.41
84/89	0.84	1.11	0.74	0.75
27/89	1.34	0.83	0.88	1.22
19/90	1.21	1	1.49	1.1

* Units: 100 µm.

covered only by the inner parts of the menisci, that the subchondral plate was thicker than at the edges. In most cases the central region of the medial part of the plateau was thicker than that of the lateral. The thinnest areas of the subchondral plate had about the same value on both the medial and lateral sides.

There was no predictable upper limit for the thickness of the plate, although in most cases the maximum values lay between 800 and 1500 µm (Table 2). Values larger than 1700 µm were found particularly in specimens which showed a macroscopically intact cartilaginous covering, but which microscopically showed minimal cartilage alteration. In the whole joint, however, the thickness remained above a certain minimal value of about 93 µm, only in 1 case falling below 50 µm (Table 3).

If the distributions in different plateaux were examined, there was a basic tendency to build up a central thickness maximum, surrounded by thinner zones. A plateau-like thickening of the subchondral plate in the ventral region of the articular surface about halfway between centre and periphery was found relatively often. It could even be regarded as a small secondary maximum in some cases. In joints with an overall moderately thin subchondral plate (maximum less than 100 µm) neither this type of plateau formation nor a secondary maximum was found.

DISCUSSION

Methyl methacrylate embedding makes it fairly easy to cut large pieces of undecalcified bone with a saw microtome into parallel sections of constant thickness. Shrinkage and folding are reduced to a minimum. This makes it possible to record a true 3-dimensional distribution of the parameters examined.

By selecting a group of specimens with comparatively intact cartilage it can be assumed that, in spite of the advanced age of the subjects (mean: 80.9 y) and the associated increase in the number of pathological changes, the resulting findings correspond to the 'normal' condition of the tibial plateau at this age.

According to current opinion and confirmed by our own investigations, the temporary storage of the specimens at −25 °C is well able to preserve the shape, size and content of the bone-cartilage units, and is even able to maintain their mechanical characteristics (Hvid et al. 1986; Goldstein, 1987; Swartz et al. 1991).

The maximum accuracy of the image analysis system is mainly influenced by the optical properties of the stereolupe and the enlargement used, since the resolution of the digital equipment remains unchanged. The current configuration allows an accuracy of 5–10 µm. This is permissible, since it has already been shown that the changes measured are 10 to 100 times greater than the precision with which they were measured.

After 3 cases had been measured with a very fine grid (800 µm × 3000 µm), the data acquisition procedure was altered so that greater speed was possible. Since with a fine measuring grid the differences in thickness recorded between neighbouring points were relatively slight, and a continuous distribution of the values was observable, the distance between the neighbouring points on different sections could be increased up to 3200 µm.

According to the basic rules of histomorphometry the thickness of the section measured must be at least a quarter of the diameter of a sphere having the same volume as the structure to be measured (Burck, 1969). This is necessary to avoid distortions of the measurement due to examining the same section at different depths, and applies particularly to tissue in which the objects to be measured are irregularly distributed in the section. Taking this into consideration, it appears that distances of less than 140 μm may be a source of error, because in these cases sections lying oblique to the articular surface may produce an apparent increase in the distance. Since, however, it had been decided to use only perpendicular sections, and since the technique of 'optical sectioning' (i.e. focusing on the surface) was used, this kind of error can be almost completely excluded. The distance between points on different sections was controlled with a micrometer drive when setting the advancement of the saw blade between cuts. Assuming that when the thickness of the section is adjusted with the micrometer drive an error of 2 to 3 graduations can occur, the resulting deviation from the correct value could not exceed 30 μm.

The distance between points was controlled with a calibrated ocular graticule (10 graduations = 1.5 mm) and the next measuring point of a section focused by manual displacement. Even with an error of 2 graduations, inaccuracy in the distance between the measuring points could not exceed 300 μm.

If account is taken of the greatest possible error in both directions, there is still a high probability that the chosen position must lie within a radius of 300 μm, and this corresponds to a variation of 10% in the distance between the points. Even in the worst case, the distortion of the graphic reconstruction would not affect the general arrangement of the zones or their thickness maxima and minima, and may therefore be neglected.

Clark & Huber (1990), who also investigated the structure of the subchondral plate of the tibial plateau, demonstrated that it is narrow peripherally and thick near the centre. They nevertheless came to the conclusion that not only the contours of the 'tidemark' and 'cement line', but the thickness and constitution of the plate itself are highly variable. Against this our own findings show a regular regional distribution and a concentric arrangement of the levels of thickness. The same is true for the 7–12-fold increase of the thickness from the periphery to the centre, which is more than the moderate difference mentioned by Duncan et al. (1987).

Maps showing single and collective thickness distribution patterns of the subchondral plate of the tibial plateau are not to be found in the literature. The range of thickness of 0.1–1.0 reported by Roux (1896) has not been confirmed by our findings, since we found a greater variation in the minimum and maximum values (Tables 2, 3). Variations in the minimal values measured are, however, comparatively small and should not be overvalued. In contrast to this, our measurements of the central region of the joint revealed a significantly greater thickness than that reported by Roux. This is of particular importance, because of its effect on the resulting biomechanical model (Kummer, 1962; Maquet, 1976; Pauwels, 1976; Tillman, 1978). The density of the subchondral plate of the tibial plateau was investigated by Noble & Alexander (1985). Their data as well as the findings reported by Schünke et al. (1987), who found the subchondral bone density greater in the medial part of the plateau than in the lateral, show significant agreement with our own values.

If the histologically derived thickness distribution of the tibial subchondral plate is compared with the density distribution obtained by CT osteoabsorptiometry or x-ray densitometry (Odgaard et al. 1989; Müller-Gerbl et al. 1992), the agreement is also very good. In exact agreement with our own results, a more pronounced, dorsally displaced density maximum is found in the medial articular surface, whereas that of the lateral surface is central and less marked. If the findings produced by the 2 methods are compared, it can be concluded that there is a direct correspondence between the radiological parameter 'bone density' and the histologically determined parameter 'thickness of the subchondral plate'. If the thickness distribution of the subchondral plate is compared with the findings reported by Behrens et al. (1974) there is no doubt that they agree. Although Behrens and his team examined the strength of the spongiosa about 5 mm away from the surface of the tibia, their results with bone samples from 5 different regions of the tibial head correlate well with the thickness distribution of the subchondral plate: the greatest strength was found on the medial side in the central bony specimens, and laterally in those taken from a more dorsal position. Sneppen et al. (1981) and Hvid et al. (1986) also reached similar conclusions after measuring the strength of the cancellous bone at the proximal end of the tibia. Using an invasive measuring procedure, they found values for the subchondral bone that showed on average 1.9 times greater strength on the medial than on the lateral side.

Since it is essentially the same biomechanical stimulus which acts on the subchondral plate and on the bone lying directly beneath it, it seems probable that the thickness of the plate is induced by the same laws which regulate the development of the strength of the underlying spongiosa. This is confirmed by the likelihood that an increase in thickness of the plate proceeds pari passu with an increase in the strength of the region. If the findings are considered from this point of view, the increase in strength of the subchondral plate and the subjacent spongiosa must be seen in practice as a single general response in an identical locality to one and the same external (loading) stimulus. The ways in which both these regions adapt to this stimulus with morphological changes must obviously vary, even though the result is a similar alteration of the functional characteristic (namely, the strength).

Comparison of work on the thickness of the cartilage (Holmdahl & Ingelmark, 1948) with our own results shows far-reaching agreement. A more recent work by Ateshian et al. (1991) on the thickness distribution of the articular cartilage showed, as do our own results, maximum values in the central region of the joint with an easily recognisable concentric arrangement of the individual grades and a symmetry between right and left. It can therefore be assumed that the cartilage and bone of both tibiae of the same person are regularly subjected to comparable stresses, to which the cartilage and bone both react in a typical fashion. With regard to the position of the thickness maxima of the tibial articular cartilage, reports in the literature are conflicting. Ateshian et al. found the maximum in the lateral joint surface, whereas Frankel & Nordin (1980), on the other hand, observed it in the medial part of the plateau. It is there that maximum thickness of the subchondral plate of the tibial plateau is generally recorded.

The distribution of thickness in the subchondral plate fits in very well with our knowledge of the distribution of static forces over the tibial plateau. Taking into account the results obtained by Goodfellow & O'Connor (1980), it appears that the regions of the subchondral plate which are thickest are those which are subjected to the greatest loading and to the greatest local pressure pattern (Fukubayashi & Kurosawa, 1980). Although the menisci transmit most of the applied load, a pressure distribution pattern is found (especially under higher compressive loads of 3–4 times the body weight) that apparently correlates with the thickness distribution measured (Ahmed & Burke, 1983; Spilker et al. 1992).

The belief that the thickness of the plate is everywhere adapted to the value of the loading there is confirmed by the work of Jozsa et al. (1988), who were able to show in the knee joints of rats that reduction of the load leads to a reduction of the thickness.

If the pattern of the contact surfaces described by Maquet (1976) is compared with our own results (Fig. 3), a general coincidence is found between the position of the thickness maxima measured and those regions where there is immediate contact between the tibia and femur under load. This means that all those parts of the tibial plateau are particularly strengthened at places, where direct contact with the femur takes place or where higher pressure patterns occur when the joint is in various different degrees of flexion or extension (Fukubayashi & Kurosawa, 1980; Ahmed & Burke, 1983; Spilker et al. 1992). In regions which do not come into direct contact with the femoral condyles—and are therefore subjected to less stress—the plate is much thinner. The same applies also to the tibiofemoral contact zones described by Walker & Hajek (1972), which takes up different positions on the tibial plateau depending on the degree of flexion at the knee. They also demonstrated more clearly than Maquet that the contact zones appearing on the medial side of the plateau at various degrees of flexion have in sagittal section the shape of a lengthened ellipse, due to the transmission of force and the accompanying stress loading. On the lateral side of the plateau the contact surfaces are seen in sagittal section to be closer together and more ventral than on the medial side. All these observations extend and confirm our own findings on the distribution of thickness of the subchondral plate, which have revealed regions of greater thickness in parts of the tibial plateau where higher pressure patterns are possible, and the extent and position of which correspond to the contact surfaces.

According to Frankel & Nordin (1980), the medial contact surface is usually about 50% larger than the lateral. When the parts of the subchondral plate are considered which are thicker than 400 μm, it is clear that this statement also applies to the thickness distribution.

CONCLUSIONS

Taking into account all the available evidence, it is necessary to postulate a direct relationship between the extent of the morphological entity 'thickness of the subchondral plate' and the forces transmitted thereby which manifest themselves as regional differences in different parts of the joint. This leads to the hypothesis that the morphology of the subchondral plate of the tibial plateau is determined by the functions of the joint. The characteristic determining stimulus which expresses itself in the form of the subchondral plate is the regionally variable stress. The regional distribution of thickness of the subchondral plate seems to be, under physiological conditions and in terms of its individual morphological form, a reflection of the 'loading history', i.e. the sum of all the mechanical loads to which that joint has been subjected over a certain period of time.

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