Mechanical factors and patellofemoral osteoarthrosis

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SUMMARY   This paper investigates the possible role of mechanical stress in the development of the osteoarthrotic lesions frequently observed in the patellofemoral compartment of the knee joint. First the location of these destructive lesions was determined by studying the location and pattern of contact in the patellofemoral joint. The study was carried out on 39 cadaveric knees for the range of flexion 0°–120°. It was shown that the lesions were localised to the areas corresponding to the range of flexion 40°–80°. These areas have been shown to be subjected to a low stress for most of the time and to a much higher stress for only part of the time. This mode of stressing this area of the cartilage is a consequence of the style of life of the average Western man in which the most predominant activity is level walking, during which the load and in turn the stress are much lower than they are during other ambulatory activities such as ramp and stair ascent and descent. The same area of the cartilage seems to be subject to a similar mode of stress during sedentary occupations. It is suggested that this mode of stressing the cartilage conditions it chemically, and hence mechanically, to transmit low stresses, so that when the much less frequent but higher stresses are applied it cannot transmit them without sustaining some damage.

Although it is widely accepted that mechanical factors are instrumental in the development of osteoarthrosis (OA), their role in the development of the disease is not clear and subject to diametrically opposed views. Thus, one popular view maintains that the osteoarthrotic lesions occur in highly stressed areas in the joint surfaces; that a process similar to wear occurring in engineering bearings is taking place (Leidy, 1849; Sokoloff, 1969). The opposite view to this is based on observations that incipient changes in the hip and elbow take place in regions that are ordinarily carrying little load. This prompted suggestions that it is too little rather than too much stress that initiates the osteoarthrotic process (Trueta, 1963; Goodfellow and Bullough, 1967). The degeneration of the cartilage is attributed to impaired nutrition from the synovial fluid which is pumped in and out of the pores of the articular surfaces as they are cyclically loaded during the joint activities (Linn and Sokoloff, 1965). However, it would be more accurate to say that cartilage in areas of relative disuse commonly develops mild degenerative changes. These are of no relevance to the

severe grades of OA, the pathogenesis of which is what this paper is about.

The patellofemoral compartment often bears the brunt of attack by osteoarthrosis, and the disease in the knee usually begins in this compartment. Findings of Meachim (1972) and Meachim and Emery (1974) show that destructive cartilage changes are extremely common at the patellofemoral compartment and that such changes are often readily apparent in teenagers. With advancing age destructive changes sooner or later involve virtually the whole of the patella and, particularly in women, a considerable proportion of the opposing femoral surfaces.

The study by Emery and Meachim (1973) describes in detail the topography of these lesions and classifies the degree of degenerative changes of the lesions. It also provides a description of the location of these lesions on both the femur and patella in relation to anatomical features on both surfaces. From their observations Meachim and Emery concluded that the susceptibility to wear at a particular site on an articular surface, the morphological type of change seen, and the rate of vertical progression are all determined by factors such as the local biomechanical environment at that site and the local character of the cartilage.

However, Emery and Meachim did not establish

whether the lesions occur in areas that are stressed or unstressed. Goodfellow *et al.* (1976). dealt with this aspect but not in sufficient detail. In their experiment they determined the contact areas in the patello-femoral compartment at angles of flexion of 20°, 45°, 90°, and 135° using a multiple staining technique. Schematic drawings of the femur and patella and the contact areas at the 4 angles of flexion are shown in Fig. 1. Between full extension and 90° contact moves over all the surfaces of the patella except over area *a*, which they termed the 'odd' medial facet. At 135° of flexion the latter comes into contact with the femur. Goodfellow and associates observed, as did Emery and Meachim (1975), both in the operating theatre and in the post-mortem room, that area *a* (the 'odd' medial facet), showed overt fibrillation in early stages of the disease and did not advance beyond that, even when other areas of the patella were at advanced stages of destruction. Goodfellow *et al.* (1976) therefore attributed the surface degenerative changes to habitual disuse; 'The cartilage of this facet is certainly out of contact when standing, walking, running, and probably out of contact during the hours of sleeping.'

In the present study the authors have attempted to relate the sites of the lesions on the femoral surfaces of the patellofemoral compartment to the contact occurring during the range of flexion of the knee joint and the loads transmitted, and hence to the stresses arising during normal activities.

Experimental work

MATERIALS

The experiments were carried out on 39 fresh unembalmed cadaveric knees or specimens which had been preserved in deep freeze below −20°C. The specimens had the ligaments, menisci, the capsule, and the quadriceps femoris tendon intact. The sex and age distributions are shown in Table 1.

DETERMINATION OF CONTACT AREAS IN THE PATELLOFEMORAL COMPARTMENT

The patellofemoral contact was determined at a number of angles of flexion throughout the range 0–120°. The bone ends of the joints were held in an apparatus which has been described elsewhere (Seedhom and Tsubuku, 1977), by means of which it was possible to adjust the angle of flexion. To determine the contact area at any particular angle of flexion a small quantity of casting material (usually polymethyl methacrylate or silicone rubber) was introduced between femur and patella. The patella was replaced and the quadriceps tendon was put under a small tension (usually 20–30 N) to take the slack off the quadriceps tendon and the patellar ligament and maintain the patella in place. When the casting set, the patella was lifted and the casting removed. The casting had holes which occurred where contact between femur and patella took place. When the castings were finished, replicas of both the femur and patella were made in polymethyl methacrylate. The method of producing the replicas is described in the work by Dransfield (1965). Each one of the contact castings was placed in turn on the replica of the femur, and the areas of contact were marked on its surface.

The corresponding angles of flexion of the knee (at which the various contact areas were obtained) were also indicated on the replica of the femur. In order to avoid confusion, due to too much overlap of the contact areas, a fewer number of these were indicated on the surface of the replicas of the patella, which has a much smaller surface area.

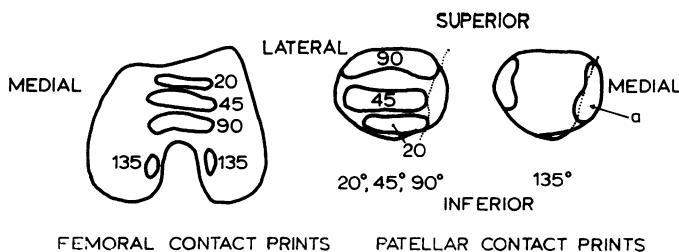The relevant question concerning the location of the contact areas in the loaded and the unloaded

Fig. 1   *Patellofemoral contact areas* (*Goodfellow* et al., 1976)

Table 1   *Distribution of knee specimens by sex and age*

Age (years)	16–25	26–35	36–45	46–55	56–65	66–75	76–85	86–95	Unknown
Male	1	3	—	3	7	4	1	1	4
Female	—	—	—	—	6	2	3	—	4

joint arises. If the application of load on the joint causes the patella to move appreciably with respect to the femur, the location of contact will be different when the joint is loaded from that when it is unloaded. The movement between the femur and patella would normally result from movement of the femur with respect to the tibia. In the experimental situation the knee specimen was firmly fixed in the apparatus, and only small movements occurred. In vivo the flexor muscles and the connective tissue surrounding the joint stabilise it and minimise these movements. If the cruciate ligaments are damaged, instability of the joint, and hence large movements, will occur between the femur and patella, and in this case the location of the contact area in the loaded and unloaded joint will differ markedly. In the 39 specimens examined in this study the four ligaments and the capsule were intact.

MAPPING OF THE OSTEOARTHROTIC LESIONS

The replicas of both the femur and the patella were photographed together. The outlines of the replicas and the areas of contact were traced on a sheet of paper. Besides the trace of each set of replicas another was made with the osteoarthrotic lesions outlines on it, together with the traces of the nearest areas of contact and the corresponding angles of flexion indicated. Thus it was possible not only to map the lesions but also to establish their locations on the surfaces in relation to the range of flexion of the knee and hence in relation to the load acting on the patellofemoral compartment during various activities.

Furthermore, the areas indicating the lesions were divided and shaded according to the degree of severity of the destruction they showed. For the first 16 specimens, the classifications was based upon the visual appearance of the replicas. The degree of destruction was classified as slight, moderate, or severe. However, from specimen no. 17 onwards the Indian-ink technique of Meachim (1972) was used to prepare the surfaces of the joint for examination before the experiment. Each specimen was examined visually before the experiment and 2 records were made to aid in mapping the lesions. The first was a colour slide, and the second was a drawing of the joint with the shapes and sizes of the lesions marked on the drawing, together with the degree of destruction indicated.

As the object of this work was to determine the location of the osteoarthrotic lesions rather than to provide a careful classification of their topography, 5 categories only where used to indicate the degree of severity of destruction on the maps. Those were: (1) areas of minimal fibrillation, (2) areas which showed darkly stained linear markings resembling ravines formed by deep vertical splitting of the cartilage, (3) areas of overt fibrillation, (4) areas of full thickness cartilage loss, and (5) areas showing eburnation.

Results

A selection of contact maps of the patellofemoral joint is shown in Fig. 2. These show how the areas of contact change shape and position as the angle of flexion is varied. The areas of contact are indicated on the whole by solid lines, but where confusion would have arisen due to possible overlap with near-by contact areas some of these were delineated by dotted lines.

Fig. 3 shows 3 specimens with the contact areas and the observed osteoarthrotic lesions mapped. In Figs. 4–7 the maps of the lesions (and nearest contact areas), are presented in incteasing order of degeneration as determined by 2 of the authors (B.B.S. and V.W.). There was disagreement about the order for only 3 specimens.
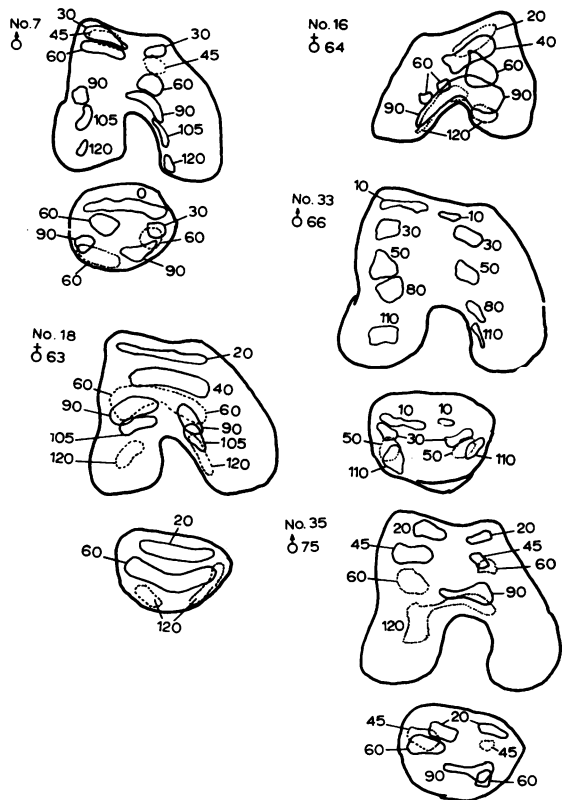

Fig. 2   *A selection of patellofemoral contact areas obtained by the present author*
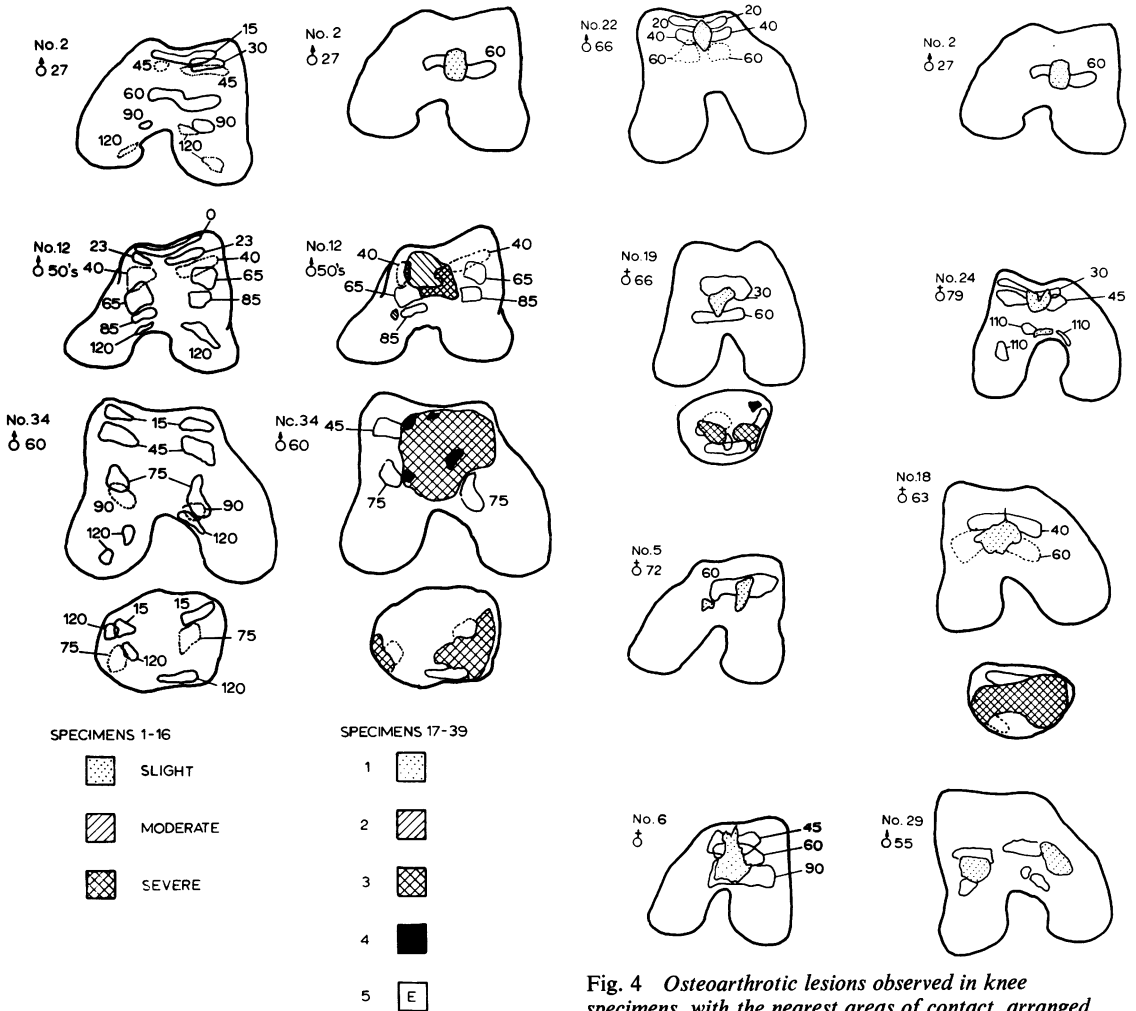
Fig. 3   *Patellofemoral contact areas and osteoarthrotic lesions observed in the specimens mapped with the nearest contact areas. Key to shading for specimens 17–39 is as follows: (1) areas showing minimal fibrillation, (2) areas which showed darkly stained linear markings resembling ravines formed by deep vertical splitting of the cartilage, (3) areas of overt fibrillation, (4) areas of full thickness cartilage loss, and (5) areas showing eburnation*

Fig. 4   *Osteoarthrotic lesions observed in knee specimens, with the nearest areas of contact, arranged in increasing order of degeneration*

Of the 39 specimens 7 are not included in the series shown in Figs. 2–7. Four of these had no lesions. The inclusion of the other 3 would have added nothing more to the data already presented.

PATTERN OF CONTACT

From the position of full extension to about 90° of flexion the contact areas on the femur of good

surfaces or surfaces which showed minimal irregularities were in the form of strips extending on both sides of the patellar groove. At about 90° of flexion and above, the contact between the femur and patella was as mentioned above or took the form of 2 areas, 1 on either side of the intracondylar notch. At about 120° the pattern was often as the latter case, but, less frequently, contact would occur on a continuous area extending above the intracondylar notch. Specimen 35 (Fig. 2) is an example of this pattern. This anomaly is explicable by the varying length of the patellar ligament. Contact on the patellar surface was on the whole consistent with that described by Goodfellow and associates. However, it was found that contact between the
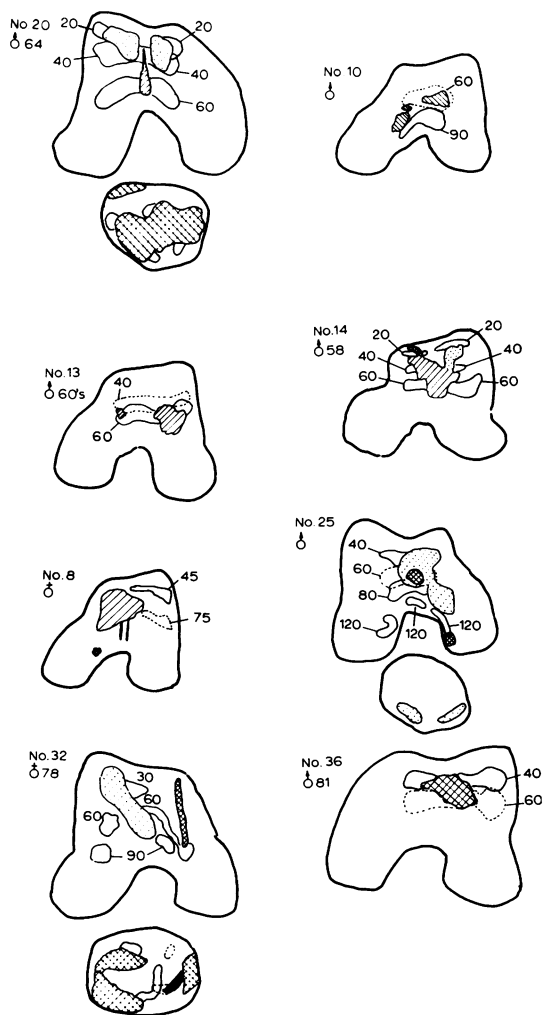
Fig. 5 *Osteoarthrotic lesions observed in knee specimens, with the nearest areas of contact, arranged in increasing order of degeneration*
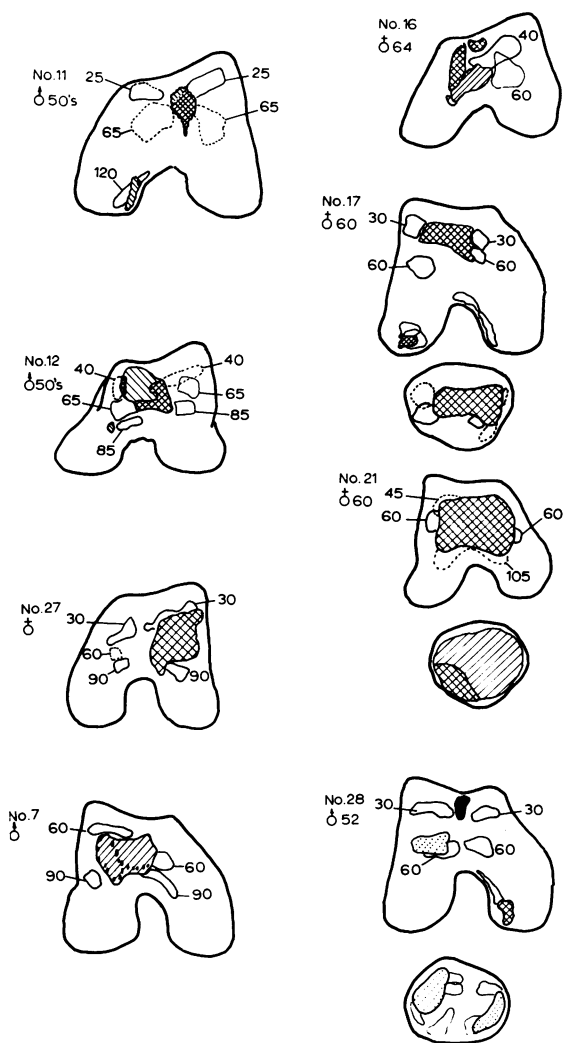
Fig. 6 *Osteoarthrotic lesions observed in knee specimens with the nearest areas of contact, arranged in increasing order of degeneration*

'odd' medial facet and the femur may take place at angles of flexion smaller than 135° (cf. 7, 33, and 18 in Fig. 2, which show contact occurring on the 'odd' medial facet as early as 90°, 110°, and 120° of flexion).

Location of contact in knees showing gross surface degeneration was marked by 2 smaller areas, generally 1 on either side of the patellar groove. Typical examples are those of specimens 7, 33, and 35 in Fig. 2. It must be remembered that these contact areas were obtained under almost no load on the patellofemoral joint. Thus when a casting was made the casting material was squeezed out of the areas

of contact between the highest spots but was trapped in the troughs in the surfaces caused by the irregularities due to the absence of the cartilage.

DEGREE OF DEGENERATION WITH AGE

The degree of degeneration of the surfaces advanced with age. The cartilage of the patella was usually more destroyed than that of the femur. There were, however, some anomalies which are of interest to note. Firstly, in some knees of old people the femoral surfaces showed no more than minimal fibrillation: specimens 22, 19, 24, 18, and 5 in Fig. 4 are examples.
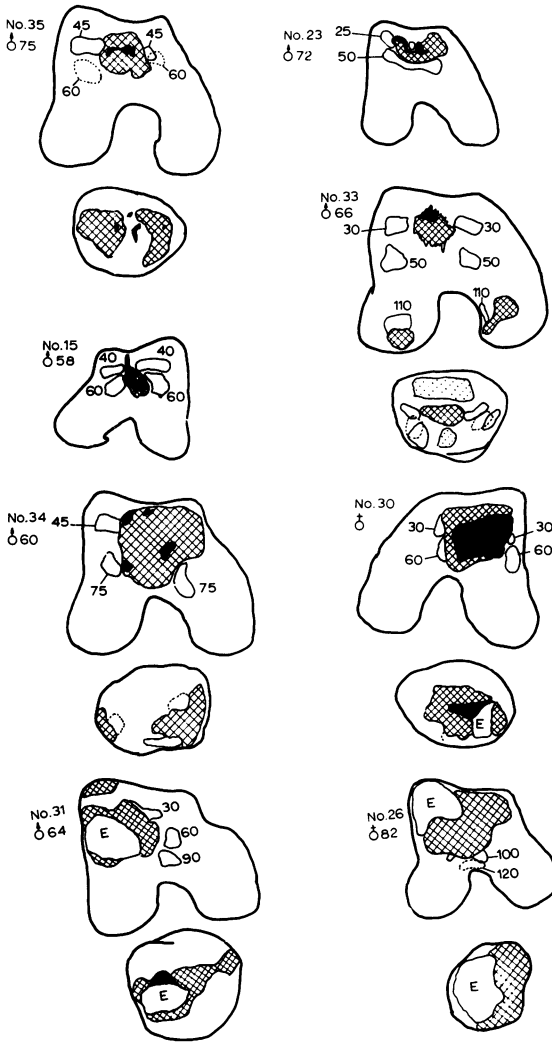
Fig. 7   *Osteoarthrotic lesions observed in knee specimens, with the nearest areas of contact, arranged in increasing order of degeneration*

Secondly, there were 2 patellae whose surfaces were better than those of the femur of the same knee (specimens 25 and 34 in Figs. 5 and 7).

SITES OF THE OSTEOARTHROTIC LESIONS IN RELATION TO THE RANGE OF FLEXION AND THE PATELLOFEMORAL FORCES

Figs. 4–7 show that the osteoarthrotic lesions do not occur randomly on the surface but are localised and correspond on the whole to angles of flexion between 40° and 80°. According to the available data on
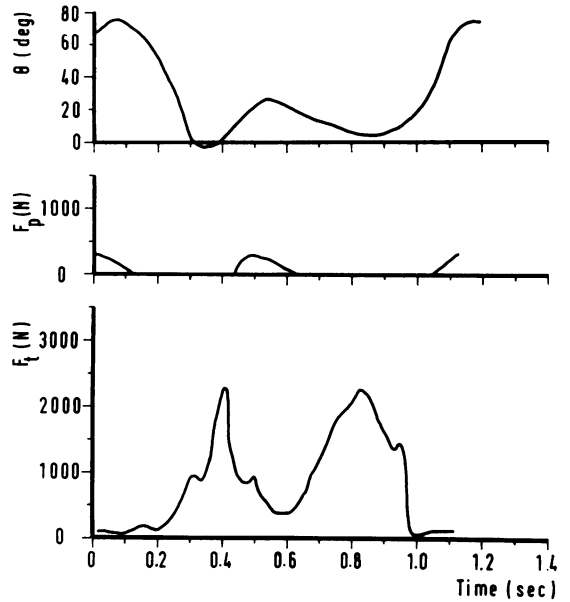

Fig. 8a.   *Knee forces during various activities: level walking.* θ, *is the angle of flexion,* F_p *is the patellofemoral joint force,* F_t *is tibiofemoral joint force*
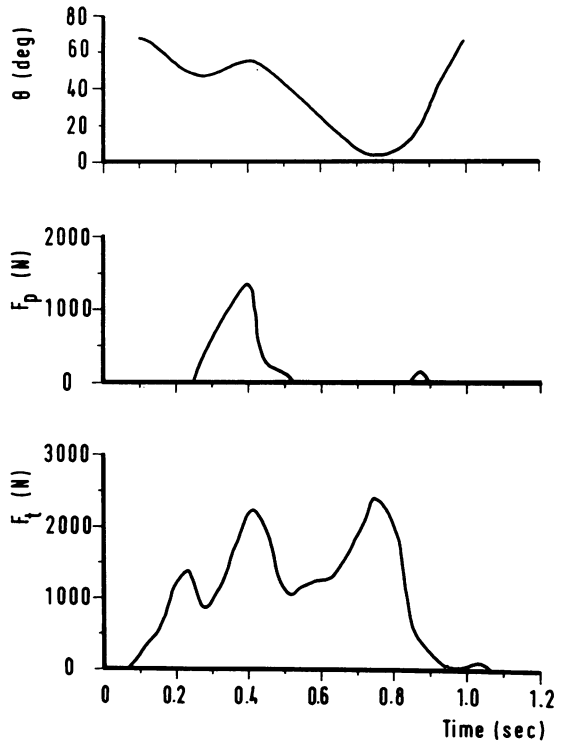

Fig. 8b.   *Knee forces during various activities: walking up ramp. (See Fig. 8a for key to symbols)*
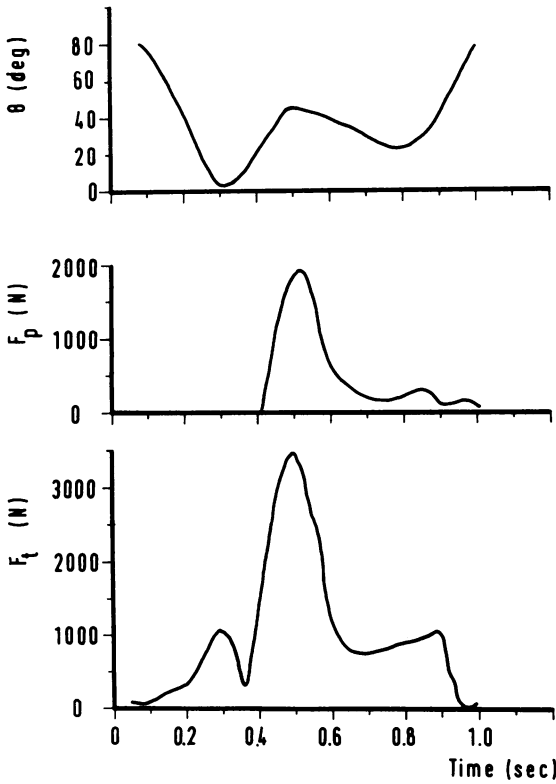
Fig. 8c. *Knee forces during various activities: walking down ramp. (See Fig. 8a for key to symbols)*

Fig. 8d. *Knee forces during various activities: climbing stairs. (See Fig. 8a for key to symbols)*

forces, peak loads occur in the patellofemoral joint in the range 40°–80° of flexion of the knee joint during a variety of activities (Seedhom, in press). This is illustrated by Fig. 8 (a–e). Thus the lesions occur in areas which experience the highest loads during a variety of activities—level walking, walking up and down a ramp, and stair ascent and descent.

Discussion

The above might lead to the conclusion that osteoarthrotic lesions are caused by mechanical stress, that is, the lesions start by collagen fibres breaking owing to fatigue under cyclic stress in the manner suggested by Weightman *et al.* (1973). However, it is important first to consider the following:

(1) What is the level of stress arising in the areas where the lesions occur, and how does it compare with that occurring in, for example, the tibiofemoral compartment?

(2) If fatigue was the one factor responsible for the observed osteoarthrotic lesions, it would be expected
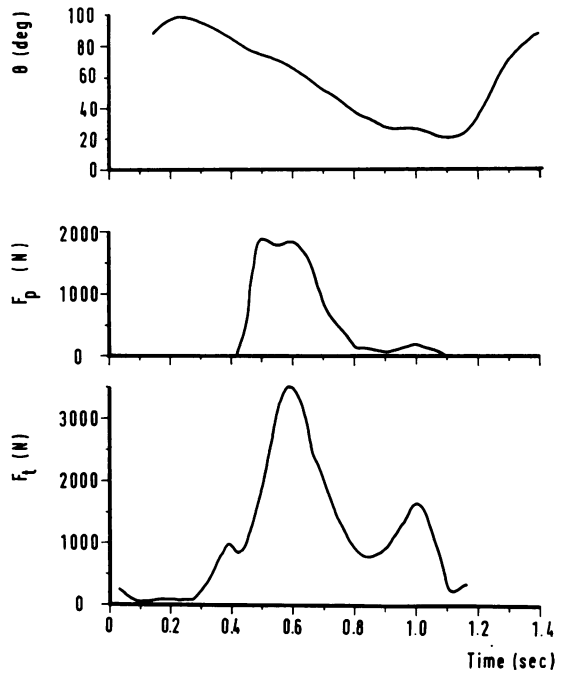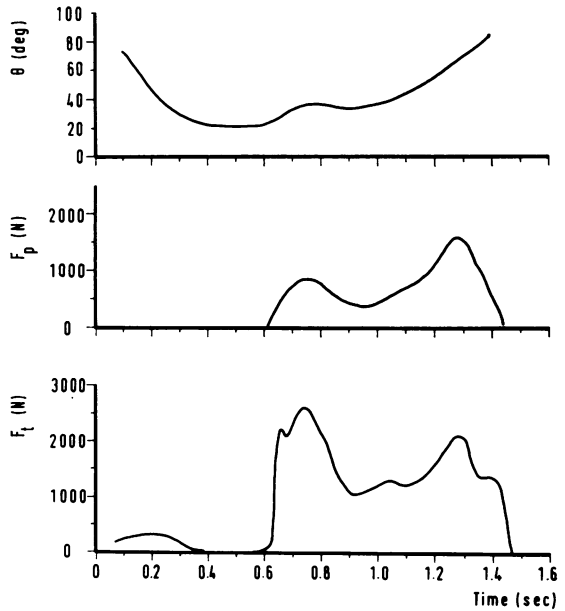

Fig. 8e. *Knee forces during various activities: descending stairs. (See Fig. 8a for key to symbols)*

that the degree of severity of degeneration would progress with age in a more consistent manner than that shown by the present results. The most striking anomaly is represented by 5 specimens of the 8 which have shown minimal fibrillation; these five are from patients who were in their seventh and eighth decade.

STRESSES IN THE PATELLOFEMORAL
COMPARTMENT

The stresses in the patellofemoral compartment were determined experimentally (Seedhom and Tsubuku, 1977) from 3 cadaveric knees which were fresh, unembalmed, and whose patellofemoral surfaces had no irregularities and showed no fibrillation. The specimens were of mainly young subsubjects. The areas of contact were determined under dynamically applied loads which corresponded to angles of flexion of 45°, 60°, and 90°. The load, contact area, average stress, and the possible activity during which the stress may have occurred are presented in Table 2.

It can be seen from the Table that during normal level walking the stress was about $1 MN/m^2$, which is low, but compares with those acting in the tibiofemoral compartment when the minisci are intact (Seedhom, 1978).

Fig. 8 (a–e) shows that the load acting on the patellofemoral joint during level walking is nearly $0·6$ times body weight, but during the other activities, such as walking up and down a ramp or stair ascent and descent, the force is between $2·5$ and 3 times body weight, that is, approximately 6 times its value during level walking. The stress during these other activities would therefore be 4 to 6 MN/m^2 (allowing for variations in the contact areas).

This shows that there is a definite difference in the mode in which the patellofemoral joint is stressed when compared with the tibiofemoral joint. The load acting on the tibiofemoral joint during the 5 activities mentioned above does not vary a great deal, and so the stress in the tibiofemoral joint, with the menisci intact, is approximately the same under these activities. The patellofemoral joint, however,

seems to be stressed at 2 different levels. The first is low, 1 MN/m^2 during level walking and the other, which is much higher, 4–6 MN/m^2 during the other ambulatory activities.

The 5 activities above (level walking, walking up and down a ramp, and stair ascent and descent) represent the main activities of people in Western countries. Furthermore, level walking is certainly the most frequent of these activities, accounting for the largest number of knee loadings. The patellofemoral joint therefore experiences a low stress for most of the time and a much higher stress for only a small fraction of the time.

HYPOTHESIS

It is proposed that the prevalence of lesions in the areas where contact occurs at the range of flexion 40°–80° is due to the mode of stressing of this area more than to the magnitude of the stress itself. Subjecting the cartilage in this area to a habitually low stress may well adapt its mechanical properties to transmit low stress, and as a consequence some damage may occur on those much less frequent occasions when it is subjected to high stress. If the damage occurs at a faster rate than that of repair, a lesion would start and would in its early stages be evidenced by minimal fibrillation.

It is suggested that the style of life is related to the prevalence of the lesions in this region of the cartilage. It may be that this particular area of cartilage is not being exercised enough to allow it to adapt mechanically in order to transmit the higher stresses without sustaining damage.

This hypothesis is consistent with some published findings. Ficat and Maroudas (1975) have shown that the glycosaminoglycan (GAG) content in the cartilage of the trochlea of the femur is lower than its normal cartilage. They have also shown that, in general, the GAG content in the normal cartilage of the trochlea is lower than that of the hip. Ficat and Maroudas concluded that 'this fact, together with the existence of the high pressure during the loadbearing, may be responsible for the frequency of the destructive lesions affecting the cartilage of the

Table 2   *Contact areas and stresses in the patellofemoral joint*

	Knee angle of flexion	Area (cm²)	Load (N)	Load (Xb.W)	Av. stress (MN/m²)	Possible activity
First knee	45°	4·72	600	0·8	1·27	Getting out of a chair aided by arms
	60°	4·32	876	1·3	2·02	Fast walking
	90°	5·44	1316	1·75	2·42	Getting out of a chair unaided by arms
Second knee	45°	2·9	529	1·0	1·8	Getting out of a chair with arms aid
	60°	4·14	438	0·83	1·06	Level walking
	90°	5·46	1150	2·2	2·2	Getting out of a chair unaided by arms
Third knee	60°	4·89	490	0·65	1·0	Level walking
	90°	6·70	1050	1·41	1·45	

patella compared with that of the hip' (p. 515). This could imply that the trochlea cartilage of the knee is at a disadvantage. This, however, may not be the case. In fact the finding of Ficat and Maroudas does not seem to be inconsistent with the hypothesis proposed above. It has already been shown that the patellofemoral areas where the lesions occur are subjected to a low stress during level walking, the most predominant of the ambulatory activities. Higher stresses occur during ramp and stair ascent and descent, which are much less frequent. Thus, rather than suggesting that the cartilage is at a disadvantage from the start, it could well be suggested that the activities of the average Western man, and hence the associated mode of stressing the cartilage, influence the chemical composition of the cartilage, and hence its mechanical strength, since they have been shown to be closely related (Kempson *et al.*, 1970).

We discuss next a popular view which suggests that in secondary occupations the joint is subjected to either little or no stress for long hours, and the lesions may thus be due to lack of stress.

There is apparently some support for this view, but it is necessary to have a closer look at sedentary activities. While sitting at a desk or at a work-table, people are seldom still for long. They frequently lean forward and backward and also flex and extend the knee. Less frequently they have to get in and out of their chairs, with or without the aid of arms. During such movements the patellofemoral joint is loaded cyclically. The frequency of loading, however, is certainly lower than that during walking and depends on the restlessness of the individual. Preliminary estimates have been made of the loads and stresses acting on the patellofemoral joint during sitting (unpublished data). At about $60°$ of flexion, during extending the knee, a load of about 200 N acts on the patellofemoral joint. The corresponding stress is about $0·5$ MN/m^2. During a sudden extension (a jerk) the load can be about 500 N and the corresponding stress $1·0$ MN/m^2. In getting out of a chair the load acting on the knee in the region of flexion 40–80$°$ is 600–1200 N with an average (4 subjects) of 900 N (Ellis *et al.*, 1978, unpublished data). The corresponding stress is $2·2$ MN/m^2. At $110°$ and above, during extension of the knee while sitting, the load acting is about 650 N and corresponding stress is 3–4$·$5 MN/m^2 (since the available area of contact is about $1·5$–2 cm). Higher stresses occur during getting out of a chair.

Thus it seems that in sedentary occupations the area where the lesions occur is stressed in a similar fashion as it is during the ambulatory activities, that is, subjected to a low stress for most of the time and to a much higher stress for only a small part of the time. On the other hand at the areas of contact corresponding to higher angles of flexion of about $100°$ and above the stresses are high for most of the time. It is interesting to note that the incidence of lesions in these latter areas is much lower (5 specimens in 39) than in the areas corresponding to the range of flexion 40$°$–80$°$ (35 specimens in 39). The above is consistent with the hypothesis proposed and may also be a possible explanation of the localisation of the lesions.

More research (prospective and retrospective), clinical and on animals, is necessary in order to support, modify, or otherwise falsify the proposed hypothesis.

Conclusions

The destructive lesions observed on the patellar surface of the femur advance with age but not consistantly. The results of the present work contain anomalies; 62% of the knees whose cartilage showed minimal fibrillation only were from persons in their seventh and eighth decades. The lesions occur in a localised manner, in areas which correspond to contact at angles of flexion between 40$°$–80$°$. The peak loads occur on these areas during the most frequent activities—level walking, walking up and down a ramp, stair ascent and descent. However, the stress occurring on that area seems to be on 2 levels. The first is a low level of 1 MN/m^2, which acts for most of the time; and the other is much higher, between 4 and 6 MN/m^2, which acts for only a small fraction of the time.

It is suggested that it is the mode of stressing the patellofemoral joint, which is related to the style of life and activities of people, that is responsible for conditioning the cartilage to transmit the much lower and more frequent stress, so that when higher stresses occur the cartilage is not capable of transmitting it without sustaining damage. During sedentary occupations, when people may sit for long hours, the cartilage of the patellofemoral joint is still cyclically stressed, though at a lower frequency than during ambulatory activities, and the frequency is dependent on the restlessness of the individual. The cartilage in the area where the lesions occur is stressed in a similar manner as it is during the ambulatory activities, that is, it is subjected to 2 levels of stress—a low one for most of the time and a much higher one for only part of the time. Furthermore, in the contact areas corresponding to 100 degrees and above (where the lesions are much less frequent) the cartilage is subject to a high stress for all the time during sedentary activities. It is suggested that this difference in the mode of stressing the various areas of the patellofemoral joint may be

related to the localisation of the incidence of the osteoarthrotic lesions.

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