THE RELATIONSHIP BETWEEN DEGENERATIVE CHANGES AND LOAD-BEARING IN THE HUMAN HIP

PETER BULLOUGH, NEW YORK, UNITED STATES OF AMERICA,
JOHN GOODFELLOW and JOHN O'CONNOR, OXFORD, ENGLAND

From the Nuffield Orthopaedic Centre and the Department of Engineering Science, University of Oxford

In 1967 the present authors read a paper to the British Orthopaedic Association in which a description of the degenerative changes observed in an unselected group of cadaveric human hip joints was related to a description of the contact and non-contact areas within the joint (Goodfellow and Bullough 1968). From the correlation of our observations we sought to answer the following questions. Why do some areas of articular cartilage nearly always degenerate, and others nearly always survive intact into old age? What is the relationship, if any, between age changes which affect the joints of us all, and osteoarthritis which afflicts only a few?

This paper records our observations and reviews their significance in the light of other studies of the degeneration of hip joints, and of the mechanics of load transfer in the hip.

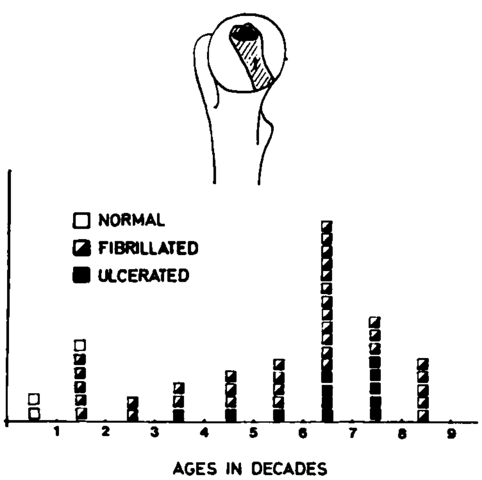

FIG. 1
The frequency of cartilage lesions on the perifoveal and infero-medial areas on the femoral head.

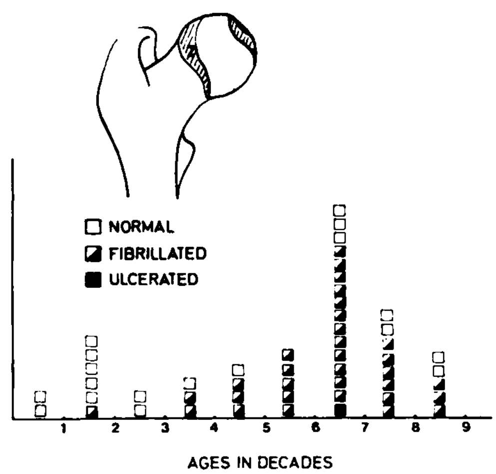

FIG. 2
The frequency of cartilage lesions on the peripheral area on the femoral head.

CHANGES IN THE ARTICULAR CARTILAGE OF THE HUMAN HIP

The following observations were made upon fifty-one hip joints collected in the post-mortem room from unselected subjects. Surface changes in the cartilage, including granulation and exposure of the fibres, is referred to as "fibrillation", erosion of the cartilage with exposure of the subchondral bone as "ulceration".

The femoral head—Degenerative changes were found almost universally in two areas of cartilage on the femoral head. In Figure 1 the diagram defines the first area, a band of cartilage extending downwards and backwards from the fovea to the inferior articular margin. The histogram below records the presence or absence of cartilage changes in this region. In this and succeeding diagrams all fifty-one joints are recorded. In every subject over fifteen years old some cartilage in this zone was fibrillated; in the middle-aged ulceration had occurred in some; and in subjects over sixty years old ulceration in this area was common.

The second zone in which cartilage changes were commonly present was the periphery of the articular surface, anteriorly and above, but not posteriorly. This is the area outlined in the diagram in Figure 2, and the histogram shows that at this site the changes did not commence so early, nor did they progress to the same degree as in the perifoveal region.

Degenerative changes at other sites than those just mentioned were found in only seven subjects. Ulceration on the back of the femoral head and on its superior surface was found in these few. They were all from middle-aged or old subjects, and the lesions differed from those just described in that fibrillation was not observed in these sites in any of our younger subjects.

The acetabulum—In the acetabulum our attention was drawn to one area, roughly triangular in outline, on the roof of the acetabulum with its base at the superior lip. Figure 3 shows the area and the frequency of lesions at this site. Figures 4 to 7 demonstrate the range of lesions observed. Figure 4 shows the surface changes at an early stage. Figures 5 and 6 show more advanced changes in middle-aged subjects, but note that the general shape of the affected area is constant, even up to the severe ulceration in an old subject shown in Figure 7. In them all the triangular area lies between and seems to define two elliptical areas of unaffected cartilage, one anterior and one posterior.

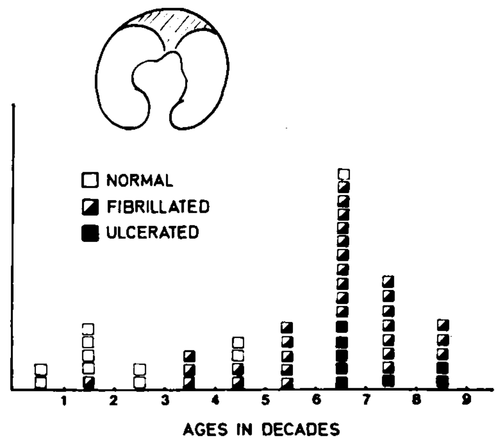

Fig. 3

The frequency of cartilage lesions on the triangular area on the dome of the acetabulum.

Parallel observations—Harrison, Schajowicz and Trueta (1953) drew attention to the early onset and eventual prevalence of cartilage lesions in the peripheral and perifoveal regions of the femoral head, and our observations accord closely with their description. The most detailed study of the post-mortem appearance of the human hip is that of Byers, Contepomi and Farkas (1970) based on more than 300 specimens, and their findings on the femoral head do not differ materially from those noted above.

As to the distribution of degenerative changes in the acetabulum, there is less unanimity. Harrison, Schajowicz and Trueta (1953) recognised no significant pattern. Our observation of the prevalence of lesions on the dome and superior margin of the acetabulum is in accordance with an earlier description by Eggers, Evans, Blumel, Nowlin and Butler (1963). In the course of investigating the pathogenesis of osteoarthritic cysts they examined eighty cadaveric hips from subjects aged sixty years or older. "Some degree of marginal erosion of the acetabular cartilage directly beneath the anterior inferior iliac spine was a constant finding." Although described as "marginal" the photographed specimens which exemplify the lesion in their paper show changes encroaching upon the dome of the acetabulum and involving the area shown diagrammatically in Figure 3.

Byers, Contepomi and Farkas (1970) described the cartilage lesions of the acetabulum as prevalent all round its rim, at both tips of the horseshoe of cartilage, and on a small area posteriorly and continuous with the acetabular fossa, but not on the roof of the acetabulum. However, under another heading and described as a feature related to the growth and development of the acetabulum, they too described a roughly triangular area at the same site as that in our Figure 3 in which the cartilage was discoloured, slightly elevated and covered with fine radiating lines. These features were associated with focal defects in the underlying subchondral bone and marginal ossification of cartilage. They did not regard this area as a

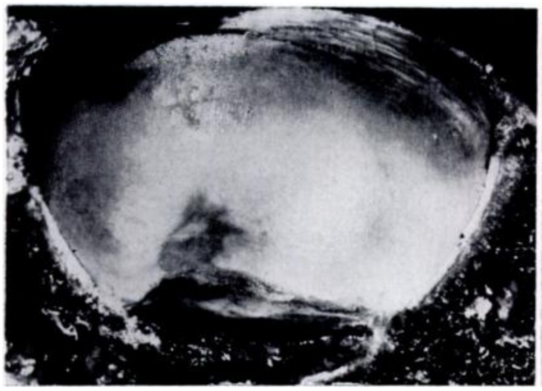

FIG. 4

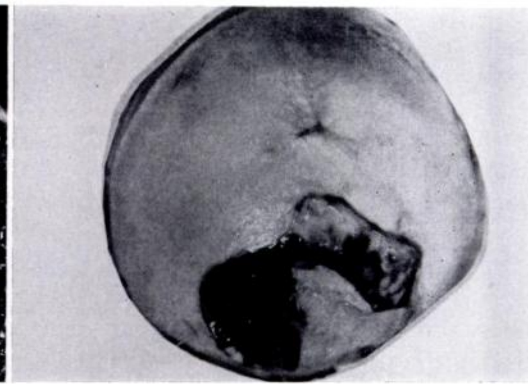

FIG. 5

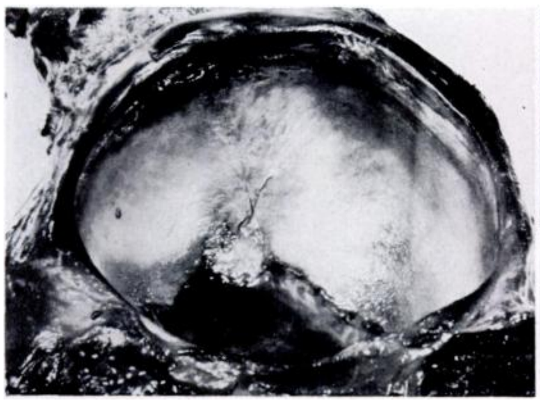

FIG. 6

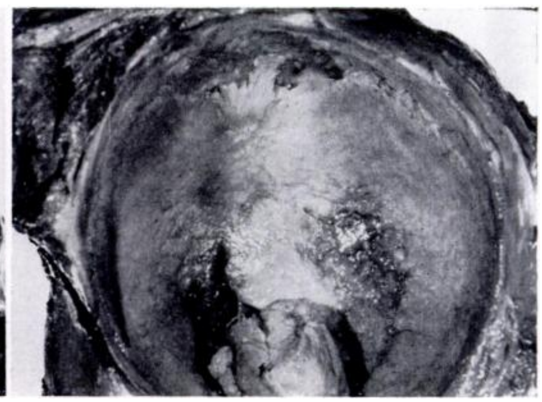

FIG. 7

The range of lesions observed on the dome of the acetabulum. Figure 4—An early lesion in a young adult. Figures 5 and 6—More advanced lesions in middle-aged subjects. Figure 7—An advanced lesion with ulceration in a joint which displays cartilage degeneration in other areas as well.

consequence of degeneration, but as a feature of the normal anatomy of the acetabulum which is developmental in origin. This interpretation appears to be difficult to sustain in the light of their own numbers, which show that the lesion was observed in only eighteen of the subjects under forty years old (44 per cent) but was present in 256 of the 322 subjects whose ages ranged from forty to ninety years (79 per cent).

Whatever interpretation is put upon the observation, it appears that in the three series of acetabuli reported the cartilage on the roof of that structure has had a different appearance from the cartilage covering the most part of its anterior and posterior surfaces.

There is evidence that for healthy survival articular cartilage needs a regime of constant or regularly recurrent contact with opposed cartilage. Harrison, Schajowicz and Trueta (1953) showed how closely the degenerative changes on the head of the femur matched the areas of cartilage which habitually lie outside the embrace of the horseshoe of acetabular cartilage. The area around and below the fovea articulates habitually with the synovium which covers the fat pad in the acetabular fossa, and the peripheral area articulates, except in abduction, with the synovial lining of the superior and anterior capsule. A similar correlation between areas of habitual degeneration and areas of habitual disuse has been demonstrated in the elbow joint (Goodfellow and Bullough 1967) and in the knee (Goodfellow, Hungerford and Zindel 1971).

The question arose whether the cartilage changes observed on the roof of the acetabulum were analogous and whether the cartilage in that area did, in fact, subsist in the living, in a mechanical environment distinct from that of the acetabular cartilage in general. It was therefore necessary to review the mode of articulation of this joint.

JOINT INCONGRUENCY

The opposed surfaces of most human joints have curvatures which are obviously incongruent and cannot be made to fit. The incongruity of the curvatures of the head of the femur and the acetabulum, though not obvious, was recognised by Walmsley (1928) and its implications were discussed by MacConaill (1950). The present authors have published the

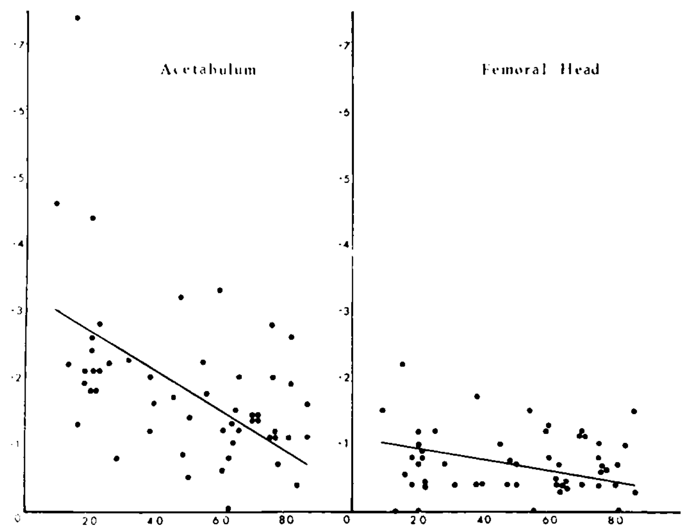

FIG. 8

The "index of sphericity" (vertical ordinate) plotted against age of the subject in years (horizontal ordinate). (Drawn from data from Bullough, Goodfellow, Greenwald and O'Connor 1968).

curvature measurements in fifty-three hips obtained at necropsy for subjects of different ages (Bullough, Goodfellow, Greenwald and O'Connor 1968). The radius of curvature was measured at four sites equidistant from one another along an equatorial circle on each surface. The difference between the maximum and the minimum radius, divided by the average of the four radii, was taken to be a measure of the departure from sphericity of each surface. Figure 8 shows this ratio plotted against age for each of the 106 surfaces examined. A statistical analysis was carried out, fitting "least square" straight lines to the data for the acetabulum and the femoral head.

Despite the scatter the conclusions can be drawn that neither the acetabulum nor the femoral head is spherical; that the acetabulum is less nearly spherical than the head; and that there is a "highly significant" decrease in the asphericity of the acetabulum with increasing age (correlation coefficient 0·399). If the joint surfaces are not spherical they cannot be congruent, though they may be more nearly congruent in some positions than in others.

Contact areas in the hip joint—As the opposed surfaces of the hip are incongruent in the unloaded state, there must be contact and non-contact areas within the articulating joint. If the incongruencies of curvature are other than haphazard, the pattern of contact should be common to all normal hips. The location of the contact areas, particularly on the femoral head, should depend upon the position of the joint and there should be a pattern of contact typical of every position throughout the range of movements.

Some experiments were carried out to define the contact areas in the unloaded state. The femoral head was painted with a fine carbon suspension and pressed manually into the acetabulum. When withdrawn, it left an imprint of its areas of contact on the acetabulum.

Figures 9 to 11 demonstrate the pattern of contact which resulted in most young and middle-aged subjects. The constant feature of this pattern was that the roof of the acetabulum failed to make contact with the head, and this was the case whatever the position in which the joint was articulated.

Some exceptions to this rule were found in middle-aged and elderly subjects. In these the contact areas were irregular and involved the dome of the acetabulum (Fig. 12).

On the basis of these experiments it was suggested that the components of the normal young hip articulate in the manner of a ball thrust into a Gothic arch. In all positions of the joint, the anterior and posterior limbs of the horseshoe of articular cartilage on the acetabulum make contact with the head, but the dome does not. In the performance of joint movement, the contact areas sweep over the surface of the femoral head, so that at 90 degrees of flexion the head makes contact on its superior and inferior surfaces.

These conclusions would have relevance to the *in vivo* condition only if similar patterns of contact and non-contact on the acetabulum could be demonstrated when the joint is subjected to physiological levels of load. For this reason a loading frame was constructed in which cadaveric hip joints could be mounted in typical anatomical positions and subjected to loads up to the maximum level encountered in normal activity. The method of detecting the contact areas developed by Greenwald (1970) was to add dye to the bath of Ringer's solution in which the loaded hip was immersed, staining the non-contact areas and leaving the contact areas unstained. The results of these contact studies have already been reported (Greenwald and Haynes 1972).

This contact study confirmed the results of the earlier experiments by demonstrating a non-contact area on the dome of the acetabulum of young subjects when the joint was under a light load, and further confirmed that this area of non-contact was essentially independent of the position of the hip joint. In contrast the acetabular contact areas proved to be very sensitive to the magnitude of the load transmitted. As the load increased, the cartilage (and probably the bone) deformed, the contact areas grew and at a certain critical load the head of the femur touched the dome of the acetabulum and contact was complete.

Furthermore, Greenwald's experiments again suggested that non-contact at the dome of the acetabulum, while typical of young joints, was often not demonstrable in the elderly. Of the joints he tested at loads of less than 20 kilograms, eleven were aged sixty years or more and twenty-nine were in the range twenty-four to sixty years. Non-contact on the dome was found in twenty-four (83 per cent) of the younger group, but in only four (36 per cent) of the older group.

Magnitude of the load required for complete contact—Because we wish to know how much the cartilage on the dome of the acetabulum is actually "used" it is important to estimate the magnitude of the load which is required to bring about complete contact. Greenwald concluded that loads in excess of about 20 per cent of the body weight were apparently sufficient to achieve complete contact, even in young hips.

We believe that the method he used—replacement of the saline bath surrounding the loaded hips by a dye solution—could seriously overestimate the size of the contact areas and consequently underestimate the load required for complete contact. In this method it was assumed that the dye spread over the non-contact areas and penetrated to the very edge of the contact areas, and in grossly incongruous joints this might well be a reasonable assumption. In a closely fitting joint such as the hip the assumption needs to be examined.

Two factors could prevent dye penetration to the edge of the contact areas. If the gap between the surfaces is not already filled with fluid, a meniscus could form between the cartilage surfaces at some distance from the contact edge. If the gap is filled with fluid, the non-contact areas would be dyed completely only if the dye is present in the joint for a sufficient time to allow diffusion of the dye molecules to the contact edge.

To examine these possibilities two segments of a femoral head were cemented to the jaws of a Vernier calipers in such a way that the cartilage surfaces could be brought into contact or separated with a known minimum gap. In one type of experiment the surfaces, after soaking in Ringer's solution, were dried with tissue before being placed in a stationary bath

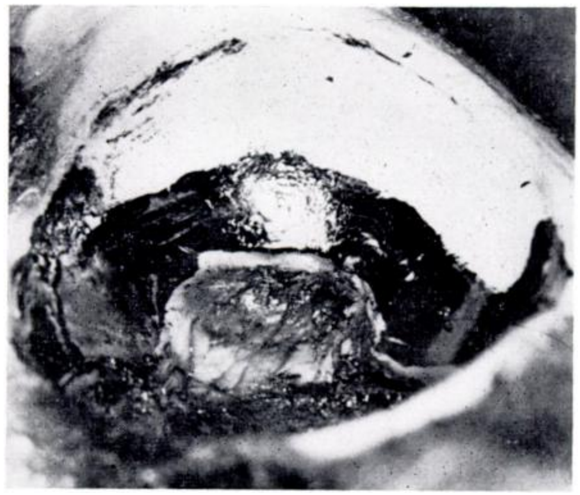

FIG. 9

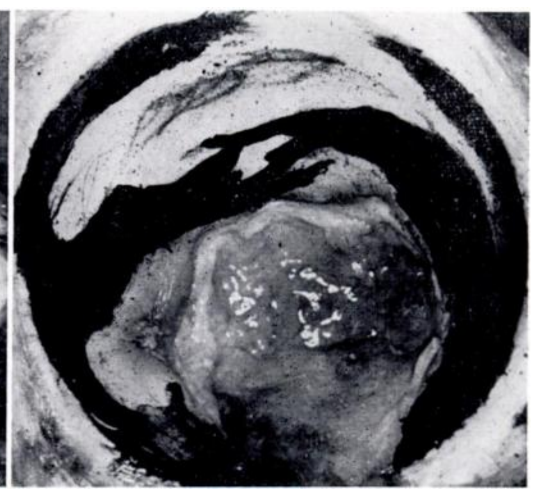

FIG. 10 FIG. 11

Positive contact prints of the acetabulum demonstrating a pattern of non-contact on the dome of the acetabulum. Figure 9—In a twelve-year-old child. Figures 10 and 11—In young adults.

of 0·1 per cent saffron dye in Ringer's solution and held there for a minute at body temperature. In another type of experiment the specimens were transferred directly from a clear bath to a dyed bath, with a ring of undyed fluid of about half an inch diameter held in the minimum gap between the surfaces. For a given pair of specimens the experiment was repeated at a number of minimum gap settings varying initially from zero to about 0·3 millimetres. The diameter of the undyed circle on each surface after each test was measured with a ruler under a magnifying glass. The results are given in Table I in which the diameters given represent the average of eight measurements. Specimen number 5 differs from the others in that the dye bath was agitated, assisting penetration of the dye. The experiments were repeated on the same specimens using methyl violet dye with very similar results.

This experiment indicates that the dye cannot penetrate beyond a minimum gap of about 0·1 millimetre. The circumstances of the experiment are probably more favourable for dye penetration than an intact joint, in that the area to be dyed was completely surrounded by dye, and the curved surfaces opposed to one another were both convex.

When it is remembered that the maximum gap between the unloaded surfaces of the hip joint is about 0·5 millimetre (Walker, Dowson, Longfield and Wright 1968), the results of this experiment will be seen to cast serious doubt on the accuracy of the dye technique for the measurement of contact areas in the hip. Once the maximum gap has diminished to 0·1 millimetre no part of the non-contact area would be demonstrated. Furthermore, were the maximum gap to lie anywhere but at the periphery of the joint the technique would suggest total contact even before this degree of congruency had been attained.

These considerations may explain why the non-contact areas defined by this method were never smaller than 30 per cent of the total area of acetabular cartilage. It is concluded that the dye technique when applied to the hip joint seriously overestimates the magnitude of the contact areas, and therefore underestimates the magnitude of the load required for complete contact.

TABLE I

The Diameter of Undyed Circle at Different Values of Minimum Gap

Specimen number	1		2		3		4		5	
Wet or dry	Wet		Wet		Dry		Dry		Dry and agitated	
	A	B	A	B	A	B	A	B	A	B
	0·0	3·1	0·0	2·9	0·0	3·4	0·0	4·0	0·0	1·0
	0·1	2·4	0·1	2·2	0·05	0·5	0·02	3·13	0·02	0
	0·2	0·8	0·15	0	0·1	0	0·04	1·8		
	0·3	0					0·08	0		

Column A: Minimum gap setting, in millimetres.
Column B: Diameter of undyed circle, in millimetres.

Cartilage creep and rate of loading—Kempson (1970) performed indentation tests on cartilage of the femoral head which imply that "creep" is an important feature of its mechanical behaviour. He measured the displacement of a rigid indentor pressed into the cartilage under a constant load, and found that the instantaneous deflection which occurred when the load was applied was followed by a deflection which increased with time. Typically after one minute the deflection had doubled, and after thirty minutes it had quadrupled.

When a part of the surface of cartilage is indented fluid tends to flow from the region beneath the indentor and to be reabsorbed when the indentor is removed. That portion of the deflection of the indentor which is attributable to fluid flow is time dependent and is termed "creep".

In the contact studies referred to above the load was held constant for approximately one minute before the dye was introduced, and the contact areas that were detected were therefore those existing after the cartilage had suffered the effects of "creep" for this period. The contact areas were therefore larger than those which existed when the load was first applied, or, to put it another way, the load required under these circumstances was less than would have been required to achieve complete contact at the moment of application. The method must therefore give an underestimate of the load required for complete contact at the loading rate typical of walking.

To summarise, the evidence suggests that loads higher than the quoted 20 per cent of body weight are required to bring the dome of the acetabulum into contact with the top of the femoral head. Greenwald and O'Connor (1971) have reported some preliminary results of an alternative method of testing in which the deflection of the bony elements of the hip is measured as they approach one another under increasing loads. The results suggest that loads of about half body weight may be required for complete contact.

The magnitude of the load transmitted through the hip—Assuming that loads of the order of half body weight must be transmitted through the hip before the dome of the acetabulum comes into contact, it has to be established whether such loads are exceeded frequently or rarely, and hence whether the cartilage on the dome is habitually in contact or not.

FIG. 12
Positive contact print demonstrating extensive contact over the dome of the acetabulum in an old subject. Also note the degenerative surface changes in the cartilage on the dome.

Comprehensive studies of the magnitude of the load transmitted through the hip have been made by Paul (1967) and Rydell (1966). Paul studied normal walking and calculated values of the hip load from measurements of limb movement, ground reaction and myographic information. Rydell studied a wide range of activities, but his results are strictly applicable only to the particular prosthesis which he used. Comparing the two sets of results for normal walking the variations in the magnitude of the load from swing phase to stance phase are generally similar, although the values determined by Paul during the stance phase are larger than those measured by Rydell. For our present purposes both studies show that in the stance phase the load exceeds body weight, rising to about four times body weight (Paul) during push off. During the swing phase the load varies from about three-quarters of the body weight with the leg in its extreme positions, down to zero in mid-swing (Paul).

From the much wider range of activities studied by Rydell we conclude that the load transmitted through the hip exceeds half body weight only when the corresponding foot is supporting a substantial proportion of the weight of the body. Certainly while sitting "no force was measured" in one subject, whilst the load measured in another was at most about 0·13 per cent of body weight. When lying either prone or supine the hip load exceeded half body weight only when one leg was actively flexed or extended from the position of full extension. These results give support to the general proposition that the hip is subjected to "large" loads only when standing, walking, running or kneeling.

To establish whether or not the dome of the acetabulum could be termed an habitual non-contact area it remains to determine the proportion of the twenty-four hour day which is spent in one foot contact. Assume that the day is divided into periods of eight hours sleeping and sixteen hours awake. A proportion of the period of wakefulness is spent sitting, the remainder standing or walking, and these proportions vary widely throughout the community. An estimate of the limits of these variations can be made from the work of Marsden and Montgomery (1971). They conducted a survey to determine the number of steps taken by a sample of fifty-seven individuals during their normal activities of daily living. Their counter registered each time a load of more than about three-quarters of the body weight was taken over the heel. They found that about 50 per cent of their sample took no more than 450 steps per hour, about 85 per cent took no more than 750 steps per hour. Only postmen averaged more than 1,200 steps per hour. These figures account for purposeful movement from one place to another, but also reflect substantial weight transfer from one foot to the other when standing still. They enable us to estimate the proportion of time spent in one foot contact by those people who, when not walking, are sitting or lying.

Assume that the normal day is divided into a period of eight hours lying and sixteen hours of activity. Assume that a particular foot is carrying substantial load for 60 per cent of the time spent walking, and that one complete step is taken in one second. Those people who average 450 steps per hour for sixteen hours spend a total of 1·2 hours (5 per cent of the day) with one particular foot in contact. 750 steps per hour represents two hours of contact (8·3 per cent of the day), 1,200 steps per hour represents 3·2 hours (13·3 per cent of the day). On the other hand a person who stands for eight hours per day probably spends about six hours (25 per cent of the day) transmitting substantial load through one particular foot.

DISCUSSION

Incongruency of the opposed surface curvatures is then a feature of the human hip joint. In the terms of mechanical engineering the dome of the normal acetabulum is "relieved", and the existence of this feature invites speculation upon its significance, if any, in normal joint function. We believe that it cannot be dismissed as a simple anatomical inexactitude because we have found a very similar design feature in other joints of this type—joints in which the convex component is more or less completely embraced by the concave one. In most mammalian joints the articular surface of the concave component is small in proportion to the surface of the male component. In man only the humero-ulnar joint approximates to the mechanical circumstances of the hip. Figure 13 demonstrates that the opposed curvatures of the humerus and ulna articulate in the same manner as the hip. The floor of the trochlea notch is relieved so that in the unloaded state there is an extensive non-contact area within the joint. Anterior and posterior articular facets are clearly defined, and parts of the non-contact area on the trochlea are not even covered by cartilage.

If there is a biological necessity to provide non-contact areas within deeply concave joints we should expect to find the same feature in the hip joints of other species—and indeed this is the case. Figure 14 demonstrates in the hip joint of a rabbit an extensive non-contact area at the expected site.

It is suggested that incongruency of curvatures of the particular type which these joints demonstrate, is necessary to ensure adequate circulation of synovial fluid within the joint. Cartilage depends upon constant wetting of its surface both for its nutrition and its lubrication, and the mechanism whereby fluid enters upon the contact areas can be shown to depend in part upon the geometry of the joints.

Consider first the common joint form in which a relatively large convex area articulates with a small concave one. Figure 15 demonstrates that in this model there is no real problem in wetting the surface of the convex component. Since only a small proportion of its surface is masked at any one time by the concave facet, small reciprocal movements (in this case of an amplitude of 45 degrees) result in exposure of the whole surface to the sump of synovial fluid. It is the concave component which presents the problem. Its surface is never exposed but must depend upon secondary wetting by contact with recently moistened cartilage from the other component.

The bigger the concave facet the greater the amplitude of movements that is required to work fluid from the periphery into the centre of the joint. Figure 16 A and B demonstrates that in a hip joint constructed on this principle the cartilage on the dome of the acetabulum and the top of the femoral head would remain outside the area of synovial fluid circulation

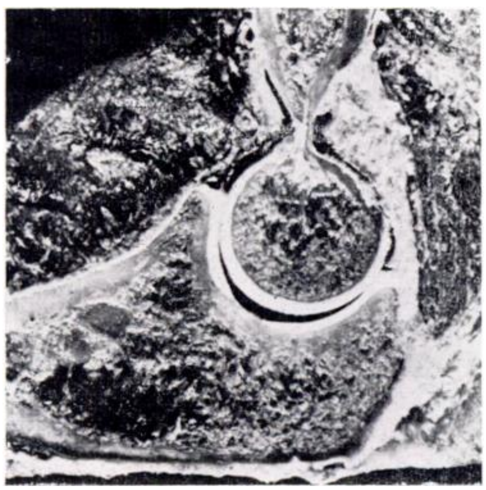

FIG. 13

FIG. 14

Figure 13—Section of the humero-ulnar joint of a young subject in the sagittal plane. The whole joint was frozen solid in a block of gelatin before section. Figure 14—Non-contact area on the dome of the rabbit's acetabulum—demonstrated by incursion of safranin dye when the components of the joint were moved under light load. This specimen is orientated with the acetabular notch below, to match the human specimens. Note that this is a negative print in which the contact areas are undyed.

during reciprocating movements of an amplitude of less than 90 degrees. During normal walking the amplitude of hip movements is about 30 degrees—much less than would be required to maintain adequate nutrition and lubrication at this site.

Of course in life the hip movement is not so simple. Associated movements of rotation, abduction and adduction must all contribute to the process of wetting those parts of the femoral head which transiently emerge from the cover of the acetabular cartilage. Nevertheless, in a congruous joint the cartilage on the dome of the acetabulum and the top of the femoral head would enjoy the least privileged environment. The slightly elliptical shape of the acetabulum allows the access of synovial fluid to this area when the joint is unloaded (Fig. 16 C).

An unavoidable result of providing a non-contact area within an articulation is that the contact areas available for the transmission of loads are less extensive than they would be in a perfectly congruous system. The human hip, which is required to transmit loads of four times body weight during walking, and still higher loads during the activities of running and jumping, has so fine a degree of incongruency of its surfaces that the compliance of its component materials allows total contact to occur when such loads are imposed.

We see in the design of this joint an ideal correlation between, on the one hand, the precise shapes of its components and, on the other, the physical properties and biological requirements of the materials of which it consists—a correlation which could be disturbed seriously by an alteration in either. In seeking an explanation for failure of the joint, attention has usually been focused on the materials—particularly the articular cartilage. We would draw attention rather to the importance of the shape.

First, we need to explain the prevalence, in the community we describe, of surface degenerative changes in specific areas of some joints—in this instance the peripheral and perifoveal areas of the femoral head and the dome of the acetabulum. In the case of the areas on the femur the correlation with areas of habitual non-contact is so convincing as not to require further comment. If the arguments in this paper are valid the dome of the acetabulum may make contact with the femoral head for as little as 5 per cent or as much as 25 per cent of any twenty-four hours, and therefore qualifies for similar description. Habitual non-contact is the result, as the term supposes, of the habits of the subject. If the men and women in our population regularly employed the full range of movements available at their hip joints, and spent their waking hours walking and running instead of sitting, there would be no areas of cartilage in the hip which were not used regularly. We assume that in such a population there would be no surface changes in the articular cartilage of these areas—but it is an assumption which cannot be proved until a survey of the joints of such a population has been undertaken.

But how can a regime of habitual non-contact with opposed cartilage result in surface degeneration? Certainly not as the result of abrasion. Nor from a quantitative failure of nutrition, for there is no problem of access of synovial fluid to the surface of such cartilage. The "pumping" action of intermittent pressure has been supposed to assist in the penetration of synovial fluid into the deeper layers of cartilage from its surface, but experiment has not supported this theory (Maroudas, Bullough, Swanson and Freeman 1968). So we are not able to answer the question except by analogy with other connective tissues which undergo atrophy as a result of disuse.

What significance ought we to attach to the existence of these changes at these sites? Because degeneration in these areas is common in young adults and the rule in older subjects, they must be assumed to exert no serious effect upon the function of the joint. If habitual disuse explains the origin of these changes it also explains why they are not, in themselves, productive of symptoms.

Do such changes play any part in the genesis of serious joint failure? Primary osteoarthritis is a disease of old people; old people's joints commonly display these age-dependent changes; and there is evidence to suggest that they are not merely coincidental. The degenerative process which results from relative disuse begins with softening of the cartilage and a decreased content of sulphated mucopolysaccharide in the matrix and ends with disruption of the collagen framework. That framework is disposed, as in other connective tissues, to resist tension forces within the material, and in the cartilage covering a joint facet it is organised as a whole. To understand this is to accept that a lesion in any part may prejudice the integrity of it all (Bullough and Goodfellow 1968).

However, to recognise that age-dependent cartilage changes may set the scene for failure in more significant areas still leaves unanswered the question why some of the joints so affected should develop the disastrous sequence of events called osteoarthritis, and others not. By the process of exclusion we have reached the hypothesis that osteoarthritis is that sequence of events which follows upon failure of the articular cartilage within an habitual contact area. Certainly to damage the articular cartilage of a joint is a sure way to induce that sequence of events. Whether it be damaged by accident or as a result of suppurative arthritis in man, or as the result of scarification or papain injection in the experimental animal, secondary osteoarthritis is predictable. In primary osteoarthritis no such extrinsic factor can be incriminated, but the disorder is characterised by an exactly similar sequence of changes and might therefore be supposed to have a similar cause, namely failure of articular cartilage in an habitual contact area.

We have given our reasons for believing that the components of the normal hip joint are precisely shaped to provide at once ideal circumstances for lubrication and nutrition of the habitually loaded cartilage, and the best possible distribution of load. The evidence both of the curvature measurements and the contact studies is that, in some old people, these design features are lost and that the components then attain to a more or less exact fit. A similar

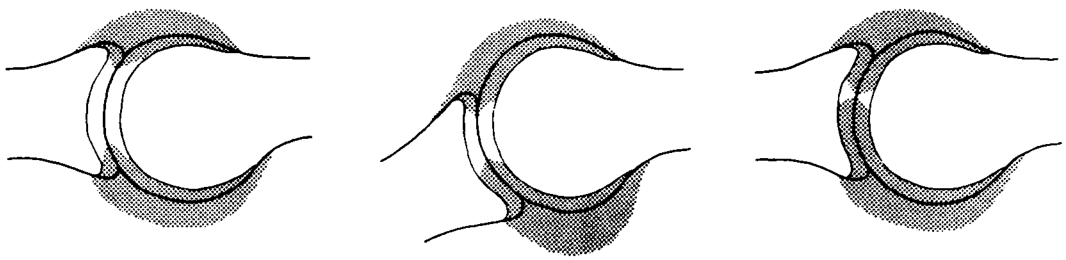

FIG. 15

Simplified model of a joint in which the articular area of the concave component is small in proportion to the area of the convex component. Reciprocal movements of 45 degrees amplitude would result in adequate "wetting" of the concave component with synovial fluid.

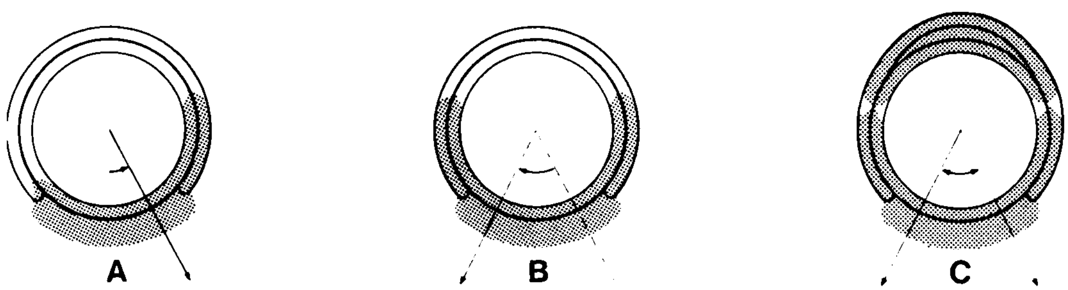

FIG. 16

Simplified model of a hip joint in sagittal section, showing the areas of cartilage secondarily "wetted" from the sump of fluid in the acetabular notch during reciprocal movements of an amplitude considerably greater than occurs in normal walking. A and B show that, were the surfaces perfectly congruent, the dome of the acetabulum and the upper surface of the head would enjoy a very poor circulation. C demonstrates the actual state of affairs when the hip is under light loads, for instance during a proportion of the swing phase of walking.

change has been observed in the humero-ulnar joints of old subjects (Goodfellow and Bullough 1967).

If the fine incongruencies of curvature are significant in providing a tolerable environment for loaded cartilage their loss would initiate an inexorable process of cartilage failure from malnutrition and abrasive wear; and furthermore the dome of the acetabulum, its cartilage degenerate from relative disuse during the regime of incongruity, would then become an habitual contact area—with disastrous consequences for the cartilage on the femoral head with which it would then make constant contact.

We believe it may prove fruitful to study the mechanisms which so precisely maintain joint incongruity in youth since failure of these mechanisms may be a significant factor in explaining the onset of primary osteoarthritis.

SUMMARY

1. A predictable pattern of degeneration occurs on both the femoral head and the acetabulum and this pattern is age dependent.
2. The degenerative areas on the femoral head are related to habitual non-use.
3. The hip is shown to be anatomically incongruent, and the dome of the acetabulum, a predictable area of degeneration, is shown also to be an area of habitual non-use.
4. The possible relationships between age-dependent degenerative changes and senile degenerative joint disease is discussed and the importance of changing geometry stressed.

The authors are grateful to the Arthritis and Rheumatism Council for their financial support, and to Mr J. M. F. Davidson for assistance with the experiments detailed in Table I. They also express their thanks to Miss Pat English for secretarial help, and to Mr Robert Emanuel and Mr Graham Bartlett for help with the illustrations.

REFERENCES

BULLOUGH, P., GOODFELLOW, J., GREENWALD, A. S., and O'CONNOR, J. (1968): Incongruent Surfaces in the Human Hip Joint. *Nature (London)*, **217,** 1290.

BULLOUGH, P., and GOODFELLOW, J. (1968): The Significance of the Fine Structure of Articular Cartilage. *Journal of Bone and Joint Surgery*, **50–B,** 852.

BYERS, P. D., CONTEPOMI, C. A., and FARKAS, T. A. (1970): A Post Mortem Study of the Hip Joint. *Annals of the Rheumatic Diseases*, **29,** 15.

EGGERS, G. W. N., EVANS, E. B., BLUMEL, J., NOWLIN, D. H., and BUTLER, J. K. (1963): Cystic Change in the Iliac Acetabulum. *Journal of Bone and Joint Surgery*, **45–A,** 669.

GOODFELLOW, J. W., and BULLOUGH, P. G. (1967): The Pattern of Ageing of the Articular Cartilage of the Elbow Joint. *Journal of Bone and Joint Surgery*, **49–B,** 175.

GOODFELLOW, J. W., and BULLOUGH, P. G. (1968): Studies on Age Changes in the Human Hip Joint. *Journal of Bone and Joint Surgery*, **50–B,** 222.

GOODFELLOW, J. W., HUNGERFORD, D., and ZINDEL, M. (1971): Chondromalacia Patellae. *Orthopaedics: Oxford.* Volume 4, 111.

GREENWALD, A. S. (1970): The Transmission of Forces through Animal Joints. Oxford: *D.Phil. Thesis.*

GREENWALD, A. S., and HAYNES, D. W. (1972): Weight-bearing Areas in the Human Hip Joint. *Journal of Bone and Joint Surgery*, **54–B,** 157.

GREENWALD, A. S., and O'CONNOR, J. J. (1971): The Transmission of Load Through the Human Hip Joint. *Journal of Biomechanics*, **4,** 507.

HARRISON, M. H. M., SCHAJOWICZ, F., and TRUETA, J. (1953): Osteoarthritis of the Hip: A Study of the Nature and Evolution of the Disease. *Journal of Bone and Joint Surgery*, **35–B,** 598.

KEMPSON, G. E. (1970): Mechanical Properties of Human Articular Cartilage. London: *Ph.D. Thesis.*

MACCONAILL, M. A. (1950): The Movements of Bones and Joints. *Journal of Bone and Joint Surgery*, **32–B,** 244.

MAROUDAS, A., BULLOUGH, P., SWANSON, S. A. V., and FREEMAN, M. A. R. (1968): The Permeability of Articular Cartilage. *Journal of Bone and Joint Surgery*, **50–B,** 166.

MARSDEN, J. P., and MONTGOMERY, S. R. (1971): Plantar Power for Arm Prostheses using Body Weight Transfer. In *Conference on Human Locomotor Engineering*, p. 260. Held on September 7-10, 1971, at the University of Sussex. London: Institution of Mechanical Engineers.

PAUL, J. P. (1967): Forces Transmitted by Joints in the Human Body. *Proceedings of the Institution of Mechanical Engineers*, **181** (3J), 8.

RYDELL, N. (1966): Intravital Measurements of Forces Acting on the Hip Joint. In *Studies of the Anatomy and Function of Bones and Joints*, p. 52. Edited by F. G. Evans. Berlin: Springer-Verlag.

WALKER, P. S., DOWSON, D., LONGFIELD, M. D., and WRIGHT, V. (1968): "Boosted Lubrication" in Synovial Joints by Fluid Entrapment and Enrichment. *Annals of the Rheumatic Diseases*, **27,** 512.

WALMSLEY, T. (1928): The Articular Mechanism of the Diarthroses. *Journal of Bone and Joint Surgery*, **10,** 40.