STRESS DISTRIBUTION IN THE TROCHLEAR NOTCH

A MODEL OF BICENTRIC LOAD TRANSMISSION THROUGH JOINTS

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In 16 cadaver humeroulnar joints, the distribution of subchondral mineralisation was assessed by CT osteoabsorptiometry and the position and size of the contact areas by polyether casting under loads of 10 N to 1280 N.

Ulnas with separate olecranon and coronoid cartilaginous surfaces showed matching bicentric patterns of mineralisation. Under small loads there were separate contact areas on the olecranon and coronoid surfaces; these areas merged centrally as the load increased. They occupied as little as 9% of the total articular surface at 10 N and up to 73% at 1280 N. Ulnas with continuous cartilaginous surfaces also had density patterns with two maxima but those were less prominent, and in these specimens the separate contact areas merged at lower loads. The findings indicate a physiological incongruity of the articular surfaces which may serve to optimise the distribution of stress.

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Evaluation of the stress distribution throughout the surface of a joint is often made by assessment of the contact areas. The position and size of these areas, however, depend on the forces acting on the joint as well as on the geometry of the articular surfaces (Greenwald and Haynes 1972; Bullough, Goodfellow and O'Connor 1973; Miyanaga, Fukubayashi and Kurosawa 1984). Nevertheless, the actual stress distribution cannot be derived from measurements of the joint force and the size of the contact areas because the distribution of pressure within the contact zones may not be uniform (Hehne 1983; Miyanaga et al 1984).

It is possible, however, to assess the physiologically effective pressure distribution over the surface of a joint from the functional adaptation of the subchondral tissues (Kummer 1962; Tillmann 1978; Pauwels 1980). Using the theory of 'causal histogenesis', Müller-Gerbl and her co-workers (1989, 1990, 1992) have developed the technique of CT osteoabsorptiometry (CT-OAM) to produce a surface projection of the distribution of subchondral mineralisation. The density pattern obtained with this method reflects the 'loading history' (Carter 1984; Carter, Wong and Orr 1991) of the joint surface during daily life. It is an expression of the sum of a vast number of single stress-events (Pauwels 1980; Müller-Gerbl et al 1989), but does not allow their temporal and spatial differentiation.

We have investigated both the distribution of subchondral mineralisation and the size and position of the contact areas to establish the principle of load transmission at the humeroulnar joint.

MATERIALS AND METHODS

We used the right elbows of eight male and eight female cadavers of mean age 78.3 years (60 to 90). The specimens had been fixed in 3.7% formalin and were kept in that fixative throughout the study. Those with damage to the cartilage visible to the naked eye were excluded.

Eight specimens had olecranon and coronoid cartilaginous facets in the trochlear notch separated by a zone of bone. This type of joint surface is found in about 65% of older subjects (Tillmann 1978). These specimens formed group A. In four ulnas the cartilage was divided into two areas on the medial side but there was a complete covering laterally (about 30% according to Tillmann). In another four the olecranon notch was completely covered by cartilage (5% of older subjects according to Tillmann). These eight specimens formed group B.

CT osteoabsorptiometry. The articular surfaces of the ulna were imaged in the sagittal plane at 2 mm intervals (overlapping section thickness 4 mm) in a Siemens Somatom SF CT scanner (Siemens, Erlangen, Germany). The distribution of subchondral mineralisation was then determined for each section by CT-OAM (Müller-Gerbl

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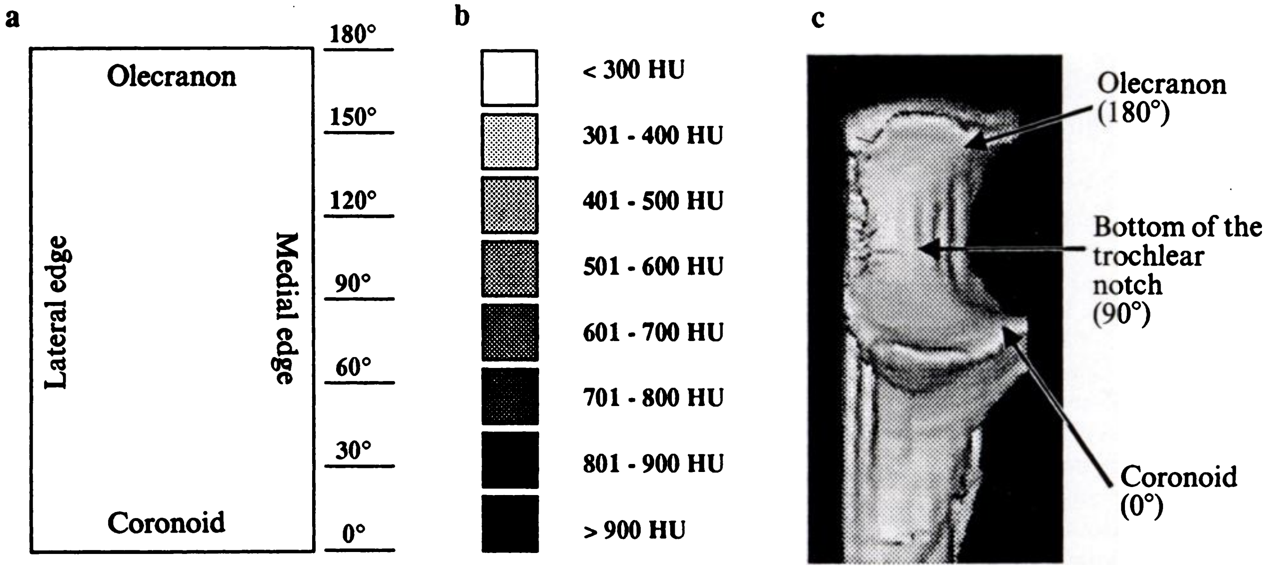

Fig. 1

Method of CT osteoabsorptiometry. Figure 1a – Template of the trochlear notch for graphic presentation of the average distribution patterns. Figure 1b – Hounsfield intervals used for the surface mapping of subchondral mineralisation. Figure 1c – Reconstruction of an individual ulnar articular surface by 3-D CT-OAM.

et al 1989, 1990), using intervals of 100 Hounsfield units (HU) from < 300 to > 900 HU. The density intervals were then projected on to a template of the trochlear notch (Fig. 1a) to provide a surface demonstration of subchondral mineralisation. Different grey values were allotted to the eight intervals of density (Fig. 1b) to facilitate comparison between groups A and B; the average density for each group was calculated using Adobe Photoshop software (Adobe Systems Europe, Amsterdam, The Netherlands).

Finally, 3-D CT-OAM (Müller-Gerbl et al 1992, 1993) was used to produce a three-dimensional reconstruction of the trochlear notch (Fig. 1c) and an image-analysing system to provide a grey-scale scheme demonstration of the eight Hounsfield intervals.

Assessment of the contact areas. The head of the radius and all the soft tissues around the joint were resected. The ulna was positioned on the table of a Zwick material testing machine (Zwick Gmbh, Ulm, Germany), so that the tips of the coronoid process and the olecranon were at the same height. The humeral shaft was fixed so that the position of the joint corresponded to 90° flexion of the elbow; thus when the bones were articulated the resultant force passed through the centre of the trochlear notch. This is in accordance with calculations made by Morrey (1985). To define the contact areas, a polyether casting substance (Permadyne, ESPE, Seefeld, Germany) was poured into the trochlear notch and the humeral condyles were pressed with a defined force into the notch by the testing machine. The structures were held immobile until the cast had set. In this way a series of casts was obtained for each joint under loads of 10, 20, 40, 80, 160, 320 and 1280 N. The articular surfaces were kept moist by physiological saline throughout the experiment.

To measure the size of the contact areas, a piece of aluminium foil was cut to cover the entire area of the potential articular surface of the ulna. The actual contact areas seen on the polyether cast were transferred to the foil which was then divided into quadrants along the longitudinal ridge of the trochlea and the transverse furrow. The size of these quadrants and of the contact areas was measured by an image analysing system (Vidas IPS, Kontron, Eching, Germany). The ratio of the contact area to the whole surface of the trochlear notch was calculated for each group for each of the loads applied. The extent of the contact areas in the sagittal plane was recorded graphically for each specimen (under the eight graded loads) by dividing the trochlear notch into 18 segments each of 10° (0° = coronoid process; 180° = olecranon; Fig. 2). Finally, summation pictures were constructed for each group in which the frequency of joint contact in each region of the articular surface was demonstrated.

To check the reproducibility of the casting method and the image analysis, six casts were obtained from one ulna under a load of 20 N, and each was subjected to the evaluation technique described above.

RESULTS

The reproducibility of the measurements of the size of the total articular surface, of the size of the contact area, and of their proportions is shown in Table I. In all cases the coefficient of variation is less than 6%.

Group A. In all eight subjects the subchondral mineralisation showed a bicentric pattern with one maximum beneath the olecranon and one beneath the coronoid joint surface. The bony furrow in the depths of the trochlear

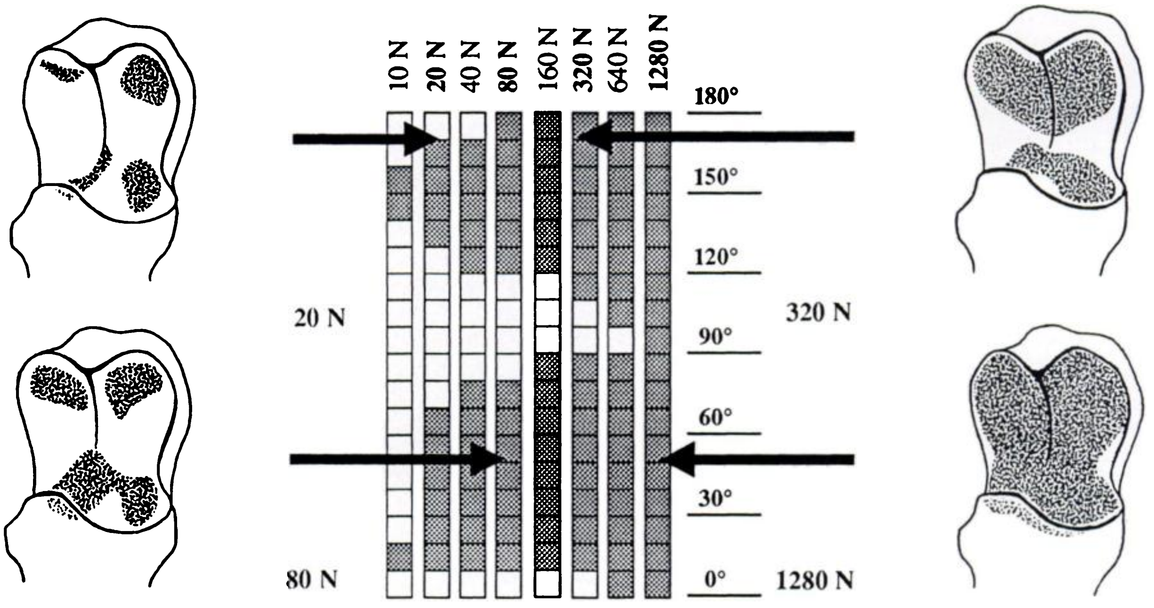

Fig. 2

Graphic documentation of the sagittal (superoinferior) extent of the contact areas under different loads.

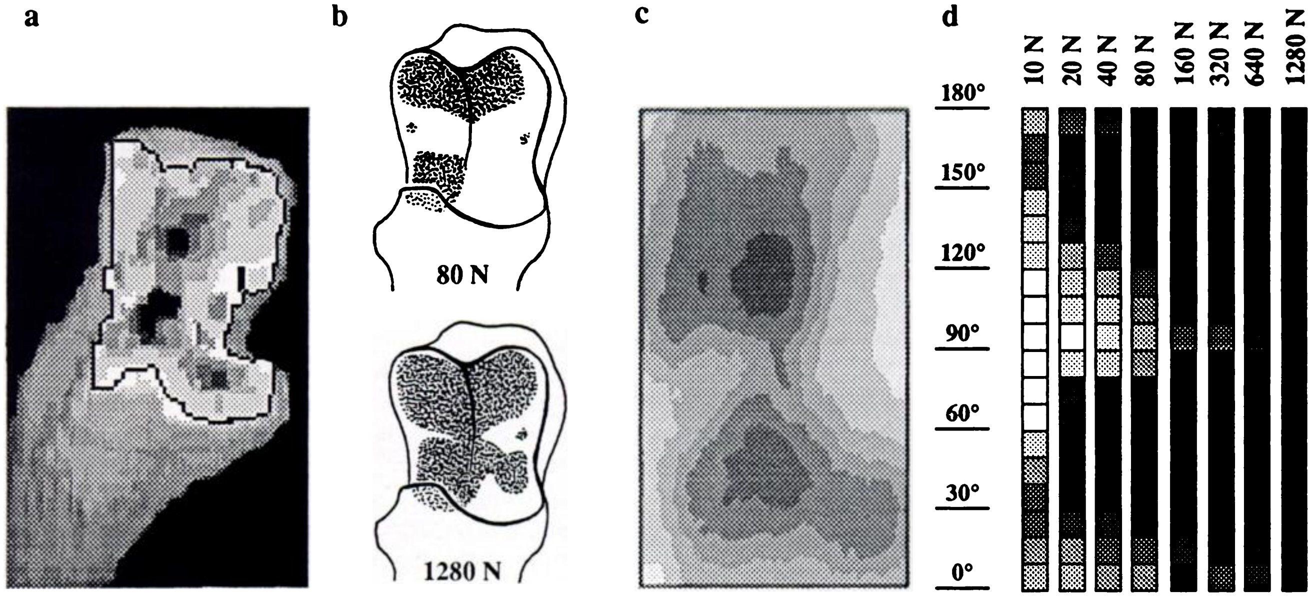

Fig. 3

Figure 3a – Subchondral mineralisation pattern of a single specimen in group A (3-D CT-OAM). Figure 3b – The contact areas at 80 N and 1280 N in the same specimen. Figure 3c – Average distribution of subchondral mineralisation (group A). Figure 3d – Average frequency of contact (white = no specimen; black = all specimens) at each of 18 sagittal segments of the trochlear notch (group A).

notch was less heavily mineralised, by as much as 300 HU. In the example shown in Figure 3a the contact areas were localised superiorly and inferiorly in the joint under a load of 80 N, and merged in the depths of the notch at 1280 N (Fig. 3b).

The average distribution of subchondral mineralisation of all eight specimens had a similar bicentric pattern (Fig. 3c), the central region of the notch showing an average mineralisation of 200 HU less than the neighbouring maxima. Under a load of 80 N, the contact areas were most commonly in the segments 30° to 80° and 130° to 170° (Fig. 3d). Under a load of 1280 N, contact extended from 20° to 180° in every specimen. The average proportionate size of the contact areas increased from about 10% at 10 N to as much as 73% at 1280 N (see Fig. 5a).

Group B. A monocentric pattern was seen in two specimens from group B. In one example (Fig. 4a) with a maximum area of density on the coronoid surface, the contact area was located centrally in the depths of the

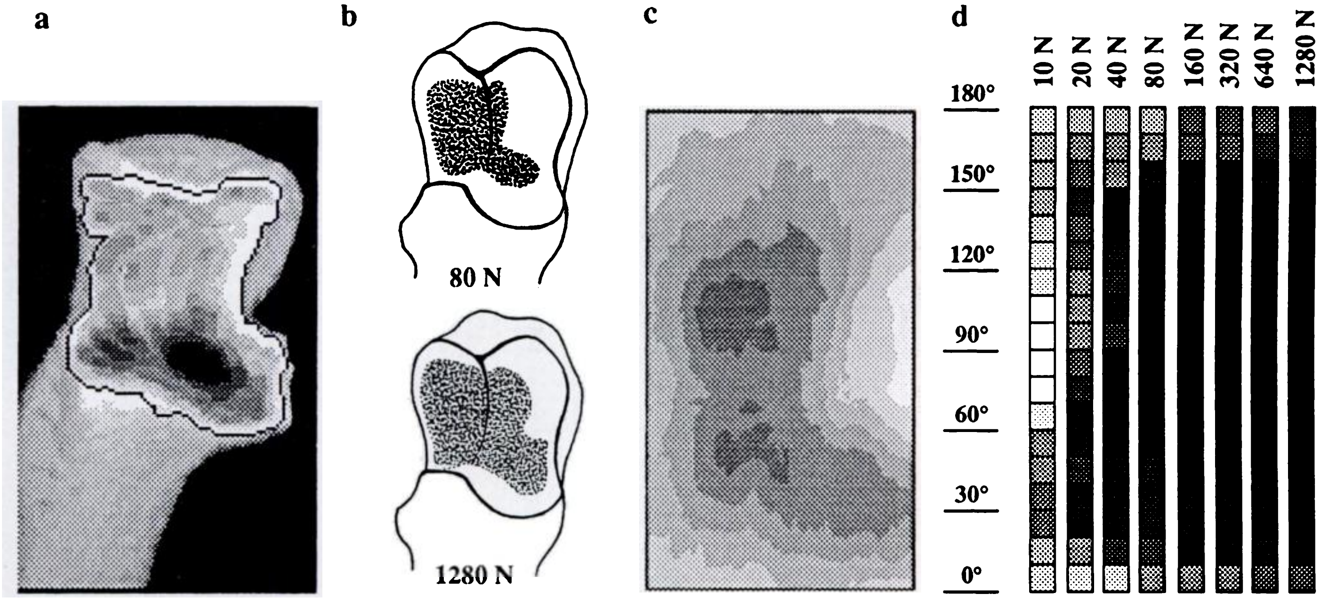

Fig. 4

Figure 4a – Subchondral mineralisation pattern of a single specimen in group B (3-D CT-OAM). Figure 4b – The contact areas at 80 N and 1280 N in the same specimen. Figure 4c – Average distribution of subchondral mineralisation (group B). Figure 4d – Average frequency of contact (white = no specimen; black = all specimens) at each of 18 sagittal segments of the trochlear notch (group B).

trochlear notch under loads of 80 N and 1280 N (Fig. 4b). Six specimens, however, showed superior and inferior maxima of subchondral mineralisation, and the summation picture of all eight specimens had a bicentric pattern (Fig. 4c). The areas of higher density were slightly more central in position than those in group A, and the difference in density between the central area and the two maxima was only about 100 HU. The contact areas were also more centrally located than in group A (Fig. 4d). Under a load of 80 N all eight specimens showed continuous contact in the depths of the notch between 50° and 130°, increasing to 30° to 150° at 1280 N. The size of the contact area was on average 9% under a load of 10 N and 64% at 1280 N (Fig. 5b).

DISCUSSION

The repeated evaluation of the size of the contact area in a single joint under a load of 20 N showed that the results were reproducible, and that both the casting method and the image analysis allowed quantitative evaluation. This does not mean that the absolute values obtained here can be directly transferred to the physiological condition of the joint. Kurrat (1977) claimed that formalin fixation had no influence on the thickness of the cartilage, but slight shrinkage before or during the investigation cannot be excluded. The effect of thicker cartilage, however, is to make load transmission through the peripheral contact areas even more pronounced, because thicker cartilage increases the incongruity between the trochlear notch and the trochlea. Oberländer, Breul and Kurrat (1984), who took into account the animal experiments reported by Ingelmark and Ekholm (1948), suggested that there may be a functional swelling of the cartilage of the humeroulnar joint at the beginning of physiological activity which would, of course, result in a further increase in its incongruity.

Formalin fixation may also affect the viscoelasticity of the articular cartilage, a property which, according to Mow, Holmes and Lai (1984), depends on the interaction of the fluid component of cartilage and its solid matrix. We cannot therefore exclude the possibility that an investigation carried out on unfixed material may produce slightly different absolute values. The pattern of load transmission which we have demonstrated, however, of a small load being associated with peripheral contact and

Table I. Reproducibility of measurements of six casts of the ulnar contact areas made for the same ulna under 20 N load

	Mean	**Standard deviation**	**Coefficient of variation (*percentage*)**
Size of the total articular surface (mm²)	1090	24.6	*2.26*
Size of the contact area (mm²)	159	9.5	*5.98*
Proportion of the total articular surface in contact (%)	*14.58*	*0.826*	*5.66*

higher forces causing an increase in the contact areas until they merge centrally, would not be altered in principle and the relative values measured should be valid.

The fact that separate superior and inferior contact areas can be observed at lower forces agrees well with the findings of Goodfellow and Bullough (1967) and Walker (1977), in each case of a single specimen. Goel, Singh and Bijlani (1982) also described peripheral contact areas in flexion in 13 fixed specimens but they did not report the loads applied, nor did they relate their findings to the morphology of the joint surface. Spread of the peripheral contact areas towards the centre under increasing load was reported by Stormont et al (1985) in one specimen with loads of 50 and 350 N.

Our results strongly suggest the existence of a primary physiological incongruity between the trochlea and trochlear notch when the joint is flexed to 90°. The notch is somewhat deeper than necessary for an exact fit with the trochlea as was observed by Bullough and Jagannath (1983) in a specimen from a young subject. In view of the findings of Goodfellow and Bullough (1967) and Bullough et al (1968), who reported a decrease in physiological incongruity with increasing age, it may well be true that the phenomenon which we describe would have been even more pronounced, had we been able to study younger subjects. It seems that this primary incongruity disappears as the load on the joint increases due to the deformability of cartilage and subchondral bone, and that a state of secondary congruity is reached in which the load is transmitted more homogeneously through increased areas of contact.

As has already been mentioned, the contact pressures over a joint surface cannot be realistically derived from a knowledge of the position and size of its contact areas. The long-term distribution of stress, however, is reflected by the pattern of mineralisation of the subchondral bone (Müller-Gerbl 1989, 1990), because of the functional adaptation of the connective tissues. The bicentric pattern of mineralisation in the trochlear notch, which was always found in specimens with a divided joint surface, suggests that under physiological conditions more load is transmitted by the olecranon and coronoid surfaces than by the centre. This is in agreement with X-ray densitometry measurements of sagittal sections through the trochlear notch reported by Tillmann (1978).

We believe that this method of load transmission represents an important phenomenon which is essential for the daily function of the elbow. Goodfellow and O'Connor (1975), Bullough (1981) and Greenwald (1991) have presented theoretical models by which such a primarily incongruous geometry of the joint is shown to bring about a better distribution of the stress than would a primarily congruous joint (Fig. 6). In a recent study (Eckstein et al 1994) we have investigated the effect of the geometry on the distribution of stress in joints, using the finite element method. We were able to establish that a deeper socket leads to a bicentric transmission of load and to lower stresses in the joint as compared with a perfectly congruous geometry.

The monocentric pattern of subchondral mineralisation occasionally encountered in the group with continuous cartilage agrees with densitometric findings by Tillmann (1978) and Pauwels (1980) in specimens with this articular morphology. It appears, however, to be exceptional, even within this group, for a nearly congruous geometry of the joint to bring about monocentric transmission. The bicentric pattern was more usual, even in these specimens, although they did show a higher degree of mineralisation in the depths of the trochlear notch, between the two maxima. From the casts of these

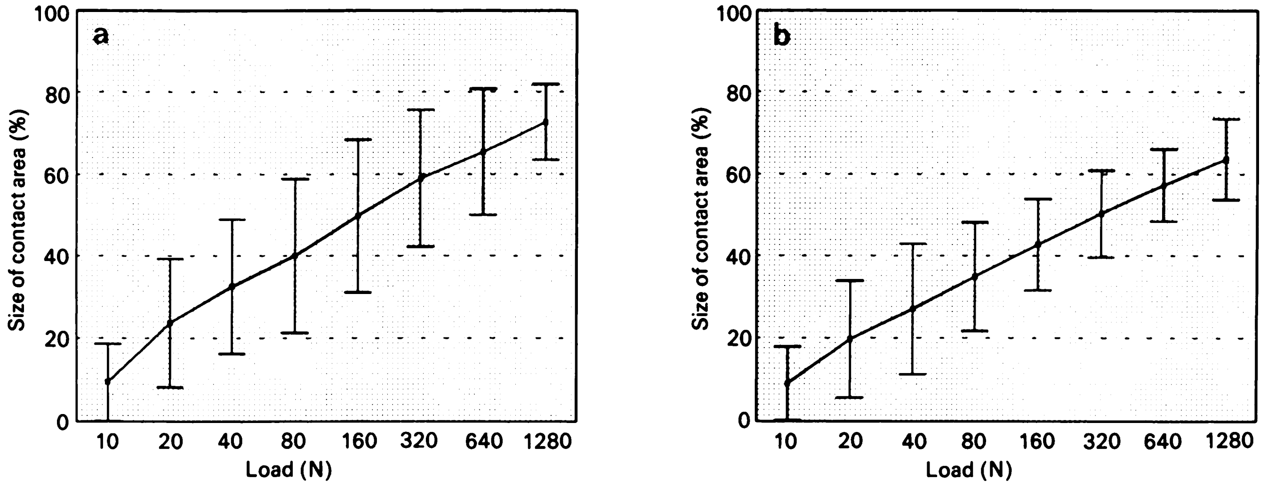

Fig. 5

Mean size of the contact areas under various loads in group A (a) and group B (b).

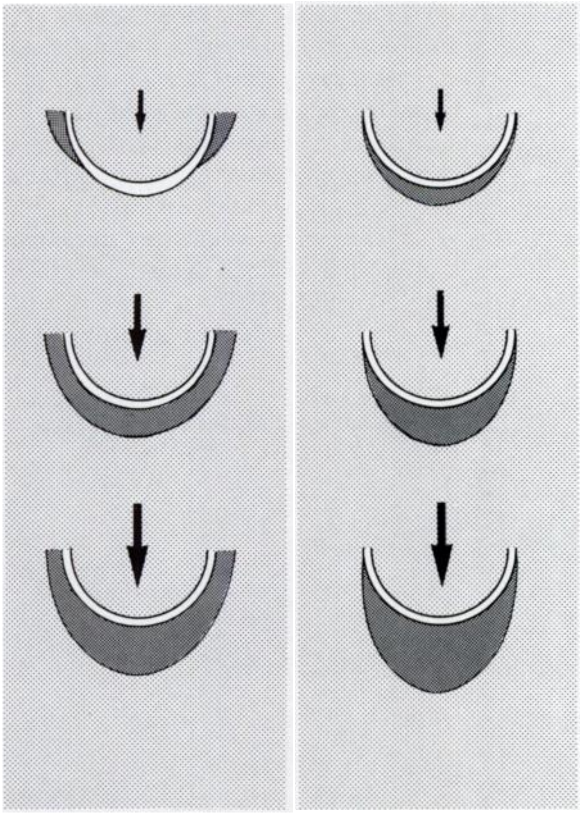

Fig. 6a Fig. 6b

Stress distribution under small (top), moderate (middle) and high load (below) according to the models of Bullough (1981) and Greenwald (1991). Figure 6a – Articular surfaces with primary functional incongruity. Figure 6b – Articular surfaces which are primarily congruous. The stress at the concave articular surface (shaded area) is more evenly distributed in model (a).

specimens it is clear that only a small increase in force is needed for the two contact areas to coalesce, suggesting a higher degree of congruity in this group. This difference cannot be explained in terms of age, since the mean age of these specimens was even somewhat lower than that of group A. As Bullough (1981) and Greenwald (1991) have postulated, the stress distribution in such joints must be less satisfactory, since less force is transmitted by the periphery of the joint surface. This has also been quantitatively shown by Eckstein et al (1994). We regard the higher degree of central mineralisation in comparison with group A as confirmation of this hypothesis.

The phenomenon of bicentric transmission of load is not confined to the humeroulnar joint. Observations on the contact areas of the hip (Bullough et al 1968; Greenwald and O'Connor 1971; Greenwald and Haynes 1972; Bullough et al 1973; Miyanaga et al 1984) and CT osteoabsorptiometric findings in the acetabulum (Müller-Gerbl et al 1989, 1990, 1993) suggest that we are dealing here with a functional principle of load transmission in at least some of the larger human joints. In addition to optimising the stress distribution, Bullough et al (1973) and Bullough (1981) suggested that more satisfactory conditions for nourishing the articular cartilage may thus be provided (intermittent stress and increased circulation of the synovial fluid) together with greater stability of the joint.

In order to assess the degree of incongruity required for the most advantageous load transmission in a joint, further research needs to be undertaken to measure incongruity accurately and to calculate the distribution of stress within incongruous joints.

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