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Physiological incongruity of the humero-ulnar joint: a functional principle of optimized stress distribution acting upon articulating surfaces?

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Abstract. Investigations into the distribution of subchondral bone density in the human elbow have suggested that the geometry of the trochlear notch deviates from a perfect fit with the trochlea, and that the load is transmitted ventrally and dorsally rather than through the centre of the humero-ulnar joint. We therefore decided to make a quantitative assessment of the degree of incongruity between the two components in 15 human specimens (age distribution 60 to 93 years) with different types of joint surface. Polyether casts of the joint cavity were prepared under loads of 10, 40, 160 and 640 N. The thickness of the casts was then measured at 50 predetermined points, and an area distribution of the width of the joint space represented in a two-dimensional template of the trochlear notch. The reproducibility of this procedure was tested by image analysis. At a load of 10 N, only a narrow space was present ventrally and dorsally in the joint, but in the depths of the trochlear notch a width of 0.5 to 1 mm was recorded in the centre, and up to 3 mm at its medial and lateral edges. Specimens with continuous articular cartilage showed a lower degree of incongruity than those with a divided articular surface. As the load was increased to 640 N, however, the original incongruity between the articular surfaces disappeared almost completely. The joint surfaces became more congruous, probably because of the viscoelastic properties of the articular cartilage and the subchondral bone, and the contact areas merged in the centre of the joint. It is suggested that this physiological incongruity brings about an optimal distribution of stress over the articular surface during the transmission of the load, and it may lead to better nourishment of the articular cartilage by providing intermittent mechanical stimulation and circulation of the synovial fluid.

Key words: Incongruity – Humero-ulnar joint – Elbow-joint physiology – Stress distribution – Joint loading

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Introduction

Recent CT osteoabsorptiometric research (CT-OAM) on living subjects has made it clear that, at least in younger people, there is on average a greater stress acting at the periphery of the articular surfaces than at their centre. This applies especially to certain larger joints such as the hip, the shoulder and the ankle (Müller-Gerbl et al. 1992, 1993; Müller-Gerbl and Putz 1993). Tillmann (1971, 1978) was the first to show that in cases where the articular surface of the trochlear notch is divided (this being the most common type in older individuals), ventral and dorsal maxima of subchondral bone density can be demonstrated. After investigating human elbow joints by CT osteoabsorptiometry (Eckstein et al. 1993a) we were able to confirm that in most cases a bicentric pattern of subchondral mineralization can be found in the ulna, the mineralization under the ventral and dorsal aspect of the joint surface exceeding that under the joint centre by up to 300 Hounsfield units. This distribution of the mineral salt content in the subchondral bone is thought to reflect the long-term stress acting on the joint surfaces (Pauwels 1955, 1960, 1963; Kummer 1962; Tillmann 1971, 1978; Carter 1984; Müller-Gerbl et al. 1989, 1992; Carter et al. 1991). It can be concluded from this that, on average, more load is transmitted through the dorsal and ventral regions of the articular surface than in the depths of the trochlear notch. Such a stress distribution can most plausibly be explained by the fact that, in all sagittal sections through the joint, the trochlear notch is deeper than would be necessary for an exact fit with the trochlea of the humerus (Tillmann 1971, 1978; Oberländer et al. 1984).

The concept of incongruity in human joints is certainly not new. Walmsley (1928) described the incongruous shape of the hip joint over 60 years ago, and since then many investigators, using various different methods of approach, have confirmed it (Bullough et al. 1968, 1993; Greenwald and O'Connor 1971; Greenwald and Haynes 1972; Goodfellow and Mitsou 1977; Rushfeldt and Mann 1979; Afoke et al. 1980; Miyanga et al. 1984;

Müller-Gerbl et al. 1992, 1993). This kind of incongruity has also been observed in the humero-ulnar joint of younger people (Goodfellow and Bullough 1967; Bullough et al. 1973; Bullough and Jagannath 1983). Nevertheless, these reports have been limited to qualitative comments on sagittal sections, and few examples have been given. Our object was therefore to assess the degree of incongruity quantitatively in a larger sample of human humero-ulnar joints and to investigate the dependence of this incongruity upon the joint loading.

Materials and methods

We examined 15 dissecting-room specimens (8 female and 7 male), with an age range of 60 to 93 (mean 78) years. These were allocated to groups in accordance with the morphological appearance of the cartilage covering the trochlear notch as described by Tillmann (1978) and Oberländer et al. (1984). Eight specimens showed a complete division of the cartilaginous joint surfaces of the ulna by a transverse bony furrow (Fig. 1a, group a). In four, the division appeared only on the medial side, with the cartilage continuing right across the surface laterally (Fig. 1b, group b). In three specimens the cartilaginous surface was uninterrupted throughout (Fig. 1c, group c). Specimens with cartilaginous damage visible to the naked eye were discarded from the investigation, and in no case was there any evidence of pathological change near the joint or of systemic disease of the locomotor apparatus.

The specimens were fixed in 3.7% formalin and, after being opened, kept in the same solution for 6 months. The head of the radius, the surrounding soft tissues, the joint capsule, the collateral ligaments and the meniscoid folds were resected.

For the mechanical investigation, each humeral shaft was fixed in the mounting of a Zwick material-testing machine so that the long axis of the humeral condyles was at right angles to the testing table (Fig. 2). In order to avoid angulation of the joint surfaces the ulna was fixed to the latter, while keeping its articular surface in close contact with that of the humerus. The coronoid process and olecranon were situated at the same distance from the top of the table. Owing to the anterior rotation of the condyle, and the 30° posterior rotation of the trochlear notch relative to the ulnar shaft, this corresponded to 90° flexion at the elbow joint. In this way the resultant force was, following Morrey's (1985) calculations, brought to lie in the centre of the trochlear notch. The joint surfaces were separated by lifting the humeral component, and then sprayed with a special liquid (Wacker) to prevent the cartilage sticking to the cast. The cast was made from polyether (ESPE), which allows 3 min for modelling and takes a further 7 min to dry. The casting mixture was prepared and placed on the ulnar surface of the joint

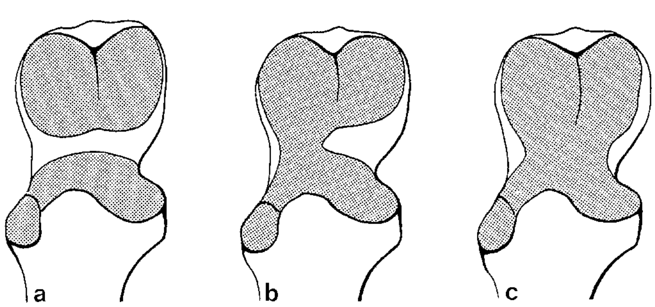

Fig. 1. Morphology of the cartilage covering of the trochlear notch according to Tillmann (1978) and Oberländer et al. (1984). Type a: complete division of the articular surface (about 65% of all cases). Type b: surface divided medially, continuous laterally (about 30% of all cases). Type c: surface continuous both medially and laterally (about 5% of all cases)

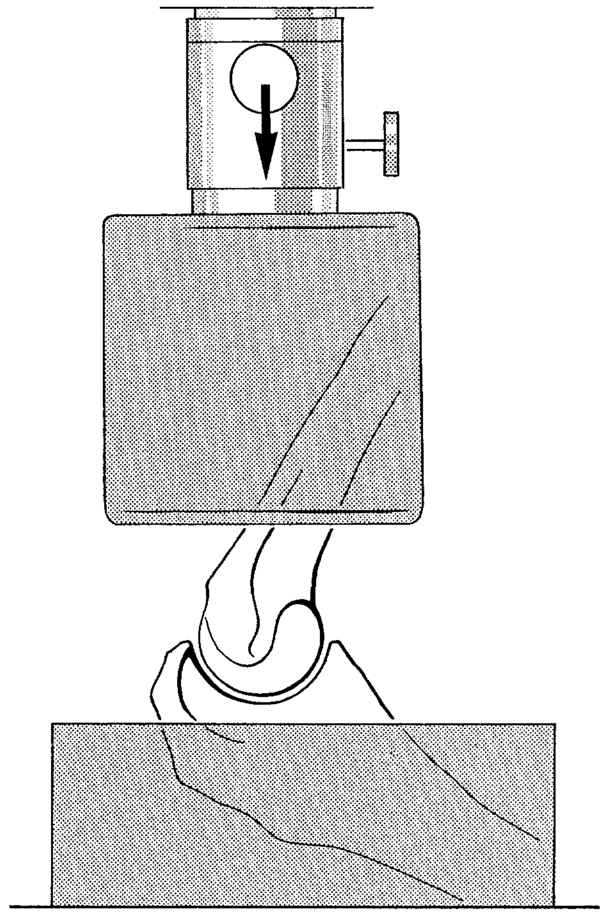

Fig. 2. Mounting of the specimens in the material-testing machine

within 1 min. The required load was applied within a further minute and kept constant until the material had set hard. Casts of each joint were prepared under loads of 10, 40, 160 and 640 Newtons, the cartilage being kept moist throughout the whole procedure with physiological saline.

The thickness of the casts was then measured at 50 predetermined points with a Mitutoyo rapid measuring device (spherical distance sensor, standardized to a pressure of 30 g) and the measurements were conveyed to a joint template (Figs. 3a, 4a, 5a). By means of a computer program (Gnuplot) the surface distribution of the thickness of the cast (or width of the joint space) was reconstructed in terms of ten thickness intervals (<0.3 mm to >2.7 mm). The mean distribution of the width of the joint space at loads of 10 N and 640 N was calculated for the groups a, b and c, the difference between the two distributions representing the degree of deformation of the tissue under increasing load.

In order to be certain that the method of casting, the measurements, and the surface reconstruction were reproducible, six casts of the same joint were prepared under a load of 40 N. From these six casts, a surface reconstruction in ten intervals was obtained by the method just described, and the distribution of cast thickness compared by means of image analysis (Vidas Plus Kontron). The measure of agreement between the six distribution patterns was obtained at 250 points in the joint template.

Results

Measurement of the casts of the specimens in group a (divided articular surface) showed that, under a load of 10 N, the width of the joint space at the ventral and

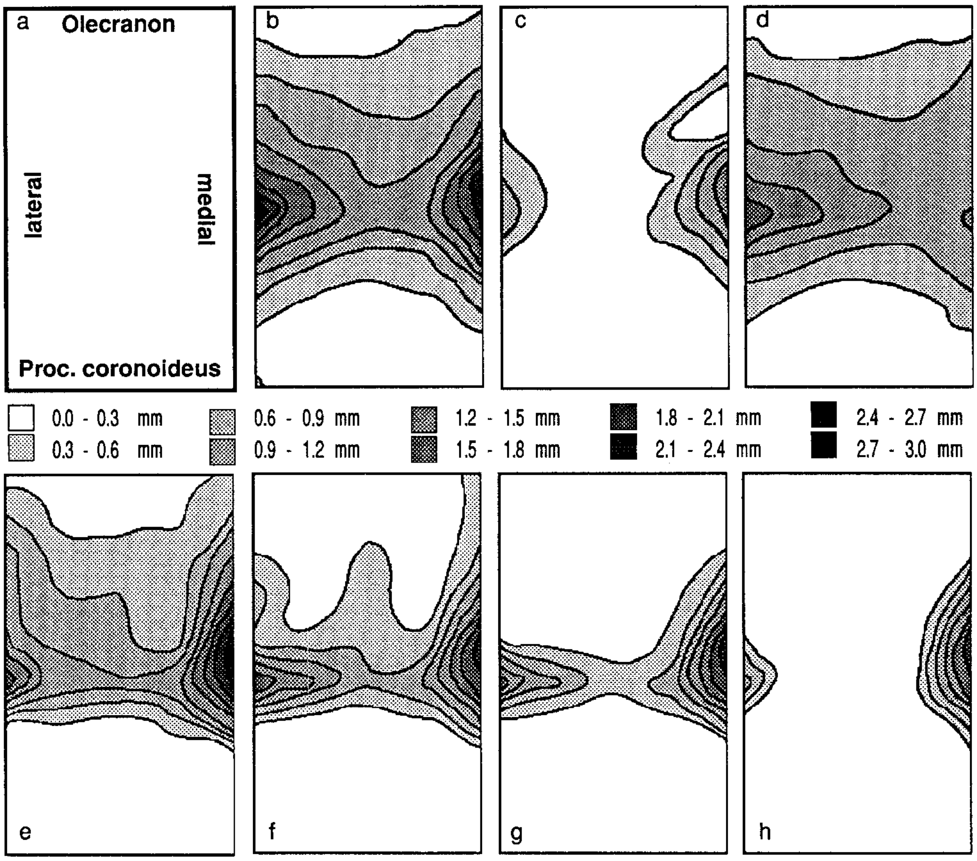

Fig. 3. a Joint surface template of trochlear notch. **b–d** Average width of joint space in eight specimens from group a (divided joint surface) under 10 N (**b**) and under 640 N. (**c**). **d** Difference in width of joint space between **b** and **c** showing the amount of deformation of the tissues. **e–h** Width of the joint space in a single specimen from group a under 10 N (**e**) under 40 N (**f**) under 160 N (**g**) and under 640 N (**h**)

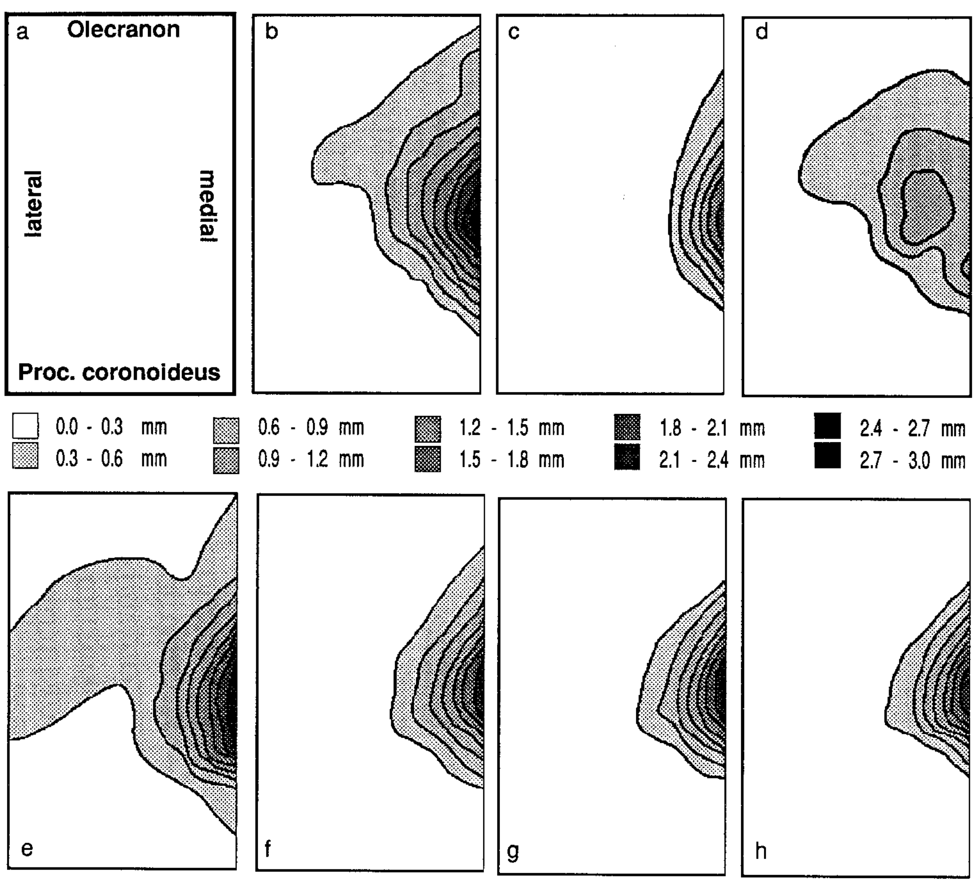

Fig. 4. a Joint surface template of trochlear notch. **b–d** Average width of joint space in 4 specimens from group b (medial surface divided, lateral continous) under 10 N (**b**) and under 640 N (**c**). **d** Difference in width of joint space between **b** and **c** showing the amount of deformation of the tissues. **e–h** Width of the joint space in a single specimen from group **b** under 10 N (**e**), under 40 N (**f**), under 160 N (**g**) and under 640 N (**h**)

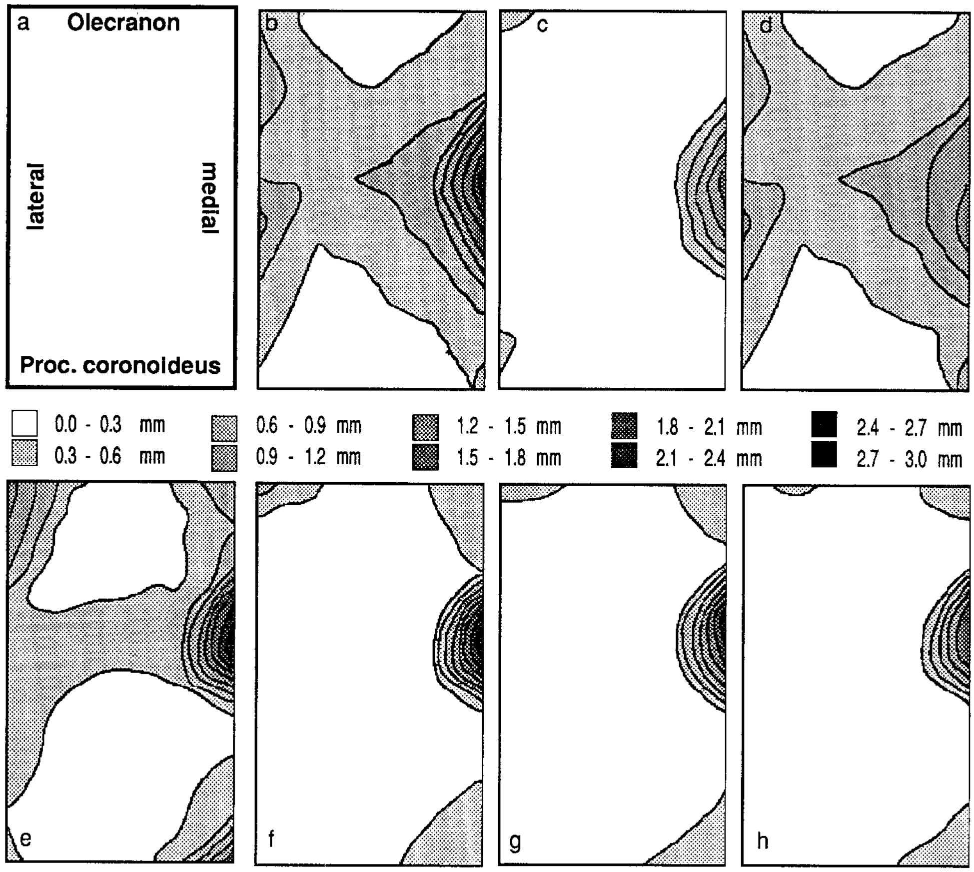

Fig. 5. a Joint surface template of trochlear notch. **b–d** Average width of joint space in three specimens from group c (both medial and lateral surfaces continous) under 10 N (**b**) and under 640 N (**c**). **d** Difference in width of joint space between **b** and **c** showing the amount of deformation of the tissues. **e–h** Width of the joint space in a single specimen from group c under 10 N (**e**), under 40 N (**f**), under 160 N (**g**) and under 640 N (**h**)

Table 1. Percentage of points (out of 250) in the template exhibiting the same thickness interval of the cast, and those showing a difference of one and more than one of the ten intervals used (taken between pairs from six casts obtained from an identical joint: C1–C6 = cast 1–6)

	C1/C2	C2/C3	C3/C4	C4/C5	C5/C6	C6/C1	Mean
Percentage of pixels in the same thickness interval	83.4%	79.6%	84.3	86.6%	79.1%	82.9%	82.7%
Percentage of pixels with a difference of 1 interval	9.5%	10.0%	6.2%	8.6%	8.3%	8.1%	8.4%
Percentage of pixels with a difference of more than 1 interval (> 0.3 mm)	7.1%	10.4%	9.5%	4.8%	12.6%	9.0%	8.9%

dorsal parts of the surface was everywhere less than 0.3 mm (Fig. 3b). In the deepest part of the trochlear notch, the space had a mean width of 1 mm, increasing to 2.3 mm medially and 2.6 mm laterally. At a load of 640 N (Fig. 3c), an effective space in the notch was only found at the medial (1.4 mm) and the lateral edge (0.9 mm), the two contact areas merging in the centre. The reduction in the width of the joint space with the load increasing from 10 to 640 N (Fig. 3d) could most clearly be seen in the depths of the notch, amounting to 1 mm medially and in the centre, and 1.7 mm laterally. Figure 3e–h shows the thickness of the casts from a single specimen in this group under loads of 10, 40, 160 and 640 N.

Specimens with a medial division only (group b) showed a different distribution pattern of cast thickness, insofar as the width of the joint space in the lateral region of the deepest part of the notch was on average less than 0.3 mm (Fig. 4b). Values up to 0.4 mm were found in the centre, and of up to 3 mm laterally. At a load of 640 N, the contact areas were continuous laterally and in the centre, whereas a width of up to 2.3 mm remained on the medial side (Fig. 4c). Reduction of the joint space took place particularly in the medial part of the depths of the trochlear notch, reaching 1.2 mm in this region (Fig. 4d). Figure 4e–h shows the thickness of each cast taken from a specimen in this group under loads of 10, 40, 160 and 640 N.

In specimens with a continuous articular surface both medially and laterally (group c) the width of the joint space in the depths of the trochlear notch reached 0.5 mm in the centre, up to 1 mm laterally and 2.7 mm medially (Fig. 5b). Under a load of 640 N, surface contact was complete laterally and in the centre, but medially the joint space remained up to 1.7 mm wide (Fig. 5c). Reduction of the space reached 1 mm in the depths of the notch laterally, 0.5 mm in the centre and up to 1,5 mm medially (Fig. 5d). Figure 5e–h shows the thickness of the casts taken from a single specimen of this group as a function of the load (10, 40, 160, 640 N).

The extent to which the method can achieve reproducible results emerged from measurements made of six casts from the same joint. The surface distribution of the cast thickness reached complete agreement with the thickness – interval at 82.7% of the 250 points compared; 8.4% of the pixels differed by one, and 8.9% by more than one of the ten thickness – intervals employed (Table 1).

Discussion

Methodology

The repeated preparation of casts from one specimen and their measurements makes it clear that both the determination of the load-dependent width of the joint space and its surface reconstruction in the template are sufficiently reproducible for quantitative evaluation of the measurements to be undertaken. The extent to which these results can be accepted as revealing the actual physiological situation is, however, subject to certain limitations. For one thing, the thickness of the cartilage has an important influence on the congruity between the components of the joint. Kurrat (1977) claims that the thickness of the cartilage is not essentially altered by formalin fixation, but the possibility that, in spite of the continuous moistening of the articular surfaces, a slight degree of shrinkage of the cartilage during the experiment may be brought about cannot be entirely excluded. This would mean, however, that the incongruity would be even more pronounced in the unifixed specimen than our measurements suggest. In other words, the geometrical incongruity between the humero-ulnar joint surfaces which has come to light during this investigation cannot on these grounds be attributed to an artefact. If anything, the values represent an underestimation of the true figures.

A further effect which may increase the incongruity under in vivo conditions was described by Oberländer et al. (1984). Considering the results of certain animal experiments reported by Ingelmark and Ekholm (1948), they suggested that movement at the elbow joint may lead to a transient functional swelling of the cartilage. They argue convincingly that a 5% increase in the thickness of the cartilage could cause an increase in the incongruity between the joint surfaces sufficient to lift the trochlea 1.3 mm out of the trochlear notch. This again supports the suggestion already made that, under physiological conditions, the degree of incongruity may be quantitatively more pronounced. The effect of a functional swelling of the cartilage may therefore increase the primary incongruity between the joint surfaces of the humero-ulnar joint.

It also seems possible that contraction of the triceps during daily activity exerts a pull on the olecranon and tends to prevent a decrease in incongruity by limiting the distortion of the bony elements. This is an effect which our experimental method did not take into account.

It is difficult to assess the effect of formalin fixation and the replacement of the synovial fluid with casting material on the viscoelastic properties of the articular cartilage. This, according to Mow et al. (1984), depends essentially on the interaction between the fluid elements and the solid cartilaginous matrix. Up to now, however, there is no work dealing with the observed experimental changes in these terms. However, results obtained from work on the unembalmed human hip joint (Miyanaga et al. 1984) clearly show that reduction in the primary incongruity between the joint components with increasing load also takes place without formalin fixation. According to these authors, the viscoelastic deformation of the components of the joint is not only accounted for by the elastic properties of the articular cartilage, but also by those of the subchondral bone. This is in agreement with results reported by Radin and Paul (1970) and Radin et al. (1970) which emphasize the importance of the subchondral bone for the transmission of load through a joint. It can be assumed that the mechanical characteristics of the bony tissue are not, so far as our investigation is concerned, greatly influenced by formalin fixation. We therefore think that it is perfectly possible to derive characteristic principles of pressure transmission through the humero-ulnar joint from these experiments.

Results

Our findings extend the observation made by Bullough et al. (1973) and Bullough and Jagannath (1983) that a sagittal section through the ulnar is slightly elliptical rather than circular, so that the depth of the trochlear notch exceeds the radius of the trochlea. The surface reconstruction of these results makes it clear that the degree of incongruity recorded is dependent upon the position of a sagittal section through the joint, and in general increases from the centre towards the medial and lateral edges.

Our results refute those of Shiba et al. (1988), who worked out the geometry of the humero-ulnar joint by image-analysing photographs of thin sagittal sections. These authors certainly admitted the existence of different radii of curvature between the articular surfaces of the olecranon and coronoid process, but, unlike us, came to the conclusion that there is a certain "sloppiness" between humerus and ulna which must depend upon the greater diameter of the trochlear notch in comparison with the trochlea itself. It seems to us probable that an inbuilt methodological error – perhaps the drying up of the articular cartilage or some distortion in the image analysis of the photographs – is responsible for the discrepancy between our results and theirs.

Our findings are, however, supported by the results of contact-area studies in the same joint (Goodfellow and Bullough 1967; Walker 1977; Goel et al. 1982), in which a light load produced surface contact at the periphery and a contact-free zone in the depths of the trochlear notch. The central merging of the contact areas with higher loading (Stormont et al. 1985; Eckstein et al. 1993b) agrees with our observation of a secondary reduction in the incongruity between the joint surfaces when the load is increased. According to Bullough (1981) and Miyanaga et al. (1984), this can be accounted for by the viscoelastic deformability of the cartilage and the subchondral bone.

The suggestion put forward by Tillmann (1971, 1978), that there is a connection between the incongruity and both the extent of the cartilage covering in the trochlear notch and the distribution of subchondral bone mineralization, is supported by the present investigation. The incongruity is more marked in individuals with divided joint surfaces than in those with a continuous layer of cartilage. In cases where the medial part of the joint is divided and the lateral continuous, it can even be seen that the incongruity of the medial part of the joint exceeds that of the lateral. It therefore follows that the incongruity, by determining the mechanical environment, seems to bring about adaptive biological changes in the articular cartilage and the subchondral bone, which may be interpreted in terms of causal histogenesis (Pauwels 1960; Kummer 1962; Tillmann 1978). The incongruity between the components of the joint may limit the degree of mechanical deformation of the cartilage in the depths of the trochlear notch to such an extent that it regresses (Tillmann 1978; Oberländer et al. 1984). The distribution of mineralization of the subchondral bone, which reflects the long-term distribution of stress over the articular surface (Pauwels 1955, 1963; Kummer 1962; Tillmann 1978; Müller-Gerbl et al. 1989, 1992), may also be regarded as an adaptation to the way load is transmitted through the joint. This process was interpreted by Carter (1984) and Carter et al. (1991) as a biological response to the "loading history" of the tissue. It can be concluded from the bicentric pattern of subchondral mineralization of the trochlear notch (Tillmann 1971, 1978; Müller-Gerbl and Putz 1993; Eckstein et al. 1993a) that this incongruity is of some importance during the day-to-day use of the joint.

It is certainly true that the articular surfaces become secondarily congruous under higher loads, and that as a result of this the contact area spreads over a great part of the articular surface (Eckstein et al. 1993b). Conclusions about the local stress can nevertheless hardly be drawn, since the distribution of stress within the contact areas remains unknown (Hehne 1983; Miyanga et al. 1984). The bicentric distribution of the subchondral mineralization does suggest, however, that the incongruity is not merely of importance when the joint is relatively unloaded, but plays a decisive role in the distribution of stress throughout the articular surface under natural physiological conditions also.

Bullough (1981) and Greenwald (1991) have put forward models to show that a primarily incongruous geometry offers considerable advantages when it comes to the distribution of stress during load transmission throughout the articular surfaces of joints (Fig. 6). They have pointed out that this type of architecture guarantees better conditions for the nourishment of the articular cartilage, by providing intermittent stimulation and encouraging the circulation of the synovial fluid. So far, these models have been based only on theoretical considerations and cannot therefore be made the basis of

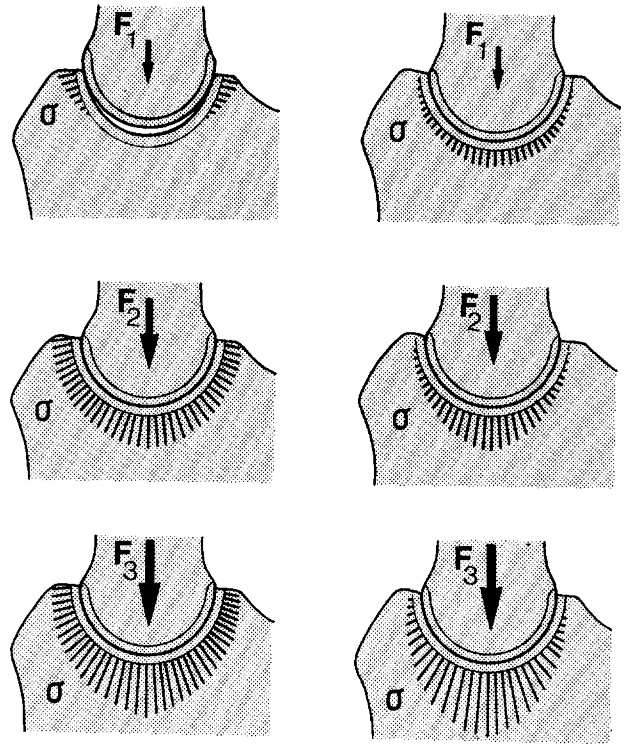

Fig. 6. Differences in the distribution of the stress (σ) over joint surfaces with varying geometry according to models by Bullough (1981) and Greenwald (1991): stress distribution under slight (F_1), moderate (F_2) and high load (F_3). Left side: primary incongruity of the joint surfaces; right side: primary congruity of the joint surfaces. Under middle and high load, a primarily incongruous joint shows a more even distribution of the stress over the articular surface than does a primarily congruous joint

quantitative pronouncements. In order to assess how important incongruity is as a "functional" principle of stress reduction, further research on the geometry and on the stress distribution over the articulating surfaces of diarthrodial joints will be necessary.

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References

Afoke NYW, Byers PD, Hutton WC (1980) The incongruous hip joint: a casting study. J Bone Joint Surg [Br] 62:511–514

Bullough PG (1981) The geometry of diarthrodial joints, its physiological maintenance, and the possible significance of age-related changes in geometry-to-load distribution and the developement of osteoarthritis. Clin Orthop 156:61–66

Bullough PG, Jagannath A (1983) The morphology of the calcification front in articular cartilage. J Bone Joint Surg [Br] 65:72–78

Bullough P, Goodfellow J, Greenwald AS, O'Connor S (1968) Incongruent surfaces in the human hip joint. Nature 217:1290–1291

Bullough P, Goodfellow J, O'Connor J (1973) The relationship between degenerative changes and load bearing in the human hip. J Bone Joint Surg [Br] 55:746–758

Carter DR (1984) Mechanical loading histories and cortical bone remodelling. Calcif Tissue Int 36:519–524

Carter DR, Wong M, Orr TE (1991) Musculoskeletal ontogeny, phylogeny, and functional adaptation. J Biomech 24:3–16
Eckstein F, Steinlechner M, Müller-Gerbl M, Putz R (1993a) Mechanische Beanspruchung und subchondrale Mineralisierung des menschlichen Ellbogengelenks – eine CT-osteoabsorptiometrische Studie. Unfallchir 96:399–404
Eckstein F, Löhe F, Steinlechner M, Müller-Gerbl M, Putz R (1993b) Kontaktflächen des menschlichen Humeroulnargelenks in Abhängigkeit von der Anpreßkraft – ihr Zusammenhang mit subchondraler Mineralisierung und Gelenkflächenmorphologie der Incisura trochlearis. Ann Anat (in press)
Goodfellow JW, Bullough PG (1967) The pattern of aging of the articular cartilage of the elbow joint. J Bone Joint Surg [Br] 49:174–181
Goodfellow JW, Mitsou A (1977) Joint surface incongruity and its maintenance. J Bone Joint Surg [Br] 59:446–451
Goel VK, Singh D, Bijlani V (1982) Contact areas in human elbow joints. J Biomech Eng 104:169–175
Greenwald AS (1991) Biomechanics of the hip. In: Steinberg ME (ed) The hip and its disorders. Saunders, Philadelphia, pp 47–56
Greenwald AS, Haynes DW (1972) Weight bearing areas in the human hip joint. J Bone Joint Surg [Br] 54:157–163
Greenwald AS, O'Connor JJ (1971) The transmission of load through the human hip joint. J Biomech 4:507–528
Hehne HJ (1983) Das Patellofemoralgelenk. Enke, Stuttgart
Ingelmark BE, Ekholm R (1948) A study on variations in the thickness of articular cartilage in association with rest and periodical load. Acta Soc Med Upsalien 53:61–74
Kummer B (1962) Funktioneller Bau und funktionelle Anpassung des Knochens. Anat Anz 110:261–293
Kurrat HJ (1977) Die Beanspruchung des menschlichen Hüftgelenk 6. Eine funktionelle Analyse der Knorpeldickenverteilung am menschlichen Femurkopf. Anat Embryol 150:129–140
Miyanaga Y, Fukubayashi T, Kurosawa H (1984) Contact study of the hip joint: Arch Orthop Trauma Surg 103:13–17
Morrey BF (1985) The elbow and its disorders. Saunders, Philadelphia
Mow VC, Holmes MH, Lai WM (1984) Fluid transport and mechanical properties of articular cartilage: a review. J Biomech 17:377–394
Müller-Gerbl M, Putz R (1993) Zur Morphologie und Mechanik der Gelenke in Abhängigkeit vom Lebensalter. In: Aktuelle Osteologie (in press)
Müller-Gerbl M, Putz R, Hodapp N, Schulte E, Wimmer B (1989) Computed tomography-osteoabsorptiometry for assessing the density distribution of subchondral bone as a measure of long term mechanical adaptation in individual joints. Skeletal Radiol 18:507–512
Müller-Gerbl M, Putz R, Kenn R (1992) Demonstration of subchondral bone density patterns by three dimensional CT osteoabsorptiometry as a noninvasive method for in vivo assessment of individual long-term stresses in joints. J Bone Miner Res 7 [Suppl 2]:411–418
Müller-Gerbl M, Putz R, Kenn R, Kierse R (1993) People in different age groups show different hip joint morphology. Clin Biomech 8:66–72
Oberländer W, Breul R, Kurrat HJ (1984) Die Querfurche des Ellbogengelenkes. Eine biomechanische Deutung ihrer Entstehung. Z Orthop 122:623–742
Pauwels F (1955) Über die Verteilung der Spongiosadichte im coxalen Femurende und ihre Bedeutung für die Lehre vom funktionellen Bau des menschlichen Knochens. 7. Beitrag zur funktionellen Anatomie und kausalen Morphologie des Stützapparates. Morph JB 95:35–54
Pauwels F (1960) Eine neue Theorie über den Einfluß mechanischer Reize auf die Differenzierung der Stützgewebe. 10. Beitrag zur funktionellen Anatomie und kausalen Morphologie des Stützapparates. Z Anat Entwicklungsgesch 121:478–515
Pauwels (1963) Die Druckverteilung im Ellbogengelenk, nebst grundsätzlichen Bemerkungen über den Gelenkdruck. 11. Beitrag zur funktionellen Anatomie und kausalen Morphologie des Stützapparates. Z Anat Entwicklungsgesch 123:643–667
Radin EL, Paul IL (1970) Does cartilage compliance reduce skeletal impact loads? The relative force-attenuating properties of articular cartilage, synovial fluid, periarticular soft tissues and bone. Arthritis Rheum 13:139–144
Radin EL, Paul IL, Lowy M (1970) A comparison of the dynamic force transmitting properties of subchondral bone and articular cartilage. J Bone Joint Surg [Am] 52:444–456
Rushfeldt PD, Mann RW (1979) Influence of cartilage geometry on the pressure distribution in the human hip joint. Science 204:413–415
Shiba R, Sorbie C, Siu DW, Bryant T, Derek T, Cooke DV, Wevers HW (1988) Geometry of the humeroulnar joint. J Orthop Res 6:897–906
Stormont TJ, An KN, Morrey BF, Chao EY (1985) Elbow joint contact study: comparison of techniques. J Biomech 18:329–336
Tillmann B (1971) Die Beanspruchung des menschlichen Ellenbogengelenkes. 1. Funktionelle Morphologie der Gelenkflächen. Z Anat Entwicklungsgesch 134:328–342
Tillmann B (1978) A contribution to the functional morphology of articular surfaces. Thieme, Stuttgart
Walker PS (1977) Human joints and their artificial replacement. Thomas, Springfield
Walmsley T (1928) Articular mechanics of the diarthroses. J Bone Joint Surg 10:10–22