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EXPERIMENTAL FRACTURES OF THE ADULT HUMERUS*

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Abstract—It is possible to reproduce the common fractures occurring in the adult humerus by simple mechanical methods. This has allowed a detailed examination of the morbid anatomy of the fractures and the measurement of the forces involved. A mechanical classification of fractures of the humerus is advanced which, it is suggested, may be generally applicable to long bones. Fractures of the shaft of the humerus, or any long bone, vary according to the nature of the violence applied, whereas fractures at the proximal and distal ends are dependent on the anatomy of the bone which, in turn, is related to the embryological development of the epiphyses.

THE MECHANICAL factors involved in the production of fractures of the adult humerus were studied. The objectives were, firstly, to see if the common fractures could be reproduced using simple loading systems, and hence to compare these with the loading systems which occur in life and, secondly to study the details of the morbid anatomy of the fracture site. On the basis of the experimental findings, a simple mechanical classification of fractures of the humerus due to indirect violence is advanced.

In clinical practice the mechanism of injury is reconstructed on the basis of the patient's history of the event (if remembered clearly), the examination and the radiographs. Inevitably there is a certain amount of conjecture involved in this process. Theoretically, fracture mechanisms and patterns can be deduced from the first principles of stress analysis (ALMS, 1961). Experimentally, known forces may be applied to a bone in the laboratory and, in so far as the resultant fracture mimics that seen clinically the clinical force distribution, and hence mechanism, may be inferred.

Whereas the appearance of a fracture at clinical examination is the end result of a series of events, experimentally controlled fractures have the advantage that they may throw light on some of the intermediate stages. The bone can be observed as it fractures and the process can be interrupted at any stage. The direction and magnitude of the forces applied can be accurately controlled. Fractures not usually exposed at operation can be seen. Radiographs can be directly correlated with the visible morbid anatomy of the specimen. The mechanical properties of specific bones can be studied, despite the absence of the soft tissues, circulation, nerves and muscles. The understanding of the mechanism and morbid anatomy of fractures so obtained may lead to more effective treatment.

From the standpoint of a mechanical classification of fractures it may be observed that violence may be offered to the skeleton in one of three ways:—

(1) directly, as by impact or crushing;
(2) indirectly, as when typically the moving body weight is reacted by some point distal in the limb which is fixed to the external environment; for example the fixed foot, reacting the falling body weight, or the fixed hand reacting the falling body weight when a subject falls on to the outstretched palm;
(3) by muscular force.

Where direct violence occurs, engineering analysis and classification is not likely to be profitable because the stresses are high and are localized, so that typically comminution is

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marked and the mechanism is self-evident. In examples of indirect violence, however, engineering analysis is likely to be valuable because the nature and location of the resultant fracture depends on the mechanical properties of the skeleton and an understanding of the loading mechanism and consequent stress distribution. In the third group, fractures produced by muscular forces, engineering analysis is again not very helpful, principally because these fractures are rare.

METHOD

In life, a long bone, for example the humerus, may be loaded in compression, bending, torsion or tension. Compression may be applied in the long axis of the bone or at right angles to it. Potentially, each method of loading will produce a specific effect on the bone, but in practice the nature of the joints at the ends of the bone may restrict the types of load which can be applied. For example, neither bending nor torsion can be applied to the proximal end of the humerus through the shoulder joint without first using all the available movement of this joint, so that the ligaments exert enough restraint to transmit the applied moment (which may be accompanied by damage to these ligaments or other soft tissues).

The experiments described in this paper were designed to reproduce the common types of clinical fractures of the humerus. The possible effects of each method of loading on various levels of the bone will be considered later.

Adult human humeri without evidence of pre-existing disease were used. All were X-rayed to exclude any unexpected abnormality. The bones were removed during post-mortem examination and stored at $-18°C$, and allowed to thaw to room temperature before experiments.

Fractures were produced as follows:

(1) the proximal end of the bone was loaded by compression, either in the line of the long axis of the bone or perpendicular to it;
(2) by bending the shaft;
(3) by torsion of the shaft;
(4) the distal third of the bone, including the elbow joint and proximal thirds of the radius and ulna, was loaded with the elbow either flexed or extended.

An Amsler Testing Machine was used to apply the load in all experiments except torsion, and for this an Avery Torsion Machine was employed. With each machine loads could be measured with an accuracy of $\pm 0 \cdot 5$ per cent. These machines are commonly used for testing the strength of materials in the engineering laboratory.

ANATOMICAL FEATURES

Proximally the scar of the epiphyseal plate remains as a dominant feature, clearly separating the epiphysis from the diaphysis in all specimens. The medullary cavity stops short of the epiphyseal plate in younger bones, but in the osteoporotic bones of the aged the cavity extends right up to the plate, and the greater tuberosity may be an empty shell (HALL, 1963).

At the distal end the trochlea is closely gripped by the ulna, and thus forces from the forearm are readily transmitted to the humerus. The supracondylar area is a strikingly thin bony lamina.

The ossification of the upper end of the bone is of importance in relation to the pattern of separation of this part of the humerus in adult fractures; there are three secondary centres. The head appears in the first year of life, and the centres for the greater and lesser tuberosities in the second and fifth years respectively. All join together in the sixth year to form a single upper epiphysis which, in turn, fuses with the shaft at twenty years.

RESULTS

Fractures produced at the proximal end of the humerus

Clinically, fractures in this region are often divided into abduction and adduction varieties, although, as MCLAUGHLIN (1959) has pointed out, they can apparently be changed from one group to another by varying the degree of rotation at the shoulder when radiographs are taken.

The injury is usually the consequence of a fall on to the outstretched hand, less frequently on to the point of the shoulder. In the first example, the head of the humerus is driven upwards against the acromion and in the second the head is compressed against the glenoid.

In order to reproduce the first of these two clinical mechanisms of force experimentally, the distal end of a cadaveric bone was embedded in a plaster of Paris mould with the shaft vertical, and placed in the Amsler Machine. A load was then applied to the head (Fig. 1a) so as to compress it in the long axis of the shaft. The resulting fracture closely resembled the clinical type at this level (Fig. 1b). There was considerable impaction of the head on to the surgical neck and the bone split into three main fragments—head, greater and lesser tuberosities (Fig. 1c)—and also along the line of junction of these previously separate ossification centres with the shaft. This constant pattern of fragmentation was first noted by CODMAN (1934) from his findings at operation.

This finding suggests that there is no morbid anatomical basis for dividing these fractures into abduction and adduction varieties. The mean load at failure for six bones broken in this manner was 1100 lbf. (range 600–1850 lbf.).

The second clinical mechanism—falls on to the point of the shoulder—was reproduced by placing the humerus horizontal with the articular surface of the head facing upwards, and applying compression between this surface and the underlying greater tuberosity, which rested on a bed of plaster of Paris (Fig. 2a). A constant fracture occurred along the line of the anatomical neck, but the tuberosities did not separate as in the previous group (Fig. 2b). In life separation of the tuberosities may perhaps be brought about by the pull of the rotator cuff muscles and, understandably, the fracture of the anatomical neck may be associated with a dislocation of the shoulder (MICHAELIS, 1944).

The mean load at failure for five bones broken in this manner was 742 lbf. (range 224–1344 lbf.). Thus the compressive strength of the proximal end of the humerus is roughly the same, irrespective of the loading axis.

Fractures of the shaft

(1) *Bending*. Transverse fractures of the shaft of the humerus are probably the result of the application of a three point bending system to the arm, as, for example, when a man falls against a projecting object. In clinical practice the middle third of the bone is by far the most common site for the fracture (KLENERMAN, 1966).

The middle third of the bone was loaded in three point bending by supporting the bone on small rollers at each end and applying the central load through a saddle shaped piece of wood to reduce local stress concentration (Fig. 3a). Typical transverse fractures resulted irrespective of whether the bone was placed lying anteroposteriorly or with the lateral surface upwards. The fracture line tended to run transversely across the bone until just beyond halfway, when it veered towards the distal end in a low L-shape. Loose butterfly fragments were not found, although in four of twenty consecutive humeri there were cracks preparatory to the separation of such fragments (Fig. 3b). This incidence (20 per cent) corresponds to the incidence of butterfly fragments in a clinical series (KLENERMAN, 1966). Muscular forces *in vivo* might well have resulted in the complete separation of the potential butterfly fragments seen experimentally.

Provided that the shaft of the bone had not been unduly stripped of muscles and periosteum, there was a well defined soft tissue hinge left intact on the side of compression (i.e. the side of the application of the central bending force).

The mean bending moment at failure for fourteen bones broken in bending was 1066 lbf. in.

(2) *Torsion*. Torsional loading was applied by an Avery Torsion Machine (Fig. 4a). The torque was transmitted by means of universal joints attached to small metal containers in which the bone ends were set in plaster of Paris.

Loading the shaft of the humerus in torsion produced spiral fractures similar to those seen clinically, i.e. the fracture line followed a complete turn of 360° (in the line of a tension helix)

Table 1. The distribution of spiral fractures of the shaft of the humerus

Level	14 Experimental fractures				39 Clinical fractures	
	External rotation	Internal rotation	Total	%	Total	%
Proximal third	4	4	8	57·0	12	31
Middle third	1	2	3	21·5 } 43	9	23 } 69
Distal third	2	1	3	21·5	18	46

and its upper and lower ends were then connected by a longitudinal fracture (Fig. 4b).

The level at which fractures occurred varied and showed no definite relation to internal or external rotation. In thirty-one patients seen and reported previously (KLENERMAN, 1966) the distribution of such fractures was: proximal third, twelve; middle third, nine; distal third, eighteen. The levels at which fractures occurred experimentally are shown and contrasted with clinical distribution in Table 1. It will be seen that compared with the experimental distribution clinical fractures are more common in the distal two-thirds of the bone. It is possible that in life the attachments of the deltoid and pectoralis major muscles support the proximal third of the bone in torsion and that, therefore, fractures occur more frequently in the distal two-thirds. The bone in the testing rig is supported only at its proximal and distal ends, and this perhaps accounts for the relatively greater frequency of fractures in the proximal third.

There was a consistent soft tissue hinge which remained joining the vertical limbs of the fracture (Fig. 4c). Butterfly fragments were rare.

The mean figure for the load at failure of fourteen bones broken by torsion was 488 lbf. in. (range 195–815 lbf. in.). This is less than half the mean moment required to cause failure in bending (1066 lbf. in., as quoted above).

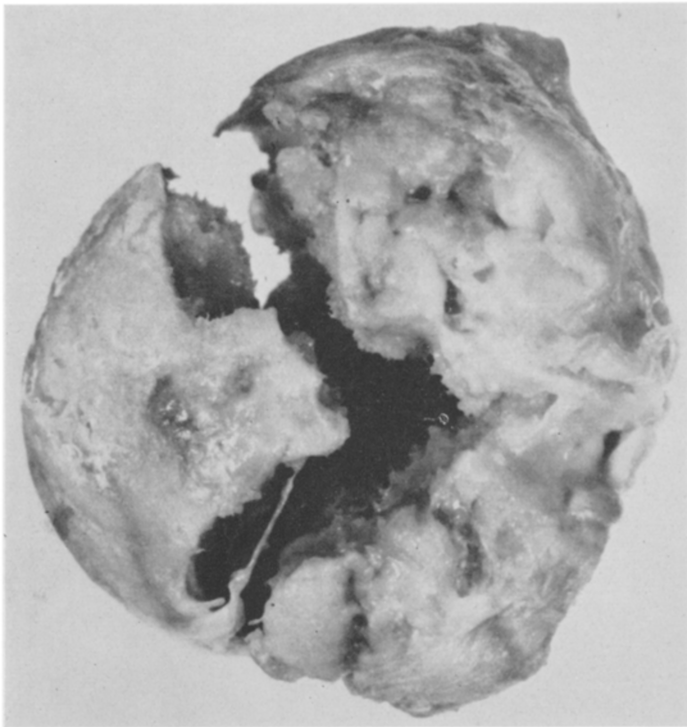
Fractures at the distal end of the humerus

The common fracture in the adult in this situation is of the T- or Y-shaped variety, and results from a fall on to the point of the elbow (WAINWRIGHT, 1962). It appears that the olecranon notch, which fits the trochlea very closely, acts as a wedge which is driven upwards between the trochlea and capitellum. The thin bony lamina in the supracondylar region then splits to either side. Fractures of this type were produced experimentally by applying a load to the distal shaft of the humerus, which had been embedded in a mould containing plaster of Paris, with the elbow flexed at 90° and resting on the firm surface of the testing machine (Fig. 5a). Eleven specimens were tested in this way. In four, fractures of the Y-type resulted, and in seven there were fractures of the tip of the olecranon.

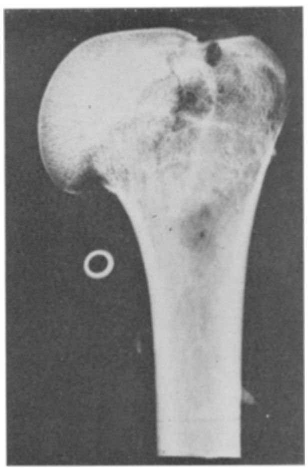
The development of a fracture of the humerus (as distinct from the olecranon process of the ulna) appeared to depend upon the degree of elbow flexion. It was noted that when the elbow remained flexed at 90° the olecranon fractured, whereas when the elbow continued to flex as the load was applied the Y-shaped fracture was produced. The explanation for this is probably related to the fact that the humero–ulnar joint is in the close-packed position at 120°, i.e. their is total contact of the joint surfaces. When the joint is extended, contact is lost at the medial side of the trochlear notch (HALL, 1965). In addition, at 90° flexion the narrowest portion of the trochlear notch of the ulna is in contact with the humerus.

It is interesting to compare the radiographs with the actual specimens, as the damage to the articular surface is always more than would appear on the films (Figs. 5b and c). This is due to the shadow of the olecranon obscuring the

(a)

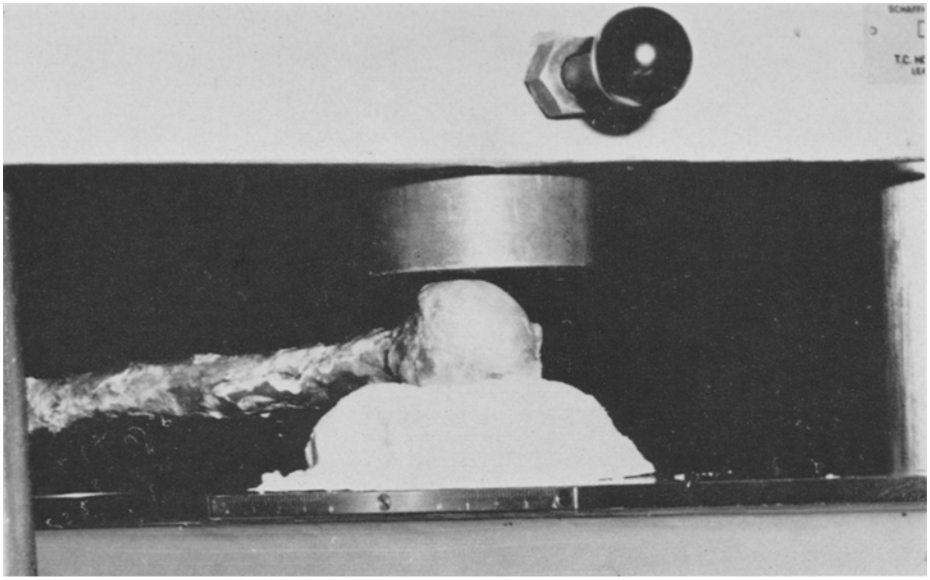


(c)

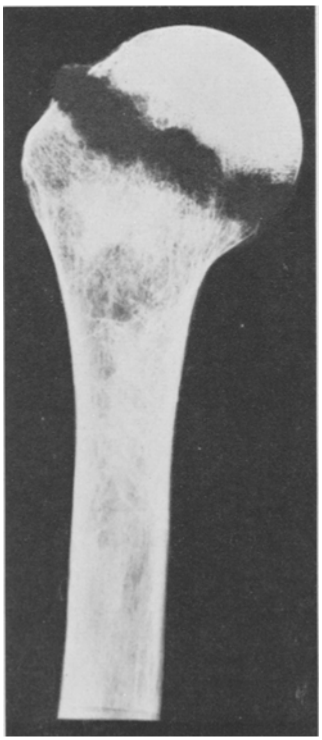


(b)

FIG. 1. Vertical compression; (a) Method of loading, (b) Radiographs of typical fracture produced, (c) Macroscopic appearance of fracture showing the mode of fragmentation into head, greater and lesser tuberosities.

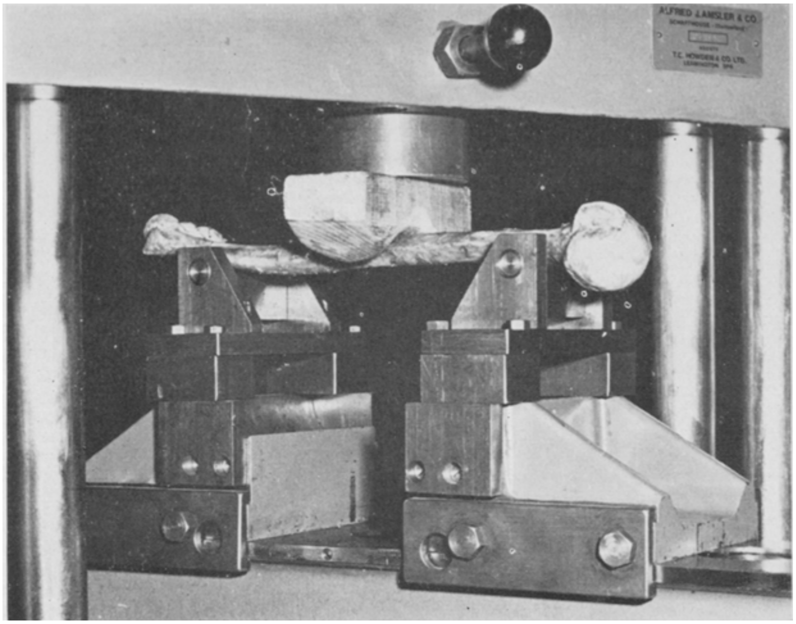


(a)



(b)

FIG. 2. Horizontal compression; (a) Method of loading, (b) Radiograph of typical fracture produced.



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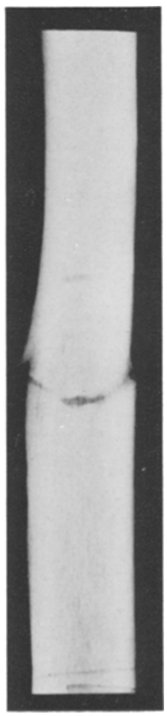
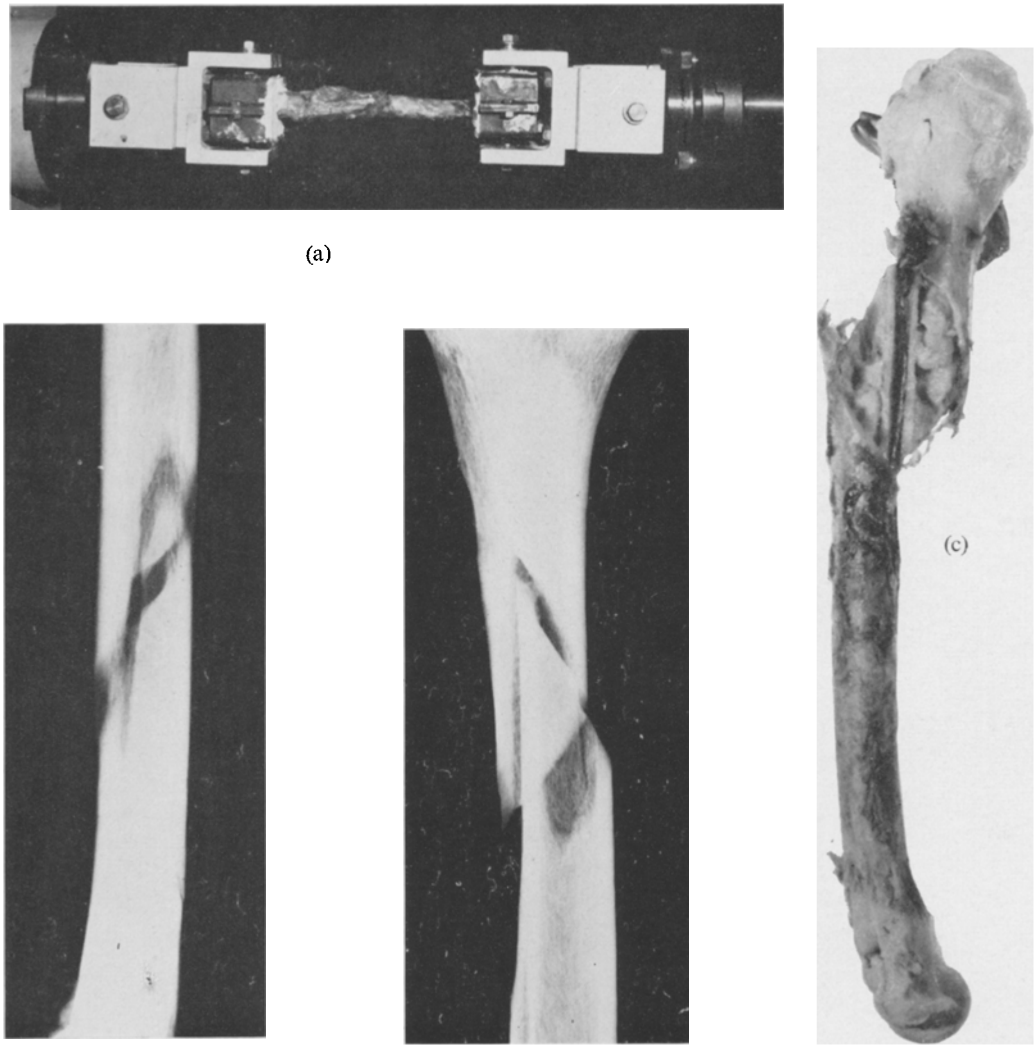
(bi)



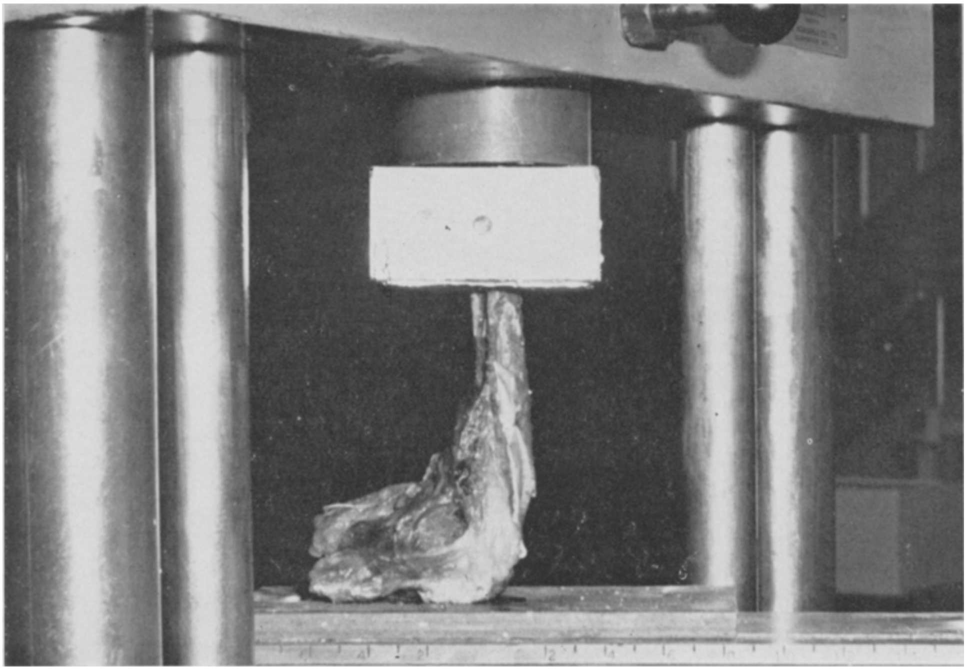
(bii)

FIG. 3. Three point bending; (a) Method of loading, (b) Radiograph of typical fracture produced.



(bi) (bii)

FIG. 4. Torsion; (a) Method of loading, (b) Radiograph of typical fracture produced, (c) Macroscopic appearance showing posterior soft tissue hinge.



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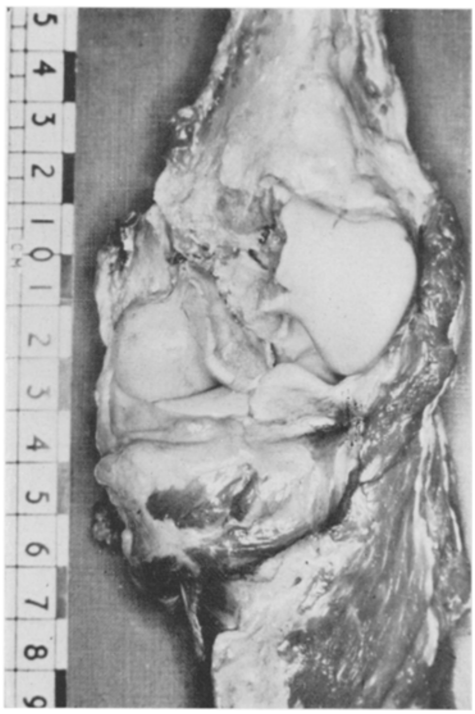

(c)

FIG. 5. Loading of isolated elbow joint; (a) Method of loading, (b) Radiograph of typical fracture produced, (c) Macroscopic appearance of the same fracture.

Table 2. A mechanical classification of fractures of the humerus due to indirect violence

Stress responsible	Mode of loading	Site of fracture		
		Proximal end	Shaft	Distal end
Compression	Compression in the long axis of the bone	Three fragment fracture	No fracture because the shaft is stronger in compression than the ends of the bone	Y-shaped fracture
	Compression at right angles to the shaft	Fracture along anatomical neck (and dislocations on occasions)	—	—
Tension	Bending	No fracture because of adjacent multi-axial joint (the shoulder)	Transverse fracture	? avulsion of epicondyles
	Torsion	No fracture because of adjacent multi-axial joint (the shoulder)	Spiral fracture	No fracture—torsion between hand and humerus occurs at radio-humeral joint
	A combination of bending or torsion and axial compression	No fracture because of adjacent multi-axial joint (the shoulder)	? Oblique fracture ± butterfly fragment	?

trochlea to a certain extent and to the fact that the curved articular surface of the humerus is not well displayed in radiographs.

The average load at failure was 814 lbf., a value comparable to that for the vertical compressive strength of the proximal end of the bone.

A MECHANICAL CLASSIFICATION OF FRACTURES OF THE HUMERUS DUE TO INDIRECT VIOLENCE

A summary of the various methods by which the humerus might be loaded and the suggested resulting clinical fractures is shown in Table 2. Some but not all of these fractures have been confirmed by producing them experimentally. A dash indicates that the particular mode of loading cannot be applied indirectly. A query against a fracture indicates that this result is only speculative and has not been confirmed experimentally.

It will be seen that a compressive load applied in the long axis of the humerus produces a fracture at the proximal or distal cancellous end of the bone, but not in the shaft. This is due to the fact that in axial compression the shaft is very much stronger than the trabecular ends. At the proximal end of the bone the fracture produced is the familiar clinical fracture of the surgical neck of the humerus, and this has been found regularly to involve the separation of three fragments—the head, the greater tuberosity and the lesser tuberosity—from the shaft. At the distal end the appropriate fracture is the Y-shaped fracture with the stem of the Y running down into the articular surface of the humerus between the trochlea and capitellum and extending proximally into the region of the coronoid and capitular fossae and thence medially and laterally to complete the Y. The latter fracture occurs only when axial compression is applied through the flexed elbow and appears to be dependent upon the anatomy of the articular surfaces of the elbow.

At the proximal end of the bone, violence (which by a slightly stretched definition may be regarded as indirect) applied to the lateral aspect of the humerus may be reacted medially by the body weight so as to produce a compressive load on the humerus in a line at right angles to the long axis of the shaft. The consequent fracture runs round the anatomical neck of the humerus to separate the head, but this fracture did not experimentally go on to involve the tuberosities. It is easy to see how, clinically, the continuation of this force would produce a medial dislocation of the head of the humerus from the shoulder. No comparable mechanism is possible at the distal end of the bone (unless, theoretically, the subject were to fall sideways with the arm held to the side so that the body-weight reacted the force attributable to impact with the ground: such a mechanism appears most unlikely on *a priori* grounds and the history of a fall of this kind never occurs clinically).

When a hollow cylinder, such as the shaft of the humerus, is bent or twisted, lines of tensile or compressive stress develop within the structure. It has been found experimentally that when the shaft of the humerus is bent a transverse fracture develops starting at the point of maximum tensile stress on the convex surface of the bend. This fracture runs more or less transversely across the shaft, becoming oblique about half way across the circumference. The possibility of the separation of small butterfly fragments as part of this mechanism has been observed.

When the shaft of the humerus is subjected to a turning moment a spiral fracture develops, again in the lines of maximum tensile stress, which are now distributed as a series of helices running around the shaft. The fracture line follows the helix and when it has transversed a full circumference of the bone, the fracture is completed by a longitudinal crack connecting the proximal to the distal end of the helix.

Thus fractures in the shaft of the bone attributable to bending or twisting are produced by tensile stress, and may be regarded as tension fractures, in contrast with those of the cancellous proximal and distal ends of the bone, which are compression fractures.

Neither a bending nor a turning moment can be applied to the proximal end of the bone in life because the application of such a force results in movement of the adjacent multi-axial shoulder rather than in loading of the bone. At the distal end of the humerus it is in principle possible to load the humerus by bending the elbow in the direction of abduction or adduction of the forearm with the elbow extended, and also in the direction of hyperextension. Such mechanisms can be expected clinically to produce avulsion fractures of ligamentous structures on the tension side of the bend, or compression fractures of the opposite side, but they have not been examined experimentally. Torsion may also occur, but it seems likely that to some extent turning moments applied to the hand would result in pronation or supination of the forearm or rotation at the shoulder rather than in the application of a significant turning moment to the humerus.

Other loading mechanisms are in principle possible, namely a combination of bending or torsion with or without axial compression. These have not been examined experimentally but on theoretical grounds it might be anticipated that such a mechanism applied to the shaft would produce a long oblique fracture, or alternatively a large butterfly fragment.

If the results of specific methods of loading the humerus are compared with what is known of the fracture patterns in other long bones, e.g. the suggestions of similarity. Fractures of the neck of the femur have been produced in both the transcervical and trochanteric region by compression in the long axis of the bone (EVANS, PEDERSEN and LISSNER, 1951; SMITH, 1953; FRANKEL, 1960). Trochanteric fractures have also been reproduced by compression applied perpendicular to the long axis of the bone (EVANS, PEDERSEN and LISSNER, 1951; SMITH, 1953). Shaft fractures may be transverse, oblique or spiral, and, as with the humerus, the middle third is most commonly affected. Clinical experience leads to the suggestion that condylar and intercondylar fractures of the femur, like the Y-shaped fracture of the humerus, are the result of compression, the patella taking the place of the olecranon (FISK, 1962). This similarity between the humerus and femur illustrates what is perhaps the basic pattern of fractures in all long bones.

In life the forces acting to produce the final displacement of the fracture fragments include those attributable to muscle action as well as those attributable to external violence. Muscular activity is of importance in life in three ways. Firstly, tension fractures may occur when a force applied to a limb is reacted by a muscle which is contracting at the time. A possible example of such a mechanism may be some fractures of the olecranon and patella. Secondly, muscular contraction may affect the distribution of fractures within a long bone; for example, as already suggested, the muscles which are inserted into the proximal third of the humerus may protect the proximal end of this bone from spiral torsional fractures. Thirdly, after a fracture has occurred muscular action may be responsible for displacement of the fragments. This role of muscular action is well illustrated in the case of the humerus by fractures of the proximal end of the bone due to axial compression. Experimentally the separation of the fragments is relatively constant, and the fragments are firmly impacted into each other by the compressive load, so that the fracture fragments are stable. In life, disimpaction and displacement is presumably attributable to muscular action. In some elderly patients, it may also be relevant that ageing or osteoporosis produce extensive resorption of cancellous bone. Hence the fragments may be less firmly interlocked in the first place.

CONCLUSION

Fractures of the shaft of the humerus, or any long bone, vary according to the nature of the violence applied, whereas fractures at the proximal and distal ends are dependent on the anatomy of the bone, which is in turn related to the embryological development of the epiphyses.

SUMMARY

It is possible to reproduce the common fractures occurring in the adult humerus by simple mechanical methods. This has allowed a detailed examination of the morbid anatomy of the fractures and measurement of the forces involved.

A mechanical classification of fractures of the humerus is advanced which, it is suggested, may be generally applicable to the long bones.

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FRACTURES EXPÉRIMENTALES EFFECTUÉES SUR L'HUMÉRUS ADULTE

Sommaire—Il est possible de reproduire les factures usuelles survenant sur un humerus adulte à l'aide de moyens mécaniques simples. Cela a permis d'effectuer une observation détaillée de l'anatomie pathologique des fractures et de mesurer les forces misent en jeu. L'auteur propose une classification mecanique des fractures de l'humérus qui pourrait s'étendre à l'ensemble des os longs. Les fractures du corps de l'humérus, ou de tout autre os long, varient en fonction du choc reçu, tandis que pour les extrémités distales et proximales elles sont liées à l'anatomie de l'os, qui à son tour dépend du developpement embryologique des épiphyses.

EXPERIMENTELLE FRAKTUR DES ADULTEN HUMERUS

Zusammenfassung—Es ist möglich, mit einfachen mechanischen Verfahren die übliche Fraktur des adulten Humerus zu reproduzieren. Dadurch konnte die Anatomie der Frakturen untersucht und die Messung der beteiligten Kräfte durchgeführt werden. Es wird eine mechanische Klassifizierung der Humerusfrakturen vorgeschlagen, welche für lange Knochen im allgemeinen Gültigkeit hat. Frakturen des Humerusschaftes oder anderer langer Knochen variieren in Abhängigkeit von der angreifenden Gewalt, während die Frakturen am proximalen und distalen Ende von der Anatomie des Knochens abhängen. Diese steht in Beziehung zur embryologischen Entwicklung der Epiphysen.