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Anatomic basis of ligamentous control of elevation of the shoulder (Reference position of the shoulder joint)

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Summary. The authors describe in detail the position of greatest stability of the shoulder joint. They review the mechanical importance of this position in the overall physiology of the shoulder-girdle and stress the essential role of two articular ligaments of the shoulder joint (the coracohumeral and inferior glenohumeral ligaments) in arrival at this reference position. There thus exists a passive control, of ligamentous origin, of movements of the shoulder-girdle. The position is essential if the shoulder is to benefit from the full range of movement and full stability which it needs in every day functioning.

Bases anatomiques du contrôle ligamentaire de l'élévation de l'épaule (position de référence de l'articulation scapulo-humérale)

Résumé. Les auteurs décrivent en détail la position de plus grande stabilité de l'articulation scapulo-humérale. Ils analysent l'intérêt mécanique de cette position dans la physiologie globale de la ceinture scapulaire et soulignent le rôle essentiel de deux ligaments articulaires de la scapulo-humérale (ligament coraco-huméral et ligament gléno-huméral inférieur) dans l'accès à cette position de référence. Il existe donc un contrôle passif d'origine ligamentaire des mouvements de la ceinture scapulaire. Cette position est indispensable pour que l'épaule puisse bénéficier de toute son amplitude de mobilité et de toute la stabilité dont elle a besoin dans la physiologie courante.

Key words : Shoulder – Shoulder joint – Articular ligaments – Stability – Preferential position

Whether elevation of the upper limb is initiated by a movement of flexion or abduction, it is by a primarily ligamentous mechanism that the humerus is placed in the plane of the scapula in the so-called reference position. This position corresponds to the maximal osteo-ligamentous stability and amplitude of elevation of the shoulder joint.

Historical

The question of the plane of reference of movements of the scapula was raised a long time ago. Johnson [9, 10], in 1930, urged choice of the plane of the scapula as the plane of reference for describing movements of the shoulder. Saha [13], in 1950, described the "zero" position of the shoulder in elevation beyond 150°. Since then, very many studies [5, 7, 15] retaining the usual planes employed in anatomy have been devoted to description of a scapulo-humeral rhythm with the object of specifying the transition in elevation of the shoulder. A series of experimental observations made on the shoulders of non-embalmed anatomic subjects and in the living enabled us to identify the importance of the plane

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Fig. 1a-d
a,b Shoulder held in reference position; the skin, deltoid and arm muscles have been removed. **a** posterior view **b** inferior view **c,d** Complete elevation of the upper limb in life **d** frontal view; the axis of the body of the humerus is parallel to that of the spine of the scapula **c** lateral view of scapula; the axis of the body of the humerus is parallel to that of the lateral border of the scapula

a,b Epaule tenue en position de référence pièce écorchée, résection du deltoïde et des muscles du bras : **a** vue postérieure **b** vue inférieure **c,d** Elévation complète du membre thoracique chez le vivant : **d** vue de face : l'axe du corps de l'humérus est parallèle à celui de l'épine scapulaire **c** vue de profil de la scapula : l'axe du corps de l'humérus est parallèle à celui du bord latéral de la scapula

of the scapula in the description of movements of the shoulder-girdle and of the upper limb. We were also able to identify certain mechanisms involved in attaining this position.

Material and Methods

Performance of the study relied on several techniques: direct simulation of the role of the muscles moving the shoulder joint, a study of global passive mobilization of the shoulder-girdle, and obtaining anatomic sections and colored imprints. The study protocol has previously been discussed in detail in the work of one of us [8].

Active direct mechanical study

The shoulder studied was fixed in a rigid framework in such a way that the medial border of the scapula was

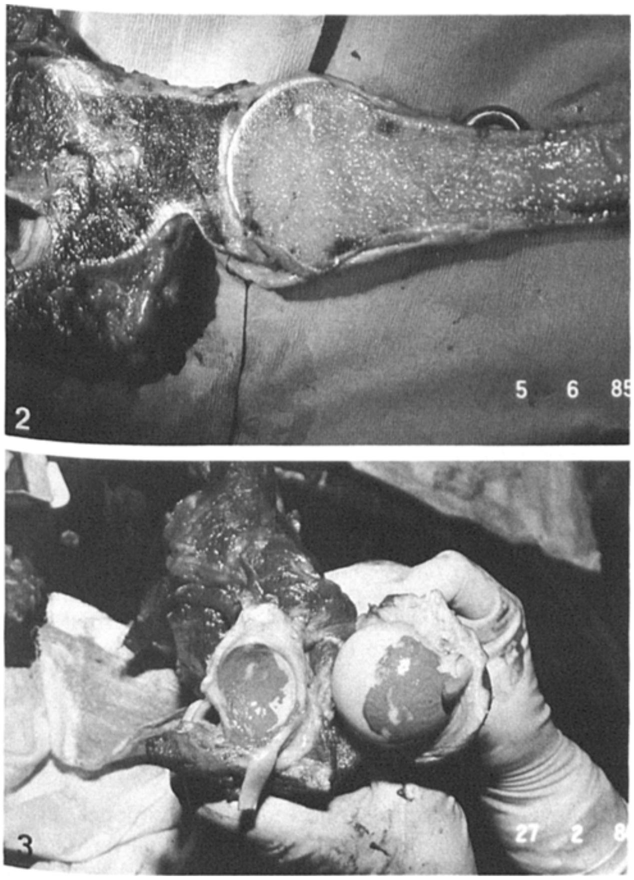


Fig. 2, 3
2 Section of a fresh specimen held in reference position; congruence of the surface is complete **3** Colored imprints made in a shoulder held in the reference position; the areas of contact between the humeral head and the glenoid are identical

2 Coupe d'une pièce fraîche tenue en position de référence : la congruence des surfaces est complète **3** Empreintes colorées prises sur une épaule tenue en position de référence. Les surfaces de contact entre tête humérale et glène scapulaire sont identiques

vertical. The frontal plane of reference is the vertical plane passing through the bisector of the angle formed by the axis of the clavicle and the superior border of the scapula, a plane virtually corresponding to the anatomic frontal reference plane. This arrangement alllowed reproduction of the actions of the muscles moving the shoulder joint by direct traction on their tendons.

Passive movement of the shoulder

The subject was placed in strict lateral decubitus. In the initial position the arm remained by the side of the body. The positions of the humerus and scapula were defined by two reference points, one fixed on the humerus, the other on the scapula. The humerus was moved passively through different trajectories and the movements of the scapula over the thorax as well as the changes of position within the shoulder joint were studied. Subsequently, we studied the changes in the play of movement produced by successive section of different capsulo-ligamentous components of the shoulder joint.

Staining of contact areas

A thin layer of dye was applied to one of the articular surfaces. When the two surfaces were brought into contact, it was possible to note the imprint of the zone of contact. The reverse procedure was then performed to verify that the surfaces obtained were the same.

Nomenclature of movements

Normally, movement of the humerus is the resultant of the two movements taking place, one between the scapula and the thorax, the other in the shoulder joint. Definition of movements of the shoulder merely by the trajectory of the humerus has the advantage of simplicity but does not allow precise description of the contribution of each articulation [2]. While aware of this reservation, we have retained the following description for purposes of simplicity: flexion takes place in a vertical antero-posterior plane; abduction takes place in the vertical and frontal plane; elevation is a less well defined movement taking place between these two planes. This nomenclature will be used whatever the movement studied, either global movement of the entire shoulder-girdle or movement of the shoulder joint alone.

Results

Description of the preferential position of the shoulder joint

Complete elevation of the shoulder-girdle can only be achieved if the shoulder joint is placed, from one moment to another, in a quite particular position that we call the preferential position. When the shoulder joint is in maximal elevation, some 110° on average, it is necessarily found to be in this position.

Geometry of the position (Figs. 1a, b, c, d). Frontally, the long axis of the humerus is a prolongation of the spine of the scapula; laterally, the axis of the body of the humerus is a prolongation of that of the lateral border of the scapula. The axis of the body of the humerus is perpendicular to the plane of the glenoid cavity. The humerus is situated in the plane of the scapula. Radiology in the living confirms these data.

Congruence of articular surfaces (Fig. 2). This was studied in sections made in unfrozen specimens main-

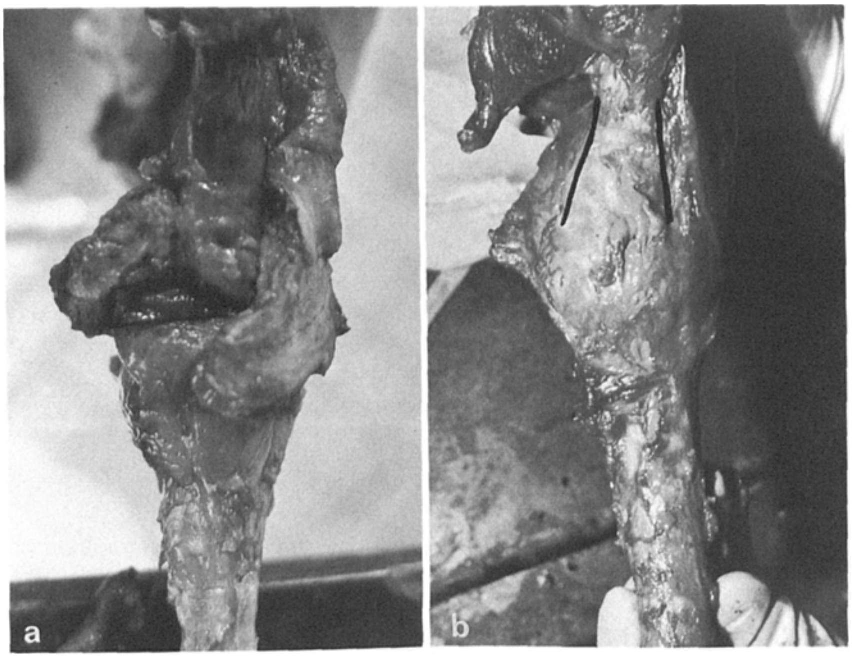


Fig. 4a,b
Final position of coracohumeral and inferior glenohumeral ligaments with the joint in the reference position; the margins of the ligaments are outlined in black **a** superior view : the coracohumeral ligament is perpendicular to the axis of the body of the humerus **b** inferior view : the inferior glenohumeral ligament is parallel to the axis of the body of the humerus

Position finale des ligaments coraco-huméral et gléno-huméral inférieur, l'articulation étant en position de référence. Les bords des ligaments sont soulignés en noir **a** vue supérieure : le ligament coraco-huméral est perpendiculaire à l'axe du corps de l'humérus **b** vue inférieure : le ligament gléno-huméral inférieur est parallèle à l'axe du corps de l'humérus

tained in the preferential position, and performed in the plane of the scapula. Congruence between the articular surfaces of the humeral head and the glenoid cavity was complete throughout the line of section. Any change of position in elevation in this same plane caused the development of incongruence between these articular surfaces. The preferential position is the only one to benefit from the complete congruence in the plane of section. This point is interesting in the context of the work of Saha [14] and Castaing [4], who state that congruence between the humeral head and glenoid cavity is altogether incomplete during elevation of the upper limb.

Contact areas. The application of a dye to the glenoid cavity allows precise determination of the contact area between the glenoid and the humeral head when the joint is in the preferential position. This is an oval surface situated at the upper pole of the humeral head and perpendicular to the axis of the humerus; this surface is equal to that of the glenoid cavity and the humeral head is closely applied to the entire glenoid cavity (Fig. 3).

Position of coracohumeral and inferior glenohumeral ligaments. In the position under study, the two ligaments are taut. The coracohumeral ligament is perpendicular to the axis of the body of the humerus (Fig. 4a), while the inferior glenohumeral ligament is parallel to the axis of the body of the humerus (Fig. 4b). These two ligaments are taut and participate in locking of the humeral head.

Attainment of preferential position: ligamentous control of shoulder elevation

Whatever the trajectory followed by the humerus during complete elevation of the shoulder, the final position of the shoulder joint is the same, i.e., the preferential position. This concept is well-known [15]; on the other hand, the mechanism controlling this positioning has so far not been recognized.

Ligamentous behavior during flexion (Fig. 5). With the humerus in neutral rotation: the tightening of the coracohumeral ligament during flexion restricts the range of this movement at the shoulder joint to an average of 75°. The movement of elevation cannot continue unless the humeral attachment of the coracohumeral ligament moves along a segment of a sphere whose center is the coracoid attachment of this ligament (i.e., for constant lenght of the ligament). In these conditions, the humerus progressively abandons the plane of flexion and approximates to the plane of abduction.

With the humerus in lateral rotation: the coracohumeral ligament is placed under tension earlier and the humerus leaves the plane of flexion at an earlier stage.

With the humerus in medial rotation: the coracohumeral ligament is placed under tension at a later stage and, theoretically, the range of flexion at the shoulder joint is greater. In this case, active lateral rotation becomes necessary to avoid direct collision between the humeral head and coracoid process, the ligament comes under tension and the movement then conforms to the preceding case.

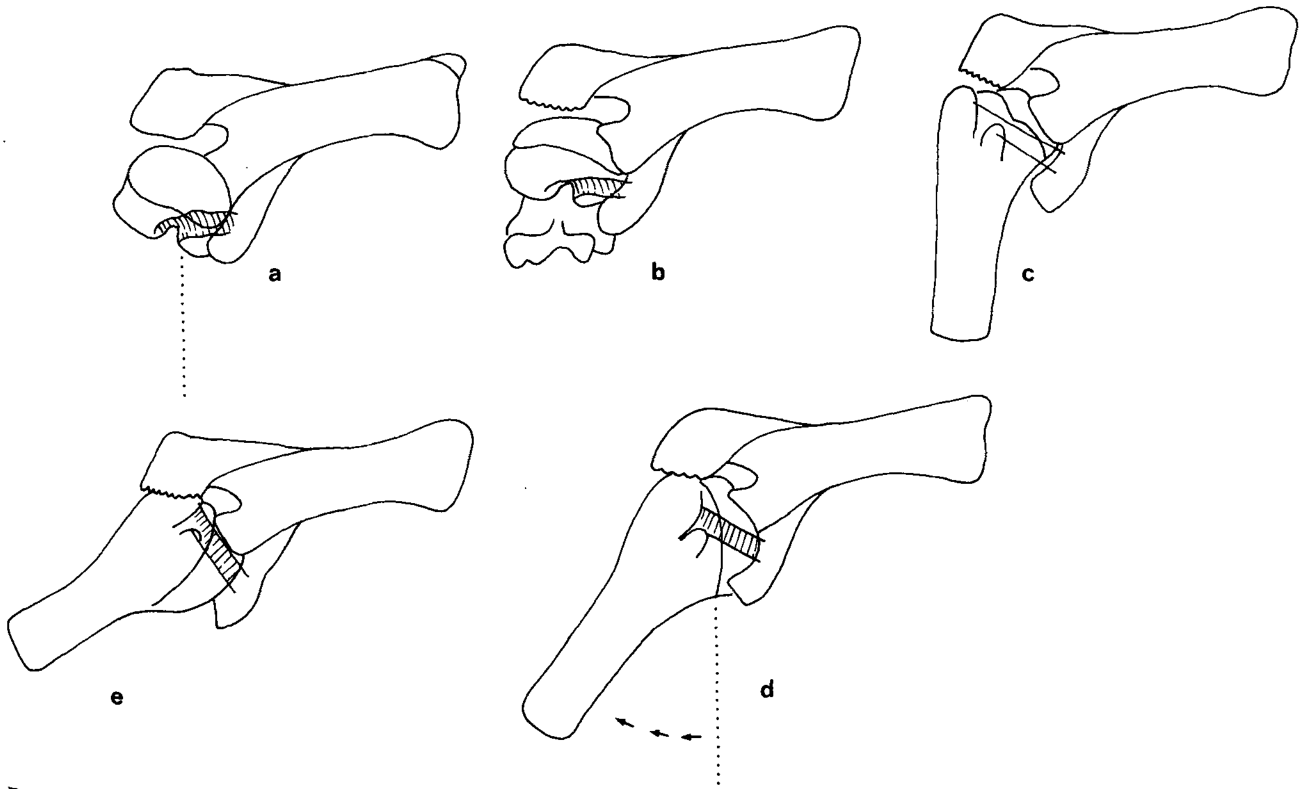


Fig. 5
Evolution of elevation of the humerus starting from a flexion movement : superior view **a** at rest the coracohumeral ligament is relaxed **b** beginning of humeral flexion **c** in maximal flexion of the shoulder the coracohumeral ligament is taut **d** to continue its movement the humerus must abandon the plane of flexion **e** humerus in position of maximal elevation

Déroulement de l'élévation de l'humérus à partir d'un mouvement de flexion. Vue supérieure **a** au repos le LCH est détendu **b** début de la flexion de l'humérus **c** en flexion maximum de l'articulation scapulo-humérale le ligament coraco-huméral est tendu **d** pour poursuivre son mouvement l'humérus doit quitter le plan de flexion **e** Humérus en position d'élévation maxima

This progressive placement of the humerus in abduction produces automatic tightening of the inferior glenohumeral ligament; the final phase of the movement of elevation of the upper limb can then commence.

Ligamentous behavior during abduction (Fig. 6). During pure abduction the tightening of the inferior glenohumeral ligament limits abduction of the humerus to an average of 90°. When this ligament is taut, the movement of elevation of the humerus can continue only under two conditions: the humerus must abandon the plane of abduction and assume a position of lateral rotation. It is necessary to leave the plane of abduction so that the humeral attachment of the inferior glenohumeral ligament may describe a trajectory situated on a portion of a sphere whose center is the scapular attachment of the ligament (length of ligament constant). The object of the lateral rotation is not to draw aside the greater tubercle, which passes without difficulty under the coracoacromial vault (except in forced medial rotation). The outcome of lateral rotation is tightening of the coracohumeral ligament and an "eccentric" movement (Fig. 7) which allows continued elevation of the humerus.

Final phase of elevation. This begins when both ligaments are taut. Whatever the trajectory followed by the humerus during elevation, there is therefore a moment when both ligaments are tight though the joint is not thereby locked. Rotational movement is still possible; the humeral head remains capable of performing a rotation during which it "screws home" in the glenoid, while the attachments of the two ligaments describe a trajectory situated on two segments of a sphere. This rotational movement described by the humeral head occurs around a different axis from that of the humerus; the latter therefore describes an approximate section of a cone, which accounts for the continuation of elevation (Fig. 7). Thus, three factors contribute to guidance of this last phase of elevation: the coracohumeral and inferior glenohumeral ligaments and the geometry of the articular surfaces. The termination

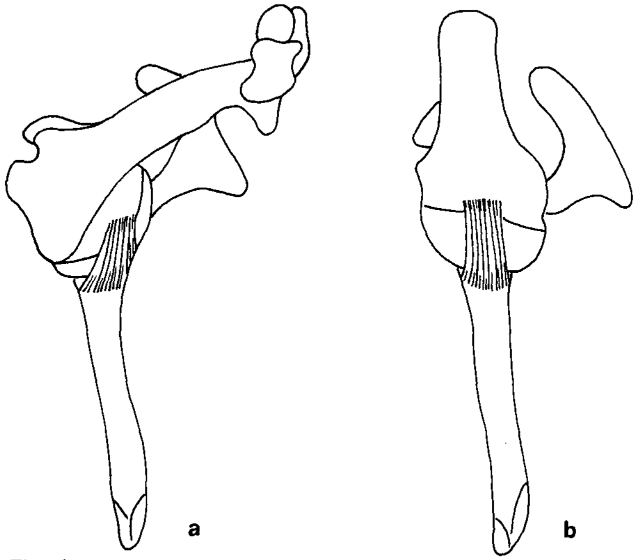


Fig. 6
Abduction of humerus, diagram of lateral view **a** in maximal abduction of the scapulo-humeral joint the inferior glenohumeral ligament is taut and limits the range of movement **b** the humerus must abandon the plane of abduction if movement is to continue

Abduction de l'humérus, schéma en vue de profil **a** en abduction maxima dans l'articulation scapulo-humérale le ligament gléno-huméral inférieur est tendu et limite l'amplitude du mouvement **b** l'humérus doit quitter le plan d'abduction pour que le mouvement se poursuive

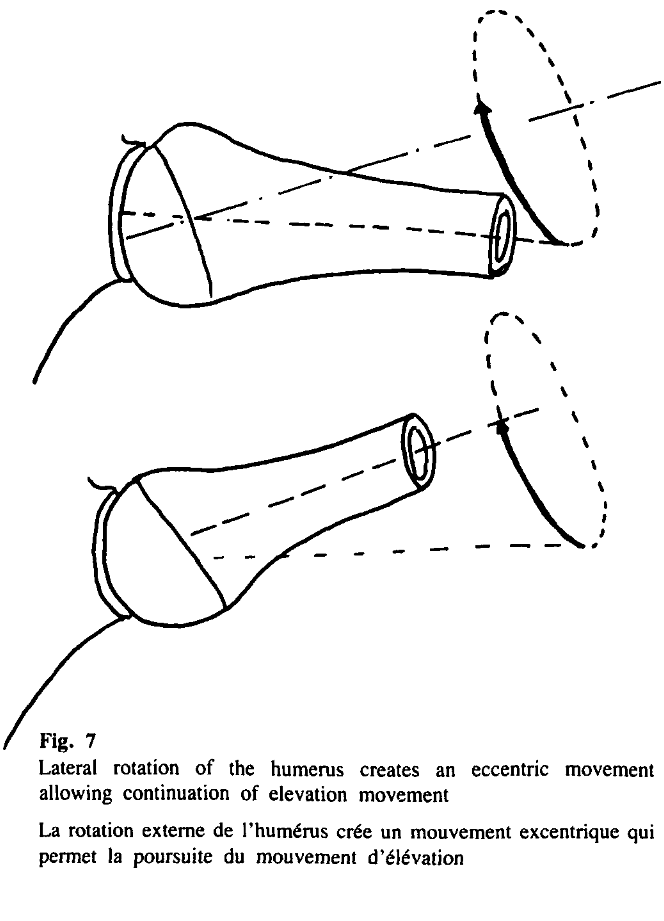


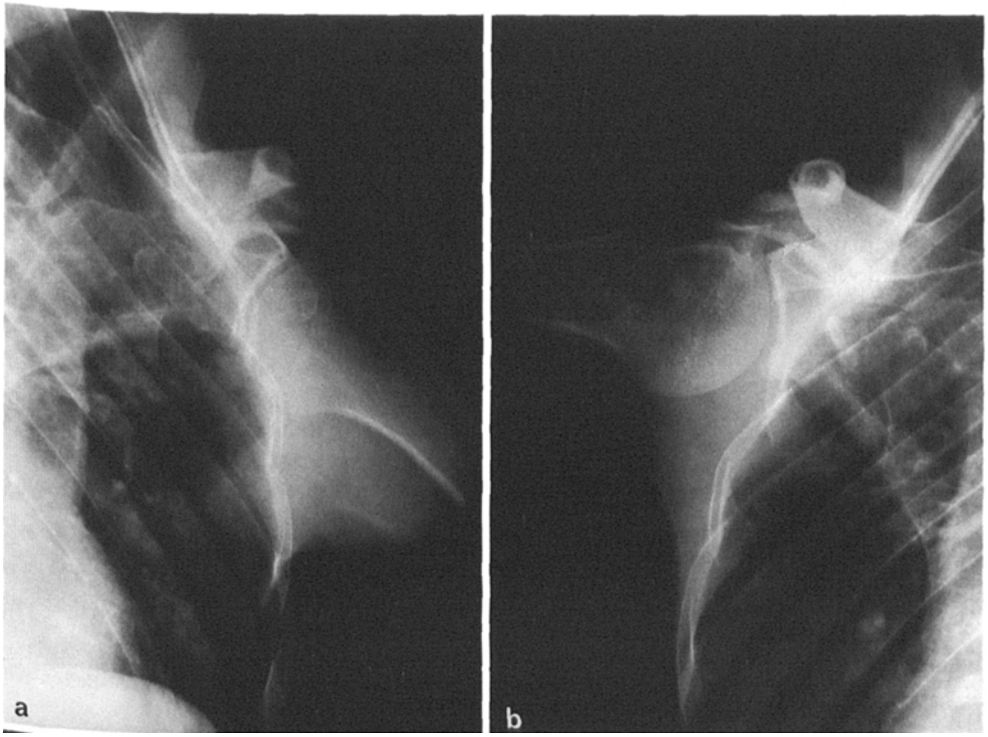
Fig. 7
Lateral rotation of the humerus creates an eccentric movement allowing continuation of elevation movement

La rotation externe de l'humérus crée un mouvement excentrique qui permet la poursuite du mouvement d'élévation

of the movement of elevation therefore corresponds to locking of the shoulder joint by tightening of both ligaments and complete insertion of the humeral head into the glenoid cavity. The limitation of movement does not therefore involve any bony or ligamentous buttress between the humeral head and glenoid cavity.

When does the shoulder joint attain the preferential position? Obviously, this must be when it is in complete elevation; but it is capable of achieving this position well before this (Fig. 8). Here we have an explanation of the so-called "inverse handbell" movement referred to at the start of certain shoulder movements [1]. At its outset, this movement corresponds to a recession of the scapula, whose lateral angle rocks downward in opposition to the handbell movement which carries the lateral angle upward. Castaing and Gouaze [3] noted that the share of scapular movement in movements of elevation with loading was greater than during movements without loading, a fact very well explained by the early access to the preferential position. The inverse handbell movement of the scapula allows production of elevation of the humerus within the shoulder joint while the upper limb is raised only very little in space, for the opening of the compass formed by the lateral border of the scapula and the body of the humerus is achieved as much by recession of this lateral border as by true elevation of the humerus. The shoulder joint can therefore be placed in the preferential position at little cost as the center of gravity of the upper limb has virtually not moved. Thus, even before having commenced the work of elevating the load, the shoulder joint finds itself in a position of the greatest stability. The work of elevation, properly speaking, is confined to the powerful muscles moving the scapula, which propel the upper limb upward by effecting on the scapula the well-known handbell movement. The motor muscles of the shoulder joint then have only to produce the locking action.

A new kinetic model for the shoulder-girdle. We are therefore led to consider that there exist at least two main types of movements within the shoulder-girdle: *rapid or ballistic movements* during which the shoulder carries out a continuous movement, benefiting from an accelerative "in series" arrangement. The muscles moving the scapula and those of the shoulder joint are effectively independent of each other, so that there exist two motors in series and the angular velocities of each joint are summed. It is this type of movement that gives occasion for the scapulo-humeral rhythm to occur [1, 7, 16]; *dynamic movements* (load-lifting), during which the shoulder first assumes the preferential position and then entrusts the motor muscles of the scapula with the task of effecting the essential lifting work by a rotational movement effected virtually locally [1]. This model of movement confirms and explains the findings of Castaing and Gouazé [3].



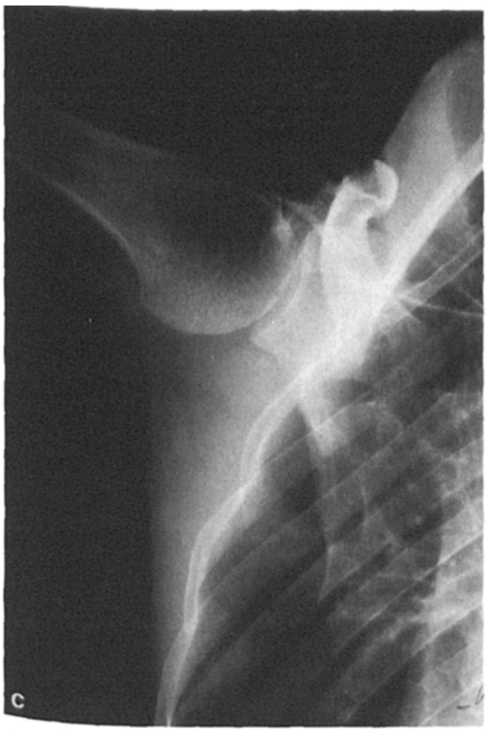


Fig. 8
When a heavy weight is carried in the hand, the inverse handbell movement of the scapula permits elevation within the scapulo-humeral joint at the expense of a moderate elevation of the humerus in space. Continuation of the movement occurs essentially at the scapulo-thoracic level **a** elevation of the humerus in space is only through 30°, whereas elevation within the scapulo-humeral joint is already virtually maximal **b,c** movement of the upper limb in space continues by a virtually pure handbell movement of the scapula

Port d'une charge lourde dans la main, le mouvement de sonnette inverse de la scapula permet une élévation au sein de l'articulation scapulo-humérale au prix d'une élévation modérée de l'humérus dans l'espace. La suite du mouvement se fait essentiellement dans la scapulo-thoracique **a** l'élévation de l'humérus dans l'espace est seulement de 30 degrés alors que l'élévation au sein de l'articulation scapulo-humérale est déjà pratiquement à son maximum **b,c** le mouvement du membre thoracique dans l'espace se poursuit par un mouvement de sonnette pratiquement pur de la scapula

Discussion

Importance of the preferential position

Mechanical stability. The area of contact is the greatest possible, so the contraints are best distributed. The axis of the body of the humerus is perpendicular to the plane of the glenoid cavity, so that the constraints transmitted to the shoulder joint have no tendency to dislocate the joint. This is consistent with the theoretic results of Poppen et al. [11], who showed that at 150° of elevation the constraints transmitted by the humerus to the glenoid were at right angles to the latter. This also applies to the findings of Turkel et al. [17] in connetion with the stability of the humeral head in complete abduction. The tension of the two ligaments holds the humeral head against the glenoid and the short periarticular muscles form a closely-fitting sleeve that adds to the stability of the whole. There is here the concept of the "close-packed position", the position of maximal stability of an articulation. In the case of the scapulo-humeral articulation, it should be stressed that this is an extreme position quite removed from the rest position.

Muscular economy at the shoulder-girdle. The muscles moving the scapula are all situated in planes adjacent to that of this bone. Therefore, the forces these muscles apply to the scapula are maximal adjacent to this plane, thereby considerably facilitating the "handbell" movements of the scapula. As against this, the components of these forces situated in a plane perpendicular to that of the body are weaker, and anterior rocking movements are difficult to compensate. Placing the humerus in the plane of the scapula approximates the center of gravity of the upper limb to the plane of the scapula, so diminishing the forces tending to swing the scapula forward. There is therefore a remarkable adaptation between the mechanical possibilities of the scapula and the constraints transmitted to it by the upper limb.

30° gain in elevation in relation to the usual reference planes. Pure flexion of the shoulder joint is limited to 75° on average, and pure abduction to 90°. But elevation in the plane of the scapula is at least 110°; therefore, access to the preferential position coincides with the greatest possible amplitude of elevation, indispensable if the upper limb is to attain complete elevation.

Role of coracohumeral and glenohumeral ligaments

What has been said clearly illustrates the importance of the role of ligamentous guidance of movements of the shoulder joint. The articular ligaments of the scapulo-humeral joint have a more complex and fundamental role than mere limitation of movement [Roux 12, Fischer 6]; their function is primarily kinetic —to guide the humerus during elevation so that the latter may attain the reference position. Like the cruciate ligaments of the knee, they ensure precise regulation of the movements of the joint.

Conclusion

In defining the anatomy and mechanical importance of the preferential position of the shoulder, we confirm the postulates of Saha and Johnston as to the importance of the scapular plane as the plane of reference for movements of the shoulder. But the importance of the preferential position of the shoulder is not limited to this. This position makes it easier to understand the mechanics of the articular complex of the shoulder and underline the remarkable adaptation of the shoulder confronted with the functional paradox of which it forms part, i.e., to provide both mobility *and* stability, to be capable of both rapid and powerful movements, and to cope with a quite remarkable inadequacy of the lateral rotator muscles. Another essential feature is the demonstration of the fact that, like the knee, the shoulder is subject to a ligamentous guidance that is indispensable to sound functional adaptation.

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