ESTIMATING SHOULDER COMPLEX MOBILITY

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ABSTRACT
Modelling shoulder motions is essential in understanding upper limb dynamic behaviour. However, the mobility of the shoulder-complex – in terms of degrees of freedom – is seldom quantified. In this paper we propose applying the theory of mechanisms and, especially, the powerful Grübler-Kutzbach formula to estimate it. This approach requires a rigorous kinematic analysis so we suggest basing it on a bone schematization derived from an extension of Demspter’s historical notation associated to a mechanical interpretation of the physiological joints involved. So doing, the proposed shoulder complex mobility leads to justifying a 9 d.o.f serial chain upper limb mode, which extends the classical 7 d.o.f arm-forearm-wrist model and completing it by adding a clavicle-like link with a 2 d.o.f. mobility.

KEY WORDS
Shoulder modelling, Shoulder kinematics, Upper limb kinematic modelling

1. Introduction

The shoulder joint is often presented as the most mobile joint of the human body. Curiously this mobility is seldom quantified. Two reasons seem to be related to this lack. Firstly, the shoulder joint is not a single joint but a complex set of joints including the shoulder girdle closed chain and its specific ‘false’ scapulothoracic joint. Secondly, this kinematic complexity is associated to a complexity of the musculature which actuates the shoulder joints. Even today certain authors still highlight this difficulty in understanding the kinematic properties of the shoulder joint complex: ‘However, the shoulder joint complex is an articulation that defies simple kinematic description’ [1] (page 113), or: ‘The shoulder joint is a complex joint with many degrees of freedom’ [2] (page 591). A consequence of the difficulty in determining the mobility of the shoulder complex leads to giving the scapula a number of degrees of freedom (d.o.f.) which are highly dependent on the study framework. Mentioning only recent studies, the scapula has nil mobility in [3] and a mobility of 5 d.o.f. in the Comprehensive Human Animation Resource Model [4]-[6], i.e. practically the two extreme values allowed for by mechanics for a single link. Several recent studies simply avoid the question of shoulder complex mobility estimates either by kinematically defining the scapula as an independent solidly oriented entity with respect to the thorax due to 3 Euler angles [7]-[9], or by considering an empirical model of the scapula, as given in the recent Stanford University model [10] which animates the shoulder complex and its musculature by using De Groot’s regression equation [11].

In the framework of this paper, we would like to show that the application of the theory of mechanisms to the physiology of joints can help in the understanding of shoulder-complex kinematics, notably in determining shoulder girdle mobility using the Grübler-Kutzbach formula. Our article is divided into four sections. In the first section, we deal with the diagrammatic presentation of jointed body links. An extension of the Demspter’s historical notation, seemed to us to be indispensable in clarifying the kinematic diagrams, and extending them to multiple joints. By associating this link-notation with a symbolic representation of the joints in their physiology, inspired from mechanical joint symbols, a general notation for a conventional representation of kinematic chains of the skeletal system is proposed. In the second section, having first justified the move from the joint physiology point of view, of our choices for the kinematic nature of the main shoulder joints, we put forward a conventional kinematic representation of the shoulder-complex. In the third section, an evaluation of the mobility of the shoulder-complex based on our kinematic analysis of the shoulder girdle is given. In the fourth, we consider the possibility of defining an open chain kinematic model equivalent to the human shoulder-complex, leading us to validate a 9 d.o.f. kinematic model of the human upper extremity, which can appear as an extension of the usual 7 d.o.f. model of the upper limb considered in biomechanism [12]-[15] by adding a clavicle-like link to it.
- **ball-and-socket joints**, with spherical-like surfaces, giving three rotation motion possibilities to the joint;
- **flat joints**, whose surfaces are flat i.e. less curved so as to be considered ideally as a flat surface; generally speaking, the flat joint allows two translation motions onto a plane and one rotation motion perpendicular to this plane;
- **condyl or ellipsoidal joints**, whose surfaces are ellipsoidal, allowing flexion-extension and abduction-adduction motions but excluding the ball-and-socket spinning motion;
- **saddle-shaped joints**, the surfaces of which are reciprocally concave-convex allowing flexion-extension and abduction-adduction motions as in condyl joints;
- **hinge joints**, whose cylindrical-like surfaces are apposed, generating a pulley-like rotation motion;
- **trochoid or pivot joints**, where the surfaces are also cylindrical-like so as to generate a rotation motion around a pivot.

Due to the specificity of articular joint surfaces, this taxonomy of physiological joints is original compared to the standard classification of mechanical joints. It is subsequently possible to suggest an equivalence between physiological and fundamental joints as given in Table 1.

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>d.o.f</th>
</tr>
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<tbody>
<tr>
<td><strong>ball-and-socket</strong></td>
<td>3</td>
</tr>
<tr>
<td><strong>flat</strong></td>
<td>3</td>
</tr>
<tr>
<td><strong>condyl or ellipsoidal</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>saddle-shaped</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>trochoid or pivot</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>hinge</strong></td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE I. GENERAL CORRESPONDECE BETWEEN JOINT PHYSIOLOGY AND CLASSICAL MECHANISM THEORY**

Such a mechanical interpretation of physiological joints is essential for the correct modelling of the physiological kinematic chains under study. However, the complex geometry of articular surfaces and, especially, the important role of ligaments in physiological joint functioning, limits this correspondence. This is the case in some flat joints, which can behave like spherical joints such as the shoulder acromioclavicular joint, or of some theoretically two d.o.f. condyl joints or saddle-shaped ones, which can be equated with three d.o.f. spherical joints if a spinning motion occurs, as will appear for the shoulder sternoclavicular joint. This specificity of each anatomical joint complicates the mechanical interpretation but does not exclude it, since it can be considered that each anatomical joint can be ideally represented by one of the classical mechanical pairs. Furthermore, and to a certain extent, the convexity of corresponding articular surfaces can be taken into account in a joint mechanical interpretation: the convex surface being the male part of the joint and the concave surface its female part. This is, however, not so simple in the case of saddle-shaped joints and of some ambiguous flat joints. Hence one reason why the kinematic modelling of the clavicle inside the shoulder girdle is a compound problem.

The modelling of physiological joints ranks with the kinematic modelling of skeletal bones. In the 1950s, W. Dempster introduced the notion of a body link defined as “a line of constant length that spans the pin axes” (page 560) [16]. This simplified representation leads to modelling the skeletal limbs as kinematic chains of rigid links by analogy with the kinematic modelling of machines. More accurately, Dempster models the bones in the form of simple links containing only two joints. For example, he models the humerus as the straight-line segment joining the glenohumeral joint and the elbow joint as illustrated in Figure 1.a. This bone modelling leads to the diagrammatic form of the human skeleton as an arborescence of simple kinematic chains, as illustrated in Figures 1.b [16] and 1.c [17].

![Fig. 1. Dempster’s kinematic notation based on a modelling of bones in the form of simple body links, (a) Scapula and humerus examples [16], (b) and (c) Application to the skeletal modelling (reprinted from [16] for scheme ‘b’ and from [17] for scheme ‘c’).](image)

Due to its high synthesis power Dempster’s notation is still today broadly used (see, for example, Engin and Tüner’s extensive paper on shoulder biomechanism [18]-[19]). However this method can be criticized for being limited to simple links only, thus ignoring the possibility of links with more than two joints. The scapula is typically a bone containing three joints. Dempster models it as the straight-line linking the acromioclavicular joint and the glenohumeral joint as Figure 1.a illustrates. By so doing Dempster ignores the existence of the ‘false’ scapulothoracic joint which has to be taken into account.
in modelling the shoulder girdle. This is the reason why this study suggests, in the spirit of machine and mechanisms theory [20], extending Dempster’s body link notation from a simple link-type model, to a complex link-type model. The theory of mechanisms indeed distinguishes “simple links” which are mechanical links with two joints, from “complex links” which are mechanical links having more than two joints. For example, the mechanism in Figure 2.a is composed of five mobile simple links four of which are simple links represented in the form of four linear segments, and one of which is a three-joint complex link represented by a hachured triangle, as Figure 2.b illustrates.

In a similar way we suggest substituting Dempster’s linear representation of the scapula by a triangular representation with the third nodes composed of the acromioclavicular (AC, glenohumeral (GH) and sternothoracic (ST), considered as mechanical joints, as illustrated in Figure 2.c.

This triangular kinematic representation of the scapula should not be mistaken for another geometric representation of the scapula, which is sometimes considered, defined by the triangle consisting of the three angles of the scapula (AI (Angulus Inferior), AS (Angulus Superior), AA (Angulus Acromialis)), or the AI with two points TS (Trigonum Scapulae) and AA (Angulus Acromialis), as illustrated in Figure 3.a. These purely geometric representations of the scapula have no kinematic meaning. The reproach, of mixing kinematic joint centres with nodes of the scapula geometric representation, can be made of Pronk’s model [21] according to which “the scapula [is modelled] by the beam elements AC-TS and TS-AI ” (page 120), as illustrated in Figure 3.b. Although the TS and AI “points” could be considered as remarkable aspects of the scapular link, helping to putting the link, as sometimes considered in kinematic studies [20], into diagrammatic form, their use in the kinematic definition of the scapular link in the end appears confusing. In particular, Pronk’s model of limiting the shoulder girdle to only the scapula and clavicle [21] (page 119), is not able to take into account the fundamentally closed chain nature of the shoulder girdle. This is the reason why we suggest basing our kinematic shoulder complex analysis on the proposed triangular kinematic representation of the scapula. Let it finally be noted that the three nodes considered designate the corresponding joint centres. In the case of spherical-like or universal joints, this is the point around which the joint rotates (although it is well known that the instantaneous centre of rotation is not constant, but is assumed to be). In the case of revolute-like joints, this is the point of the rotation axis whose projection on the gliding surface is in the middle position. And in the case of a planar-like joint, this joint centre corresponds to the middle of the gliding surface. In a more general way, it is important to note that the kinematic notation of complex links can lead to planar representation of the bone as in the case of three-joint bones (case of the scapula) or to non-planar representation in the case of more complex bones such as dorsal vertebrae involving 6 joints [22]. In any event, due to the fundamentally spatial nature of physiological joints and in accordance with Dempster’s body diagrams, the kinematic representation of bodily mechanisms is fundamentally spatial whether the involving bones have a planar or a spatial representation.

Fig. 2. Proposed extension of Dempster’s notation to complex link type-bones, (a) Mechanism example with a complex link – the link 4 – (from [23]). (b) Conventional diagram of the mechanism highlighting the polygonal representation of a complex link, (c) Three-joint kinematic representation of the scapula.

Fig. 3. Triangular representation of the scapula, (a) comparison between the usual representation of the scapula as a triangle joining three remarkable points of its geometry and the proposed one joining the three joints involved in shoulder girdle kinematics, (b) Criticism of Pronk’s model, mixing “geometric” and “kinematic” nodes in the kinematic diagram of the scapula (reproduced from [21]).
Furthermore, it is easy to combine this link notation with a joint symbolism not considered by Dempster, but introduced by his successors (Tüner and Engin for example). Subsequently, the considered Dempster notation will be used in association with the notation of classical mechanical joints as shown in Table 1, to illustrate our kinematic analysis of the shoulder complex.

3. The shoulder complex as a complex kinematic chain

Traditionally the shoulder complex is defined as a four-main joint system\(^1\) comprising the sternoclavicular, acromioclavicular, ‘false’ scapulothoracic and scapulohumeral joints. The first three constitute the shoulder girdle while the fourth links the arm to the shoulder. The specificity of the role of the shoulder girdle is to increase the mobility of the humerus, moving in its glenohumeral link. The scapulohumeral joint is obviously a ball-and-socket joint which can be modelled by a spherical joint. The modelling of the three joints of the shoulder girdle is more debatable. In particular the modelling of the two clavicular joints is a delicate question. The acromioclavicular or scapulooclavicular is often categorized as a flat joint [17] (page 61), [18] (page 48), [25] (page 321) but is also likened to a ball-and-socket joint [18], [19] which leads to modelling it by a spherical joint. The light convexity of the joint associated to the role of powerful ligaments surrounding it, appears to explain his choice of kinematic model. Conversely, the sternoclavicular joint is defined as a saddle-shaped joint which theoretically has two d.o.f., but all studies of shoulder physiology underline the existence of a clavicle axial rotation which plays a non-negligible role in upper extremity elevation, as R. Cailliet emphasizes in his classical work, *Shoulder Pain* (page 42) [27]. Subsequently the clavicle axial rotation-clearly appears as a d.o.f.. As a consequence, as V. Zatsiorsky emphasizes in his recent major publication on the kinematics of human motion, “kinematically, the sternoclavicular joint functions as a ball-and-socket joint with three DOF (page 348)” [28] in spite of its two d.o.f. saddle-shaped joint nature.

Thus, the taking into account of all clavicular joint d.o.f. leads to the modelling of the three true joints of the shoulder complex in the form of three spherical-type joints, as effected in the classical works of Dempster [17] and Steindler [26]. Accordingly, Tüner and Engin [19] represented the shoulder complex by an open kinematic chain with three links and three spherical joints, as Figure 4 illustrates.

Such an open chain modelling, still used today as in, for example, [29], is deceptive because it leads to believing that the shoulder complex has nine d.o.f. To the best of our knowledge [30] were the first to suggest a diagrammatic representation of the shoulder complex which interprets the shoulder girdle as a closed kinematic chain, as Figure 5.a reproduces. However, no kinematic modelling was deduced by these authors.

![Fig. 4. Kinematic modelling of the shoulder complex as an open kinematic chain, (a) definition of complex shoulder body links according to Dempster's notation, (b) the corresponding Engin & Tüner's kinematic model.](image)

This is the interpretation of the ‘false’ scapulothoracic articulation as a kinematic joint allowing the kinematic modelling of the shoulder girdle. Scapulohumeral articulation gives the shoulder the possibility of gliding over the back of the thorax with possible rotation around a perpendicular axis (the so-called ‘tilting’ movement). Because the scapula movement is not associated to joint surfaces, the ST articulation is not easily assimilable to a mechanical joint. Van der Helm, in his extensive paper [31], [32], considering a shoulder mechanism model derived from Pronk’s model, as already mentioned, defines the shoulder movement as a gliding movement of the two “beam-bones” AC-TS and TS-AI over the thorax, as Figure 5.b illustrates. However no type of mechanical joint clearly specifies the mobility of these two contact elements. Analysing this modelling problem of the scapula motion over the thorax, W.Maurel suggested interpreting the ST joint as a 5 d.o.f. joint-point on plan, as illustrated in Figure 5.c. This approach certainly facilitates a graphical animation of the upper extremity’s

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1 Some classical treatises model the shoulder complex with 7 joints including the suprhumeral joint, the sternocostal joint and the costovertebral joint [27] but, conversely, the suprhumeral joint “is not an anatomical but a physiological joint” [24] and, on the other hand, the sternocostal and costovertebral joints have very low mobility.

2 In a previous paper, Van der Helm considers that ‘the scapulothoracic gliding plane is modelled by two surface elements which constrain the motions of two points at the medial border of the scapula’ [33] (page 129).
natural movements but is difficult to justify from a purely anatomical point of view, because it leads to giving too much freedom to the gliding motion of the scapula over the thorax which is basically a surface to surface contact.

Face with this difficulty, it is here proposed to model the ST articulation as a simple three d.o.f. planar joint, whose first two d.o.f. express the two instantaneous translation motion possibilities of the scapula surface along the thorax surface, the third d.o.f. expressing the rotation motion of the scapula around an axis perpendicularly to the plane tangent to the two surfaces in contact. If the thorax, represented by a curved line, is considered as the mechanism frame, resulting in the kinematic diagram of the shoulder complex given in Figure 6 (note that the humerus head and the clavicle ends have been chosen as male parts of corresponding spherical joints). This diagram clarifies Tüner and Engin’s by closing the shoulder girdle kinematic chain, and Dvir and Berne’s by introducing the corresponding joint models. In comparison with the pseudo-conventional Pronk and Maurel diagrams it tries to highlight a more formal representation of the bio-mechanism, independent of any simplified anatomical diagram on which it would be drawn, and in comparison with the recent Lenarcic and Stanicic [34] formal diagram of Figure 5.d it aims to show the interest of using a correspondence table between physiological joints and mechanical joints.

Fig. 6. Proposition of a conventional kinematic diagram of the shoulder complex (the left shoulder has been represented to be in accordance with previous Fig. 1 to 4).

4. Estimate of the mobility of the shoulder complex

Mobility $F$ of a spatial kinematic chain of $n$ links one of which is the fixed frame, and which are jointed by $j$ articulations is, in general, defined as the difference between the mobility without any constraint of the $(n-1)$ mobile links and the total number of constraints $c_j$, $1 \leq j \leq j$ imposed by each joint, i.e. :

$$F = 6(n-1) - \sum_{i=1}^{j} c_i$$

Fig. 5. Some attempts at representing the shoulder complex mechanism, (a) Dvir and Berne scheme [30], (b) Van der Helm’s diagram [32], (c) Maurel’s diagram [6], (d) Lenarcic and Stanicic’ diagram [34] (see comments in the text).
Since the number $c_i$ of constraints imposed by a joint is equal to the difference between the 6 degrees of freedom of space and the degrees of freedom permitted by the joint, we obtain:

$$F = 6(n-1) - \sum_{i=1}^{j} (6 - f_i) \Rightarrow F = 6(n-1) + \sum_{i=1}^{j} f_i$$  (2)

This equation is known as the Grübler-Kutzbach formula. In the case, for example, of the serial chain composed of the shoulder girdle and of the humeral link – i.e. the thorax being considered as the fixed frame of a three link chain with two joints – its application leads to:

$$F_{shoulder\,complex} = 6(3-1-2) + F_{shoulder\,girdle} + 3$$

$$\Rightarrow F_{shoulder\,complex} = F_{shoulder\,girdle} + 3$$  (3)

which corresponds to the intuitive meaning. Conversely, as Lenarcic and Stanisic clearly show [34], the Grübler-Kutzbach formula very relevantly applies to the estimate of the number of degrees of freedom of the shoulder girdle, which is too often determined in a purely intuitive way. It is, however, important to note that Grübler-Kutzbach is not universal; and can be put into difficulty in certain geometric situations (for example, the so-called over-constrained mechanisms that require special links to achieve mobility). These situations expected, it is possible, as Tsai emphasizes, [35] to extend the Grübler-Kutzbach criterion in taking into account the possible presence of passive d.o.f. Besides obvious joint redundancies, Tsai distinguishes three types of binary links with passive degrees of freedom, synthetized in Table 2.

If we note $f_p$ as the number of passive d.o.f., Tsai puts forward the extended Grübler-Kutzbach formula, such that:

$$F = 6(n-1) - \sum_{i=1}^{j} f_i - f_p$$  (4)

This is the formula we suggest should apply to the calculation of shoulder girdle mobility. Under the assumptions made in a previous paragraph, $n$, the number of the mechanism links, is equal to 3 (torso, clavicular link, scapular link), $j$, the number of joints, is equal to 3 (two spherical joints and one planar joint), and all $f_i$ are equal to 3. But it is our opinion that the axial clavicular rotation must be considered as a passive d.o.f. due to the fact that it corresponds to a rotation around an axis passing through the centre of two spherical joints, as illustrated in the S-S diagram of Table 2. This interpretation corresponds to the non-motor role of this joint motion: in point of fact, according to Inman, Saunders and Abbott, [36] the axial clavicular rotation plays an anatomical role essential for arm elevation, because it helps draw out the ligaments enclosing the acromioclavicular joint. Thus, within the framework of a kinematic model which does not take into account any ligamentary movements, it appears as one passive d.o.f. Taking this passive d.o.f into account, the application of the Grübler-Kutzbach formula leads to the following result:

$$F_{shoulder\,girdle} = 6(3-1-3) + 3\times3 - 1 = 2 \text{ d.o.f.}$$  (5)

Note that we finally obtain the same end result as that given by Lenarcic and Stavisic [34], but the present approach appears more efficient in that it emphasizes the specific role of the clavicle within the shoulder girdle. Consequently, the total shoulder-mobility complex is estimated to be 5.

Beyond this numerical result, we wish to emphasize the generality of our approach which can be adapted to other assumptions concerning the mobility of the links of the shoulder complex. In accordance with the principles of the mechanism theory, it clearly distinguishes the joints which are concerned by the mobility analysis from the actuators (the muscles) and their annexes (the ligaments) which are not so concerned. In this way, our approach differs from the one developed, for example, by van der Helm which mixes purely kinematic constraints with muscular or ligamentary constraints. Generally speaking, a ligament, cannot reduce the mobility efficiency of a joint, but can only limit its motion range: for example, the “conoid ligament” considered in his model as a constraint in van der Helm’s model – and clearly shown in Figure 3.b of Pronk’s model from which it derives – [31], [32], plays the part, according to Kapandji, of a limitation of the angle between the clavicle and the scapula but does not determine joint mobility [24] (page 52). Moreover, in the absence of a general formula for determining the mobility of a complex kinematic chain, the mobility the authors confer on the set ‘shoulder-

<table>
<thead>
<tr>
<th>Type</th>
<th>Scheme</th>
<th>Passive degree of freedom</th>
</tr>
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<tbody>
<tr>
<td>S-S</td>
<td>Rotation about an axis through centers of ball joints</td>
<td>1 passive dof</td>
</tr>
<tr>
<td>S-E</td>
<td>Rotation about an axis through the center of the ball and perpendicular to the plane of the plane pair</td>
<td>1 passive dof</td>
</tr>
<tr>
<td>E-E</td>
<td>Sliding along an axis parallel to the line of intersection of the planes of the pairs. If the two planes are parallel, 3 passive degrees of freedom exist</td>
<td>1 passive dof 3 passive dof</td>
</tr>
</tbody>
</table>

**TABLE II. BINARY LINKS WITH PASSIVE DEGREES OF FREEDOM**

(the texts are reprinted from [35] but the diagrams have been introduced by the present author).
complex / elbow flexion-extension’ is very questionable: ‘The sternoclavicular, acromioclavicular, glenohumeral and elbow joint yield 10 DOF, the conoid ligament and the scapulothoracic gliding plane impose 3 kinematic constraints which yields a model with 7 kinematic DOF’ [37] (page 1181). Without wishing to criticise the important work of an author with the stature of van der Helm and his team on shoulder biomechanics (brilliantly synthesized in a recent paper [38] discussing Lewin’s audacious assumption [39] of a tensegrity structure of the scapula) our remark aims at stressing the interest of a rigorous and purely kinematic analysis of any physiological mechanism in helping further dynamic analysis of it.

5. Determination of an equivalent kinematic model of the shoulder complex

The determination of shoulder girdle mobility raises the question of putting the emphasis on an equivalent kinematic model in the form of an open chain, with the same mobility. Such an equivalent model could be useful in certain problems or applications, which do not need to mimic the whole of the skeletal structure of the shoulder girdle. The search for a rigorously equivalent model is a particularly difficult problem. We suggest a simplified approach, which aims at highlighting an “equivalent clavicle”. Let \( S \) be the centre of the sternoclavicular joint to which a fixed reference frame can be associated. Let \( G \) be the centre of the glenohumeral joint. Since the shoulder girdle has a two-d.o.f mobility, it is clear that two independent coordinates define the position of \( G \) in space.

Two joint variables \( \theta_1 \) and \( \theta_2 \) modelling the mobility of the sternoclavicular joint can be chosen as independent generalized coordinates. Because the distance between the sternoclavicular joint and the glenohumeral joint is clearly not constant, a third, linear and dependent, parameter has to be considered to express variable length \( SG \). An equivalent model results composed of two aligned links, the first one being joined to the sternum by a universal joint of variables \( \theta_1 \) and \( \theta_2 \), the second joined to the first by a prismatic joint dependent on \( \theta_1 \) and \( \theta_2 \), as illustrated in Figure 7. From a biomechanical point of view, this model very imperfectly expresses the orientation of the glenohumeral socket. However, it seems to us relevant because it expresses the fundamental kinematic role of the shoulder girdle: to position the glenohumeral joint in space. The suggested model differs from the more recent Lenarcic and Stavisic model [34] which considers the rotation centre of the scapula as an intermediate element; however, this more complete scapula-centred model seems to us, however, difficult to prove in a rigorous manner due to shoulder movement complexity, and more complex to put into work than our one.

It is also important to note that such a model with a passive d.o.f. – the d.o.f. of the joint dependent upon the universal joint motion – appears inadequate for use in practice. This is why we could like to emphasize the interest of a shoulder girdle model reduced to a simple link – i.e. an equivalent clavicle of constant length – joined to the thorax by a universal joint. Associated to a traditional 7R anthropomorphic robot model, a serial architecture of the human arm results in 4 links : clavicle, arm, forearm, hand – and 9 joints whose definition can be put in correspondence with joint physiology, as Figure 8 illustrates.

This structure is not new. It has already been considered in some earlier robotics [40] or biomechanics studies [41]. It is, for example, used in the 103 d.o.f. SANTOS digital human modelling environment of the Iowa University Virtual Soldier Research programme [42]. The rigorous demonstration of shoulder girdle mobility confirms its value. Furthermore, it is useful to recall the importance given to the clavicle by E.A. Codman in his fundamental essay on the shoulder [43]:

“We are proud that our brains are more developed than those of animals; we might also boast of our clavicles. It seems to me that the clavicle is one of man’s greatest skeletal inheritances, for he depends to a great extent than most animals except the apes and monkeys, on the use of his hands and arms. The clavicle holds the shoulder away from the body and therefore permits us to use our arms with power and skill in abduction, and adduction to a degree which few animals except the monkeys can approach” (pages 7 and 8).
6. Conclusion

We have tried in the framework of this article to throw light on the contribution of mechanism theory to the difficult problem of the kinematic modelling of the shoulder complex.

The notion of a “complex link” – in the meaning given by mechanism theory – seemed relevant to us so as to widen Dempster’s historical notation to bones with multiple joints such as the scapula.

At the same time, the Grübler-Kutzbach formula can be advantageously applied to biomechanisms, provided that an agreement is reached on the mechanical interpretation of the physiological joints concerned in the skeletal sub-systems under study. The application of this mechanism-type approach to the shoulder complex has led us to demonstrate that shoulder girdle mobility is equivalent to two, and that of the shoulder complex to five. The simplified model we have considered does not claim to be a substitute for more complex models of the “shoulder rhythm”. But using it validates a classical kinematic model of the upper limb with 4 links – clavicular, arm, forearm and hand – and 9 d.o.f. useful for biomechanical studies which have no need to take into account the muscles actuating shoulder-complex bones, but also in computer animation depicting humanoid robotics.

References


