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THE SHOULDER JOINT SYSTEM: BIOMECHANICS AND INSTABILITY

P.M. Calderale, C. Bignardi

Department of Mechanics, Technical University of Turin (Politecnico di Torino), Corso Duca degli Abruzzi 24 – 10129 - Torino – Italy

Abstract: The joints of the shoulder number from four to five, depending on interpretation. Together, they form one of the most complex and mobile joint systems in the human body. In mechanical terms, "the shoulder joint system" is a mechanism with multiple degrees of freedom.

The shoulder system provides a wide range of motion, to the detriment of stability. To a greater or lesser extent, instability characterizes all of the system's joints and in particular the glenohumeral joint, which has received most attention in the literature.

Without going into the merits of surgical procedures and basic theoretical studies of a mechanical nature, in this work it is presented a review with comments of the methodological developments in biomechanics which can be useful in studying the instability of the entire joint system or its parts, and which can be of assistance in selecting which type of corrective surgery should be performed.

Key words: shoulder joints system, biomechanics, instability

Introduction

The joints of the shoulder number from four to five, depending on interpretation. Together, they form one of the most complex and mobile joint systems in the human body. In mechanical terms, "the shoulder joint system" is a mechanism with multiple degrees of freedom.

Contrary to what was thought in the past, this system is highly loaded, with joint forces in the order of body weight. This observation invalidates the old distinction between load bearing and non-load bearing joints, which was based on the order of magnitude of the resultant joint forces to which the joints of the lower and upper limbs respectively are subject.

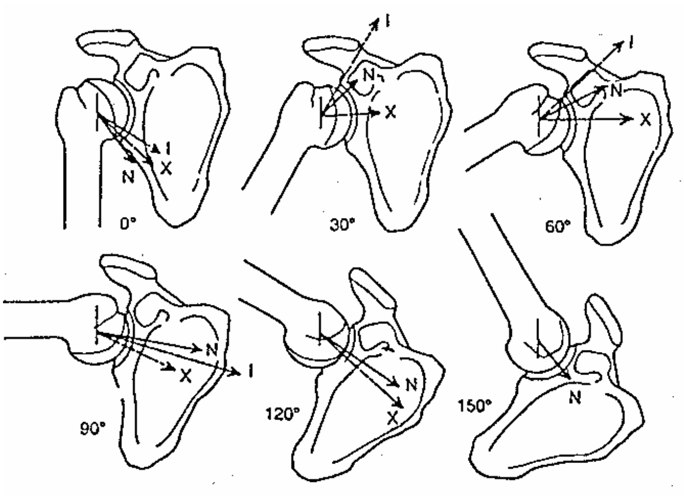

Fig. 1. Direction of the resultant force vector of the shoulder for different positions of arm abduction. The vectors N, X and I identify respectively the resultant force at the glenohumeral joint in neutral rotation, external rotation and internal rotation [1].

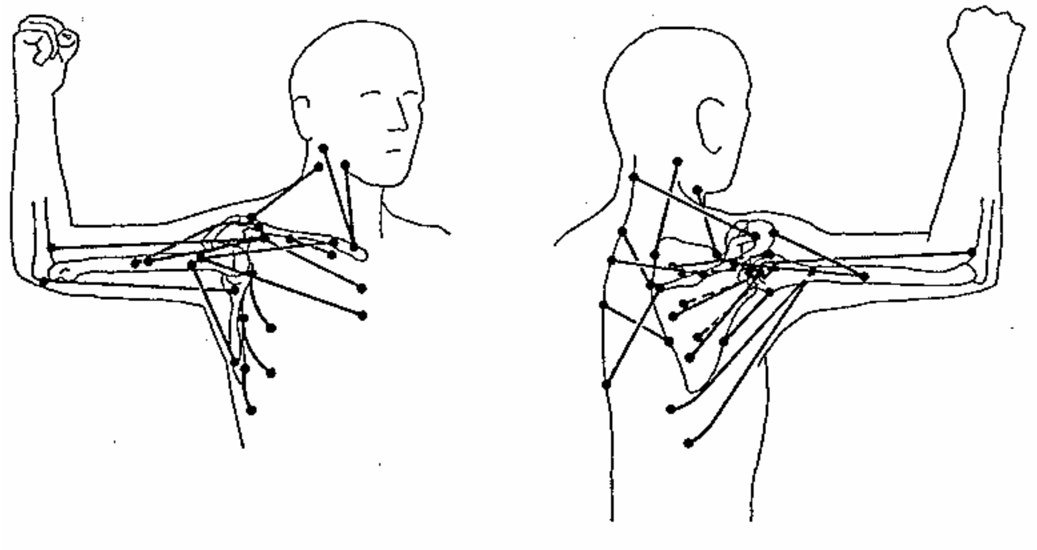

Fig. 2. Three-dimensional muscular model of the shoulder system [5].

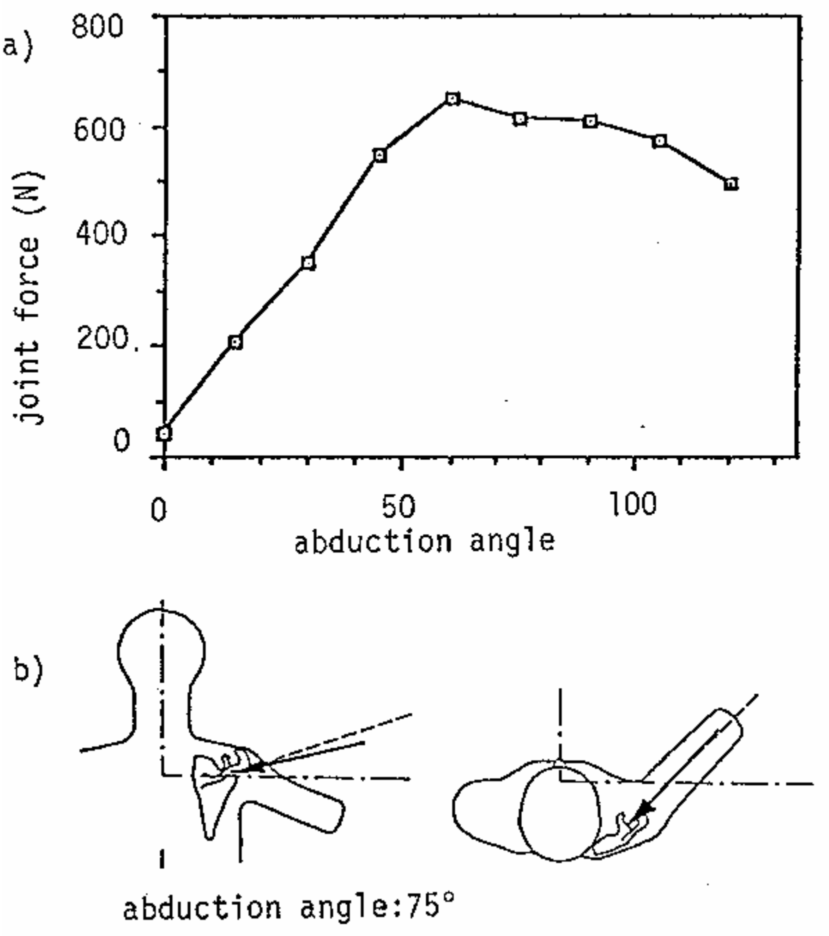

Fig. 3. a) Glenohumeral joint force levels in different abduction angles; b) direction of joint force in a 75° abduction position [4].

Poppen and Walker (1978) [1] conducted a two-dimensional study using electromiographic and radiographic techniques with muscle force assumed to be proportional to the cross-sectional area of the muscle to calculate the force of the glenohumeral joint during isometric abduction in the plane of the scapula (Fig.1). They found that the resultant joint force reaches a maximum of 0.89 times body weight at 90° of abduction. Maximum shear force on the surface of the scapula is 0.42 times the body weight at 60° of abduction, while the maximum compression force occurs at 90° of abduction and is more than 0.8 times body weight. The values calculated by these authors are around twice those obtained in the pioneering work of Inman et al. in 1944 [2, 3].

Results which are comparable to those of Poppen and Walker were recently obtained by Karlsson and Peterson (1992) [4] using a three-dimensional mathematical model based on the anatomical description of the shoulder joint system by Hogfors et al. (1987) [5] (Fig.2). The most efficient way to solve an indeterminate mechanical problem such as the analysis of the musculo-skeletal system, where a number of muscles act synergically during most movements, is to formulate what in mathematics is called an "objective function" and use optimization techniques. These authors used the sum of squared muscle stresses as an objective function, or in other words, found a solution to their mathematical formulation by minimizing the expression $\Sigma(F_i/A_i)^2$, where F_i and A_i are respectively the forces exerted by the *i* muscles considered and their cross-sectional areas. With this assumption, they obtained values of the contact force of the glenohumeral joint of around 600 N in 60-90° of abduction, or around 0.8 times the body weight of the physical reference model (Fig.3).

Amongst analytic mathematical evaluations, there are no alternatives to optimization methods with objective functions, which are chosen arbitrarily. These methods are all easily criticized, while highly reliable results are not to be expected. However, once the procedure has been verified for a particular situation - which can be reliably evaluated - we believe that these methods can without doubt be useful in indicating the order of magnitude of the values which can be calculated with them (for example muscular forces and joint forces).

The most recent methods of investigation have helped to show how the motion of the shoulder system involves all of the system's joints, and that their contribution cannot be regarded as a simple sequence of single actions, i.e. one joint after another. It would seem to be clear that several joints of the shoulder system are simultaneously active for each movement, and that the relative activity of each joint differs from individual to individual, depending on the pathology involved [6, 7].

The approach of the biomechanical engineer is thus difficult to begin with as regards mechanical investigation of the shoulder system's motion, and becomes doubly so when the subject of investigation is the system's instability.

Instability of the glenohumeral joint

The shoulder system provides a wide range of motion, to the detriment of stability. To a greater or lesser extent, instability characterizes all of the system's joints and in particular the glenohumeral joint, which has received most attention in the literature.

Instability would appear to depend on the applied forces, though a congenital capsular-ligamentous laxity also plays a role in the development of clinical instability.

Instability may make its appearance following a specific traumatic episode (macrotrauma) or after repeated microtraumas. In some individuals, on the other hand, instability cannot be connected to traumatic episodes.

Methods

The methods which have hitherto been used to study shoulder joint motion are in part the same methods used to investigate stability. Morrey and An (1990) [8] presented a classification of these methods, which we have elaborated and integrated as follows:

- The early research efforts to describe shoulder joint complex motion consisted of simple but careful observation of cadaveric materials [9–11]. This method of investigation is still used to define geometries and assessing parameters which can be of use in characterizing mathematical models or assessing causes of or predisposition to joint instability [5, 12–16].
- More recent observation techniques used both to study shoulder motion and to evaluate joint instability include one- and two-plane radiographic techniques. These techniques can be applied *in vivo* [17–23].
- Goniometers [24], electrogoniometers, stereometric methods, techniques using light-emitting diodes and ultrasonic transducers have been used in the hope of becoming part of clinical routine, but with limited success.
- More recently, a system has been developed whereby it is possible to determine the three-dimensional position and orientation of a sensor relative to a source. The six-degrees of freedom measurements are accomplished by using low-frequency, magnetic field technology to interpret the interaction of magnetic fields between three sets of orthogonal coils contained in both the source and sensor. This technique permits simultaneous measurement of a three-dimensional rotary motion and also makes it possible to calculate translation displacements [25–27].
- The best known and most efficient technique for describing a complex motion is that of tracing the centrode, i.e. the succession of the so-called instantaneous centers of rotation [28, 29]. The literature contains centrodes of the humeral head (Fig.4) and of the scapula (Fig.5) [20, 30] considered individually, as well as a centrode of the entire joint system (Fig.6) [31], which results from the contribution of the individual joints making up the system. Though considering the individual joints may be helpful in evaluating their contribution to limb movement, it can be overly simplified and lead to incorrect conclusions if the study is restricted to only one joint. This technique is suitable for easier

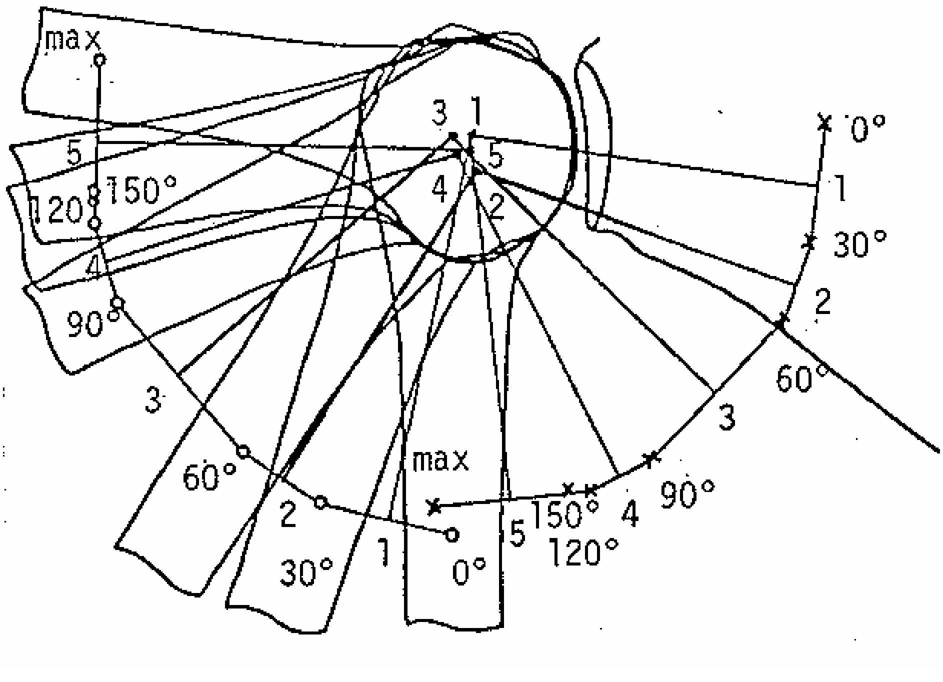

Fig. 4. Measurement of the instantaneous centers of rotation of the humeral head [20].

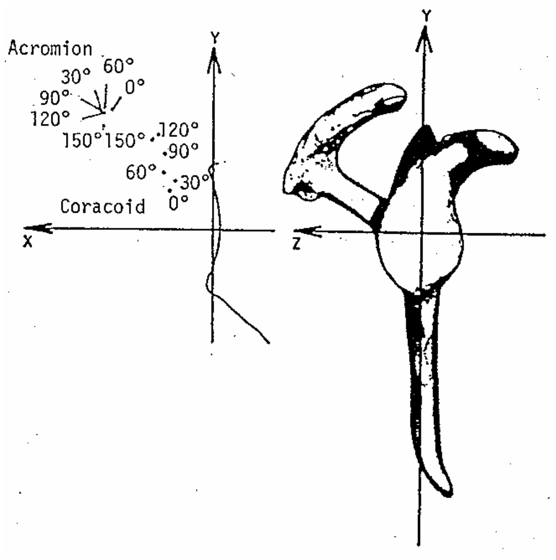

Fig. 5. The instantaneous centers of rotation of the scapula for arm elevation are focused in the tip of the acromion [20].

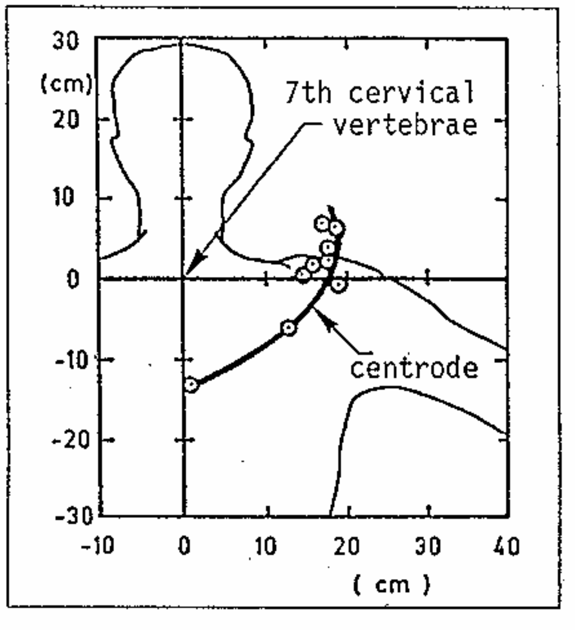

Fig. 6. The centrode path for the human shoulder system during elevation of the right arm [31].

applications if movements are analyzed which take place approximately on a plane. For markedly three-dimensional movements, it would be necessary to analyze the centrodes in three orthogonal planes, e.g. the anatomical planes. Observing only projection on a plane may be insufficient for diagnostic purposes, particularly in the presence of pathological conditions which introduce significant displacements out of the plane of the scapula.

- Among the methods which are most commonly employed in mechanics to describe the spatial motion of a rigid body, the use of the Eulerian angle system and the screw displacement axis description can be useful in studying the kinematics of the shoulder system. The first method can be adapted to investigating the motion of the glenohumeral joint; if its behaviour is assumed to be similar to that of a ball-and-socket joint, it is sufficient to consider only the rotation of the joint and neglect small amounts of translation (Fig.7). The second method is suitable for a more general description, where the rotation and translation components of displacement of the humerus relative to the glenoid or scapula are defined by a rotation around and translation along a so-called screw axis (Fig.8) [32, 33].
- A techinique used both to

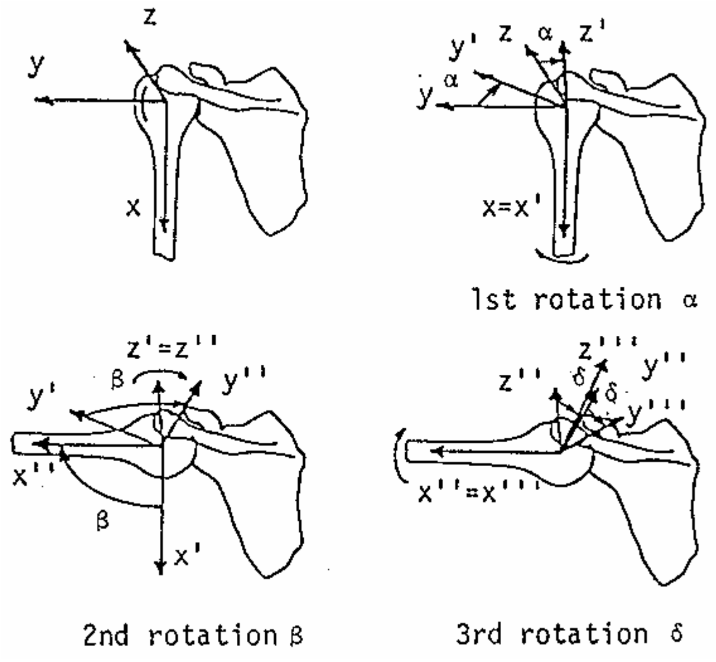

Fig.7. Three-dimensional rotation around each of the orthogonal axes is accurately described using the Eulerian angle system. Glenohumeral motion is defined by the sequence-dependent Eulerian angles [8].

investigate the contributions of individual muscles to joint motion and to validate results obtained from mathematical models is that of electromyograms. The limits of this method include the difficulty of positioning-sensors, the difficulty of interpreting myoelectric signals, and the variability of EMG-measurements [34–36].

- More recent and increasingly sophisticated methods of investigation include those employing mathematical models [4, 5, 34, 37–40].

Constraints

Studying the function and strength of a structure involves the analysis of forces and constraints, i.e. of those elements which affect movements.

Constraints providing joint stability include the following:

- The configuration of the joint structure.
- The capsular-ligamentous complex.
- The muscular complex.

A number of researchers have to a greater or lesser extent emphasized the contribution of each of these components to the stability of the shoulder system [5, 14, 17, 22, 23, 41–52].

As regards the glenohumeral joint in particular, the consensus emerging from the literature can be summarized as follows:

- Because of the shape of its articular surfaces, this joint is not inherently stable.
- The glenohumeral ligament complex prevents external rotation, and the lower glenohumeral ligament has a central role in the glenohumeral joint's anterior and inferior stability. The action of the ligaments is coordinated in such a way as to oppose joint displacement, first resisting displacement and subsequently exerting stabilizing forces opposite to the direction of displacement.
- The stabilizing function of the muscles when the upper limb is in rest conditions alongside

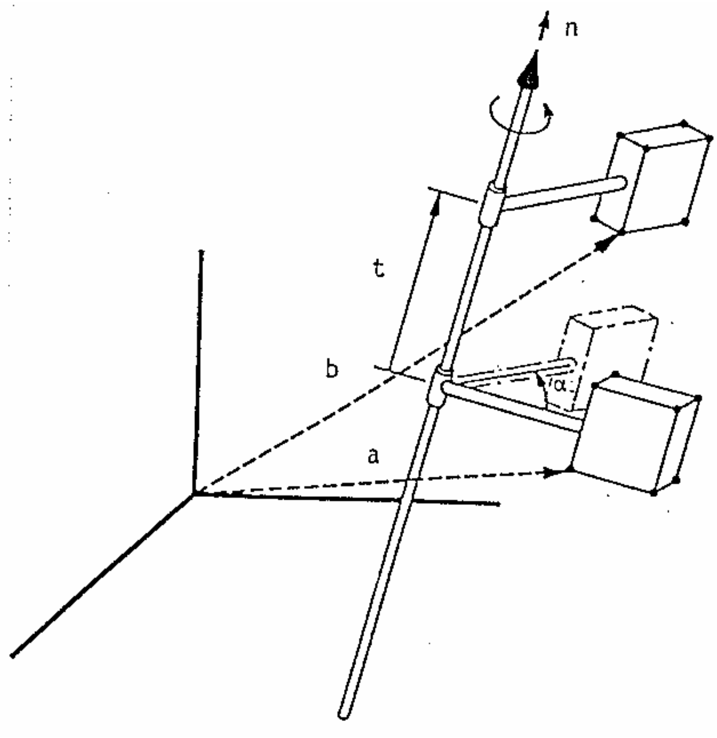

Fig. 8. Both rotational and translational components of displacement of a rigid body may be expressed by the concept of the screw axis; the unit vector *n* identifies the screw axis, vector *a* and vector *b* locate the position of the rigid body of which the motion is studied, as to three rigid axes, respectively before and after a rotation α and a translation *t* [8].

the body is minimum, and remains so up to an upper limb load of not more than 120 N [53].

Joint stability in situations other than rest is essentially ensured by rotator cuff components. The rotator cuff provides stability:

– Directly by acting as a barrier to displacements, or

– indirectly by moving the joint into a position that tightens the capsular-ligamentous complex.

Both of these actions cause an increase in the compression on the joint surfaces with an improvement in joint stability.

Still as regards the glenohumeral joint, which has received most attention inasmuch as it is most subject to instability, some authors [54, 55] have attempted to explain another aspect of joint stability, stability which is not sufficiently justified by the classic contributions indicated above, viz. geometry, capsular-ligamentous constraints and muscular action.

These studies identify a stabilizing effect in the fact that the joint is contained in a small volume closed by an undamaged capsule which ensures a controlled pressure in its interior. This concept requires that the capsule be sealed, so that air or other fluids cannot enter the joint, and that the capsule be sufficiently stiff, i.e. little capable of being deformed, to resist being driven into the joint by external pressures. When a translatory force is applied to a joint contained in a small volume closed by an undamaged capsule, a relative vacuum is created that resists translation. If the joint is vented, a relative vacuum is not created, therefore its effect is reduced or eliminated. This stabilizing effect was repeatedly described, but quantitative studies have been performed only in more recent years [16]. Tests on cadavers have shown that the translatory force required to displace the head of the humerus anteriorly and posteriorly by 6 mm, starting from the position with the head of the humerus centered in the glenoid cavity, is reduced by 73% and 24% respectively in comparison with an undamaged capsule (Fig.9).

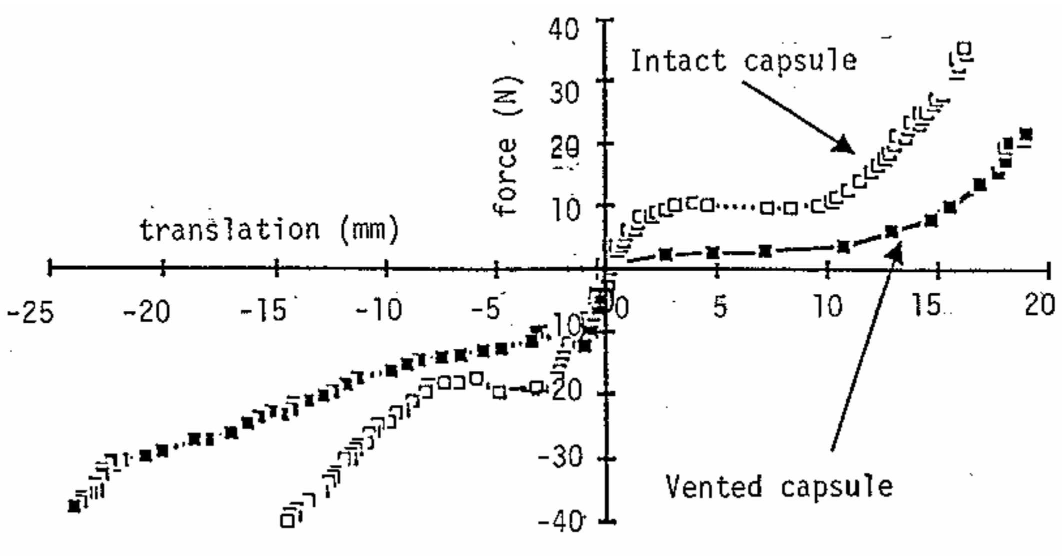

Fig. 9. Venting the capsule to the atmosphere decreases the force necessary to displace the humeral head [16].

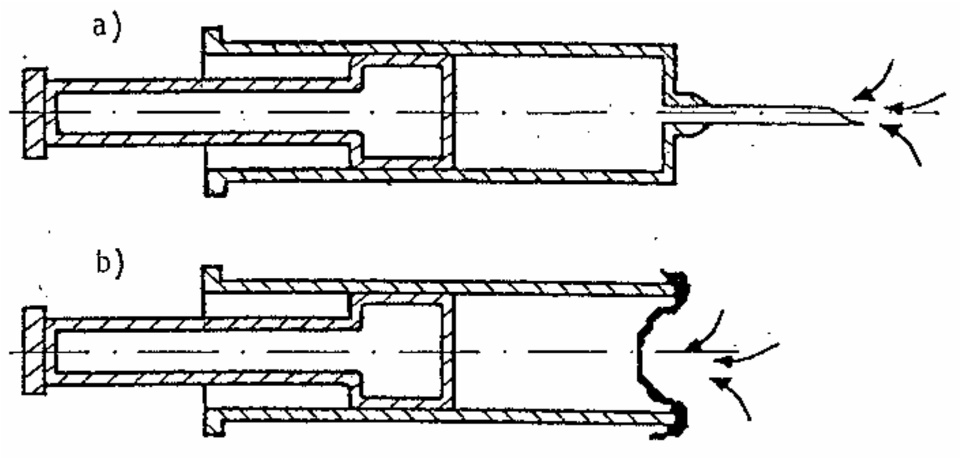

Fig. 10. Diagram of the mechanical analogy of the glenohumeral capsule to the limited volume in a syringe. The translation of the plunger is facilitated when air is admitted by uncapping the end of the syringe (a) or replacing the end of the syringe with a flexible membrane (b) [16].

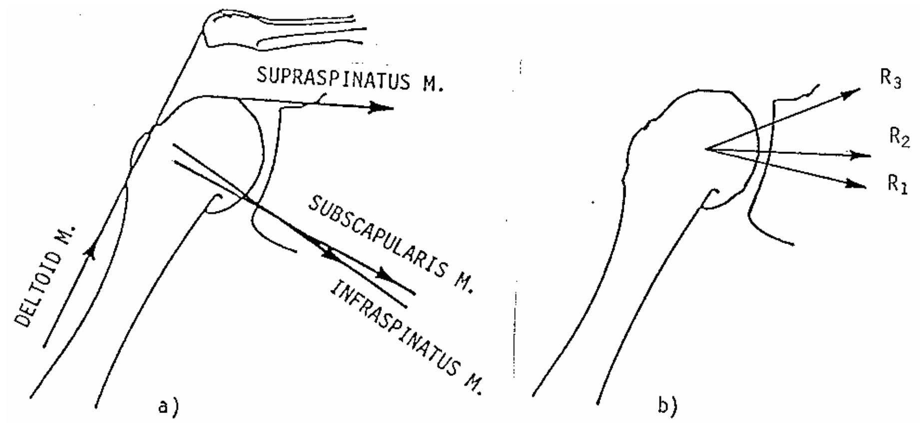

Fig. 11. a) Simplified two-dimensional vectorial model of the muscles involving the glenohumeral joint; b) the direction of the resultant force R_1 is obtained considering all the muscles showed in a), directions of R_2 and R_3 are obtained assuming that the contribution given by the action of infraspinatus muscle and the contribution given by the infraspinatus muscle and of the subscapularis muscle respectively, are nil [57].

This effect can be described in terms of a simple mechanical analogy (Fig.10): consider a capped syringe containing a finite volume of air in its barrel. As long as the syringe is capped, the plunger strongly resists translation. Translation is facilitated when air is admitted by uncapping the end of the syringe or making a hole in the syringe wall, or replacing the end of the syringe with a flexible membrane that readily invaginates when the plunger is withdrawn.

These situations can occur in the joint when the capsule is deliberately or accidentally damaged so that air or liquid enters the joint volume, or when the capsule is intact but easily distorted.

Models and methods for studying stability

It is now clear that it is very difficult to use complex mathematical models to accurately simulate the behaviour of a shoulder joint system in physiological conditions, to say nothing of pathological conditions.

Contributions to our knowledge of instability have been made using simple models designed to identify the direction of the resultant joint force corresponding to various positions of the upper limb [1, 56, 57]. These deliberately simple models make allowance only for the contributions to joint load which the literature recognizes as being the most important: among these the weight of the limb and the action of some muscles (the deltoid, the supraspinatus muscle etc.). Figure 11a shows a two-dimensional vectorial model of muscles involving the glenohumeral joint in a specific position of humerus with respect to the glenoid cavity. In this model deltoid muscle, supraspinatus muscle, sottoscapular muscle and infraspinatus muscle are considered. Figure 11b indicates how the direction of the muscular action resultant force changes as a function of the intensity of the single muscle's activity; in particular the resultant force goes through or by the glenoid cavity and therefore can have a more or less stabilizing effect. The direction of the resultant force R_1 is obtained considering all the muscles showed in Fig. 11a, while the directions of R_2 and R_3 are obtained assuming that the contribution given by the action of infraspinatus muscle and the contribution of the infraspinatus muscle and of the subscapularis muscle respectively, are nil. This example is intended to clarify a method which we believe to be valid.

Electromyographic measurements can certainly help in verifying which muscles work in the various stages of motion, but unfortunately they cannot assist us in evaluating the forces involved.

The technique of screw displacement axis description mentioned above can be applied to the study of instability. The stability or instability of the glenohumeral joint, for example, can be described by measuring the instantaneous center of rotation of the joint as the intersection between two instantaneous screw axes. If the joint is stable, the points of the intersections of all the screw axes will be confined within a small sphere. On the other hand, when the joint is unstable, the points of intersection of the screw axis will be more dispersed and confined in a larger sphere (Fig.12) [8].

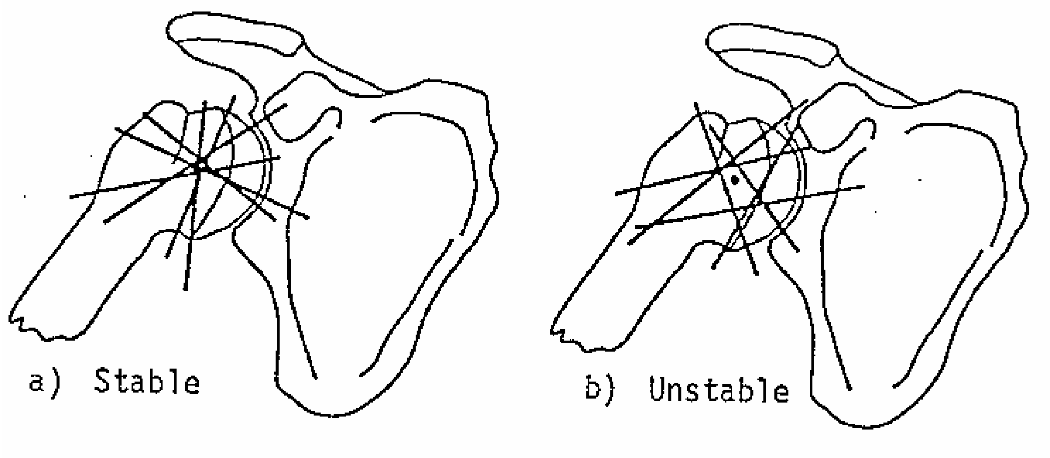

Fig. 12. The common intersection of the screw axes creates a perfect ball-and-socket joint (a). When significant translation occurs, the axes do not intersect at a single point (b) [8].

Conclusion

Without going into the merits of surgical procedures and basic theoretical studies of a mechanical nature, we will conclude with a look at the methodological developments in biomechanics which can be useful in studying the instability of the entire joint system or its parts, and which can be of assistance in selecting which type of corrective surgery should be performed.

Depending on the problem to be studied, we can choose between simple two-dimensional models and more complex three-dimensional models. With two-dimensional models, it is possible to construct a simplified model of the joint concerned and to translate all actions whereby system geometry is modified into a system of forces so that the joint resultant force can be traced. The direction of this resultant force can first be used to evaluate the degree of danger as regards instability, and then to indicate the relative worth of a specific surgical operation in terms of stability.

More accurate evaluations can be made with three-dimensional models, though as we have mentioned, at the present time it is not possible to construct a generally valid mathematical model, inasmuch as the evaluation of the modulus and direction of muscular forces depends on the objective function, which is selected arbitrarily.

Particularly as regards the early diagnosis of joint instability, we believe that a much valid method is that of identifying the instantaneous centers of rotation and the centrodes of individual joints and the entire joint system.

In this case, variation in the centrode of the entire joint system, relative to a situation which is considered to be normal, would be indicative of instability. To identify which of the joints is in fact unstable, it will be necessary to trace the centrode of the individual joints.

Routine use of the technique of identifying centrodes is currently limited by the large number of radiographs required, especially if the intention is to trace the centrode in its spatial representation by taking radiographs in the three anatomical planes. In our opinion, an exceptionally powerful diagnostic tool will become available only when non-invasive techniques instead of radiography, come into widespread use.

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Система плечевого сустава: биомеханика и неустойчивость

П.М.Кальдерале, К.Биньярди (Турин, Италия)

Отмечается, что в систему плечевого сустава в зависимости от интерпретации входят четыре или пять суставов. Вместе они образуют весьма сложную и подвижную систему сустава. С точки зрения биомеханики это механизм с многими степенями свободы. Большой диапазон движений в плечевом суставе создает опасность неустойчивости сустава, вызванной макротрещиной, накоплением микроповреждений или каким-либо патологическим процессом. Для диагностики важно своевременно обнаружить изменения в суставе, которые ведут к неустойчивости. Приводится обзор работ по моделированию поведения плечевого сустава и их классификация, предложенная авторами статьи. Наиболее эффективным методом исследования авторы считают наблюдение за движением оси винтового движения сустава в целом или его отдельных частей. Описываются различные подходы к анализу факторов, обуславливающих устойчивость системы (действие связок и мышц, наличие давления воздуха или жидкости внутри сустава). Отмечается, что подобный биомеханический анализ для каждого пациента может помочь в правильной диагностике и выборе метода корректирующего хирургического лечения. Библ. 57.

Ключевые слова: плечевой сустав, биомеханика, неустойчивость, диагностика

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