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Review

Shoulder function: The perfect compromise between mobility and stability

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Abstract

Shoulder function is a compromise between mobility and stability. Its large mobility is based on the structure of the glenohumeral joint and simultaneous motion of all segments of the shoulder girdle. This requires fine-tuned muscle coordination. Given the joint's mobility, stability is mainly based on active muscle control with only a minor role for the glenohumeral capsule, labrum and ligaments. In this review factors influencing stability and mobility and their consequences for strength are discussed, with special attention to the effects of morphology, muscle function and sensory information.

Keywords: Shoulder; Biomechanics; Joint stability; Strength; Upper extremity

Contents

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1. Introduction

The human shoulder can be seen as a perfect compromise between mobility and stability. The joint complex allows for a large range of motion, well beyond that of the hip. The particular compromise in the human shoulder is different from other animals and is believed to have played an important role in evolution. The development of a more laterally directed glenoid cavity of the scapula and a longer and more laterally twisted clavicle allowed for a freer mobility to raise the arm and facilitated vertical climbing. This has been coined the "vertical climbing hypothesis" (Isler, 2005). A second theory is that the wider use of the upper extremity for e.g. carrying food and objects might have been the incentive for bi-pedal locomotion (Latimer, 2005).

The shoulder girdle of terrestrial vertebrates has been described as variations on a general design, where elements are developed differently, based on the specific function of the upper extremity in that particular species (Starck, 1979). Depending on the function of the forelimbs, requiring specific motions and force transmission, the shoulder girdle varies among:

- A 'floating' scapula without a clavicle and with a more or less aligned humerus in running mammals, providing a large range of motion (Fig. 1a). The missing clavicle might be related to the fact that muscles are more suitable than a clavicle to counteract the pulling forces on the shoulder during running and jumping.
- A heavy bony construction sustaining large moments due to the specific locomotion, e.g. as in lizards (Fig. 1b), who pro- and supinate around their forearms. In addition, the wide placement of the forelimbs results in high gravitational moments around the shoulder (Starck, 1979).
- A heavy bony construction as in diggers such as the mole (Fig. 1c), in who large lateral forces are loading the humerus.
- A mobile construction with a floating, fork-shaped double clavicle, in flying birds, which is able to sustain the forces in the transversal plane (Fig. 1d).
- Systems with a well-developed clavicle ball-and-socket glenohumeral joint in climbing or grasping mammals like humans and apes (Pronk, 1991). The major advantage of the clavicle would be to allow the glenoid cavity of the scapula to rotate in a more lateral direction, which facilitates positioning the arm in the frontal plane and provide a large lever arm for e.g. the m. Serratus Anterior (Fig. 2).

It appears that each specific variation of the shoulder girdle is likely to be a compromise between the required mobility and the required strength (the possibility to exert external forces generated by the musculature), while both factors will have a major effect on the resulting stability of the joint complex and thus the robustness of the system.

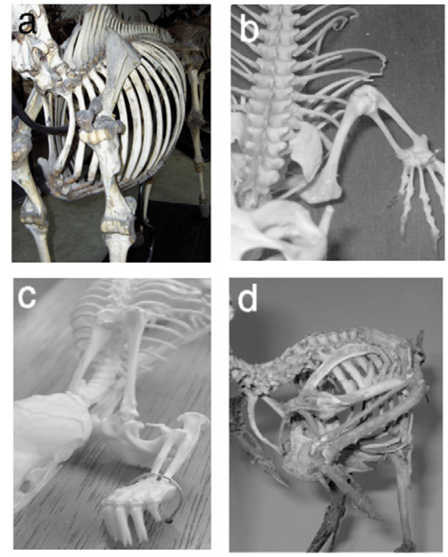

Fig. 1. Shoulder girdles of a pony (a), lizard (b), mole (c) and a crow (d).

The human upper extremity range-of-motion (ROM) covers almost 65% of a sphere (Engin and Chen, 1986a) while the humerus can be axially rotated at almost any orientation within this sphere. The combination of both, to which elbow flexion and pro/supination of the forearm can be added, determine the working area of the hand. In addition to the truly three-dimensional mobility of the shoulder complex, the system is capable of exerting forces in almost any direction. This versatility is enabled by a wide variety of mono-, bi- and tri-articular muscles. Given the 3D structure of the complex, each muscle will not only generate joint moments to meet external forces, but will also generate considerable undesired joint moment components, which must be compensated by other muscles. In addition, this effect is highly dependent on the shoulder posture at hand. It is clear that this requires a subtle co-ordination between all muscles.

In di-arthrodial joints such as the glenohumeral joint, a large mobility can only be obtained if one of the articular surfaces is considerably smaller than the other, which directly affects joint stability. For proper joint stability, the joint translations should be constrained, either by compressing the head in the socket in a spherical joint such as the glenohumeral joint, or by ligamentous structures in other joint types. If large translational forces in parallel to the articular surfaces occur, these forces must be counteracted by ligaments or stabilizing muscle activity, re-directing the joint reaction force (JRF) towards the articular surface.

The goal of this review paper is to give an overview on the current knowledge about the role of morphological structures, muscle properties and proprioceptive reflexes in the shoulder mechanism, enabling its large mobility and strength while maintaining stability.

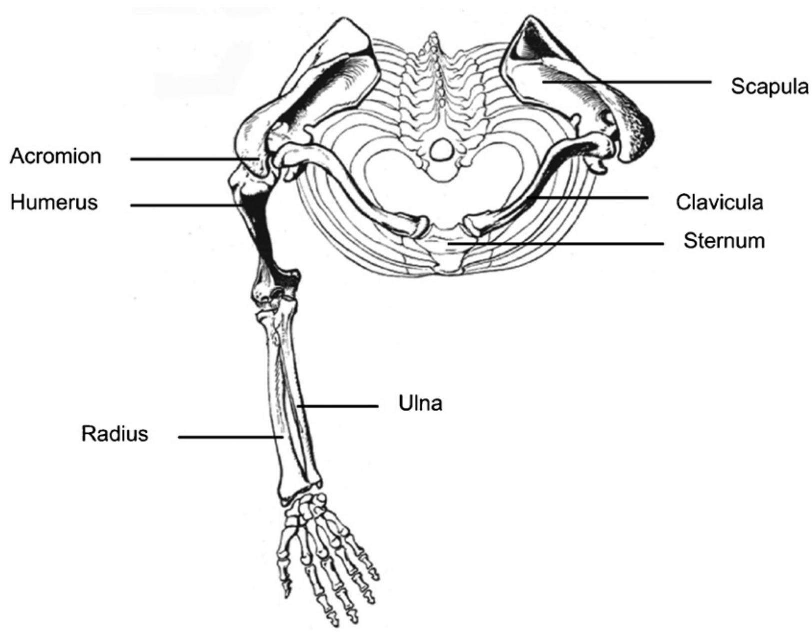

Fig. 2. The human shoulder girdle, as seen from above.

2. Mobility

The mobility of the shoulder joint is the result of motion in both the glenohumeral joint and scapulothoracic-gliding plane. This is often ignored, resulting in the description of arm motion as the rotation in a non-existent thoracohumeral joint. Most of the thoracohumeral motion takes place in the glenohumeral joint, which by itself allows for glenohumeral elevation up to 120° (Magermans et al., 2005; van der Helm and Pronk, 1995). In addition to this, the humerus is able to axially rotate about 135° relative to the scapula (Magermans et al., 2005). The remainder of the thoracohumeral motion is the result of scapular motion, especially lateral rotation, with respect to the thorax. The contribution of scapular motion to arm elevation follows a general pattern in which scapular motion is responsible for approximately 1/3rd of the total arm elevation. This process is coined the ''scapulohumeral rhythm'' (SHR) (Codman, 1934). Scapulothoracic fusion, as is sometimes performed in paralysis of serratus anterior, results in a maximal elevation capacity of around 100° (Bizot et al., 2003; Jeon et al., 2005).

The sternoclavicular joint allows clavicular elevation of 11°–15°, retraction of 15°–29° during arm elevation and especially a large axial rotation of up to 40° (Inman and Saunders, 1946; van der Helm and Pronk, 1995). Since the longitudinal axis of the clavicle is almost perpendicular to the scapular plane (see Fig. 2), the axial rotation of the clavicle and the lateral rotation of the scapula (in the scapular plane) are equivalent and require minor adjustments in the acromioclavicular joint, with maximal joint excursions of about 30°–40° (Ebaugh et al., 2005; Mollier, 1899; Magermans et al., 2005). Optimization of the axial rotation of the clavicle could reduce the acromioclavicular joint rotations to less than 10°, which required clavicular axial rotation up to 60° (Pronk, 1991).

The large mobility of the glenohumeral joint is possibly due to the small articular surface of the scapula, the glenoid surface, as well as the loose connecting capsule. In itself, the capsule is not tight enough to prevent joint dislocation: shoulder subluxation is a common phenomenon in the afflicted shoulder in hemiplegia (Yu, 2004).

2.1. Closed chain mechanism

The shoulder is a closed chain mechanism in which the humeral head is positioned by a closed chain formed by thorax, scapula and clavicle. Motions of the scapula are constrained on the one hand by the medial border of the scapula, which is pressed against the thorax by the combined action of the m. Serratus Anterior and m. Rhomboidei, and sometimes by the external load on the arm. If the scapulothoracic constraint is absent, for example in scapular winging, considerable function loss occurs, especially in forward elevation of the arm (Inman et al., 1944). On the other hand, scapular motions are constrained by the clavicle, which allows the acromion to move more or less on a sphere around the sternoclavicular joint.

It is obvious that a decrease in degrees-of-freedom of the system due to fusion, or pain, will reduce the function of the system. In addition, changes in dimensions of the elements of the mechanism will also influence the kinematic and dynamic behavior. According to Teubner et al. (1991), shortening as well as lengthening of the clavicle led to an increase in reaction forces at the sternoclavicular joint.

Recent results indicated that shortening of the clavicle by 15 mm led to a reduction in shoulder strength and, as might be expected, also to changes in the orientation of clavicle and scapula (Ledger et al., 2005).

2.2. Glenohumeral ligaments

The glenohumeral capsule is not very tight. Despite this, it comprises well-defined ligamentous structures: the coracohumeral ligament and the superior, middle and inferior ligaments (see Burkart and Debski, 2002), but also a multi-directional fiber orientation (Debski et al., 2003; O'Brien et al., 1990). The coracohumeral ligament and the superior glenohumeral ligaments are seen as inferior stabilizers for the adducted shoulder (Burkart and Debski, 2002), in addition to the limitation of external rotation (Helmig et al., 1990). The middle glenohumeral ligament is assumed to be restraining external rotation from 0°–90° abduction and to provide anterosuperior stability (Burkart and Debski, 2002). The inferior glenohumeral ligament complex is thought to be the most important stabilizer against anteroinferior shoulder dislocation.

The stabilizing function is only possible if the ligaments are exerting forces, which implies that they are stretched beyond their rest length. The glenohumeral ligaments consist mainly of collagen fibers, which have a maximal strain of about 3–7% (Malicky et al., 2002), which is equivalent with a possible rotation in the glenohumeral joint of about 9.5°.[1] Engin and Chen (1986b) recorded the passive moments during a full excursion of the humerus. In the mid-range of motion the passive moments were negligible. Only at the end range of the humeral motion, in the last 20°, passive moments increased to the maximum. Also, in the neutral position glenohumeral translations up to 5 mm are not seriously counteracted by the ligaments (Blasier et al., 1997).

It must be concluded that the mechanical contribution of the ligaments to stability in the midrange of motion will be negligible. Active mechanisms like muscle co-contraction and/or reflexes are more likely to preserve the joint stability in this motion range.

Capsulorraphy, or thermal shrinking of the glenohumeral capsule to reduce shoulder luxation, can strongly reduce the mobility of the glenohumeral joint. In a study on eight cadaveric shoulders, Gerber et al. (2003) showed that anterosuperior capsular plication of about 1 cm decreased external rotation with approximately 30° and abduction with almost 20°. After capsulorraphy the ligaments will become tight at a shorter length, and as a result the range of motion is decreased. This is in contrast with the hypothesized function of the ligaments as passive stabilizers of the GH joint.

[1]Assuming a ligament length of 80 mm, 5% elongation will result in lengthening of 4 mm. If the moment arm r is about 24 mm (average radius of humeral head), the possible rotation angle $\theta = \Delta l/r = 0.1667$ rad $= 9.55°$.

2.3. Muscle function

The shoulder muscles can be typified as relatively small with large moment arms. The moment arm of the anterior part of Deltoid during flexion lies around 25–40 mm (Kuechle et al., 1997), in comparison to 30–60 mm for Rectus Femoris for hip flexion (based on Klein Horsman et al., 2007). The large range of motion of the shoulder and the large moment arms imply large shortening ranges for these muscles. This is reflected in their fascicle lengths. The optimal muscle fascicle length for the scapulohumeral muscles varies between approximately 70 mm for Supraspinatus to 180 mm for the short head of Biceps (Langenderfer et al., 2004), with an index of architecture (fibre length over muscle belly length) of about 0.8–0.9. This is considerably longer than values reported for leg muscles, where optimum fascicle length for the plantar flexors was between 25 mm (Soleus) and 60 mm (Gastrocnemius) and between 60 and 80 mm for the knee extensors.[2] The long fascicle lengths for shoulder muscles guarantee a long active force trajectory, which covers the full movement range of the shoulder (Klein Breteler et al., 1999). In addition, the long fascicle lengths will make muscles relatively insensitive for length changes since most of their working range will be around the middle area of the force–length curve. Only for one part of the deltoid muscle Klein Breteler et al. (1999) had to conclude that its architecture was insufficient to be able to actively apply force in the full working range.

3. Strength

In a literature review on the isokinetic strength measurement of the shoulder, Codine et al. (2005) presented an overview of shoulder strength results for 10 different studies. Although reported values were of course dependent on age, sex, activity level and testing conditions (i.e. velocity and arm position), the strength ratios for different directions were comparable. Overall, subjects were weakest in external rotation and strongest in adduction. Peak reported value for adduction was 102 Nm for male swimmers at 30°/s, while external rotation scored 56 Nm (McMaster et al., 1992). For non-athletes, the latter values would be approximately 40–50% lower (Codine et al., 2005). Extension strength was higher than flexion in a ratio of about 3:2, which was also the case for the ratio internal rotation–external rotation.

3.1. Joint moments

Joint moments are determined by the muscle force and muscle moment arms. Usually, moments around three

[2]All reported values are based on cadaver measurements and laser diffraction. These values differ from in vivo reported optimum fascicle lengths based on ultrasonography where optimal fascicle lengths for VL between 80–90 mm have been reported Reeves et al. (2004).

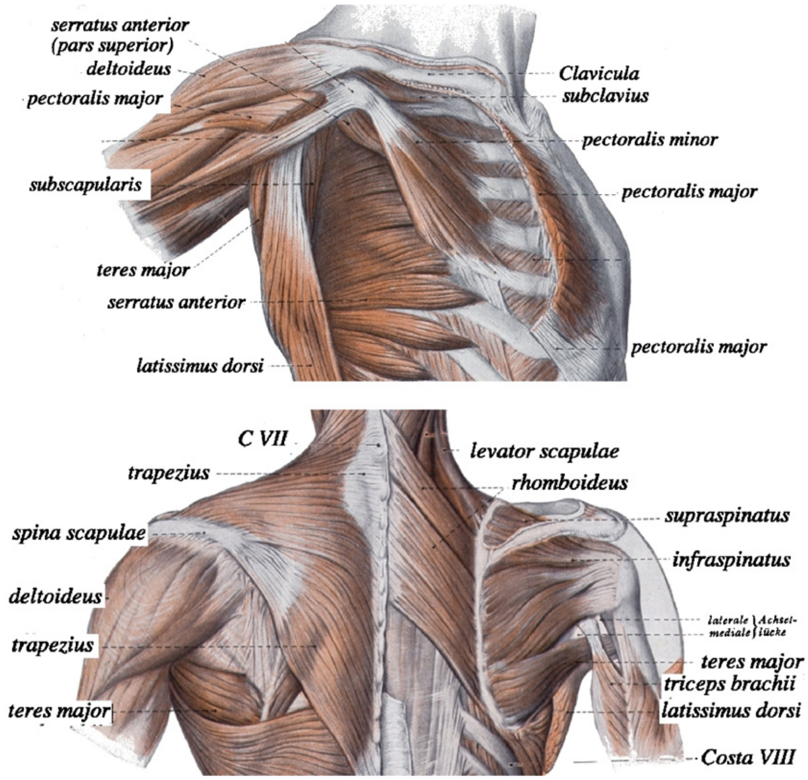

Fig. 3. Muscles of the shoulder girdle. Top: deep muscles, after removal of Pectoralis Major. Bottom: superficial (left) and deep muscles of the shoulder. (Adapted from Benninghoff-Goertler (1964). Lehrbuch der Anatomie des Menschen, 9th edition, Urban & Schwarzenberg, Berlin.)

orthogonal axes are presented as vectors, which do not agree with the standard motion descriptions that use a floating axis principle (Grood and Suntay, 1983; Wu et al., 2005).

While elevating the arm, the moments around the SC joint are slightly larger than around the GH joint. The deltoid is the largest muscle crossing the GH joint, and the muscle acts 'in series' with the m. Serratus Anterior (Fig. 3). Although the PCSA of the m. Serratus Anterior is much smaller than the deltoid (13.9 versus 25.9 cm; Veeger et al., 1991), its moment arm around the SC joint is huge (about 15 cm for the moment around the ventral–dorsal axis of the SC joint, compared to 6–8 cm for the moment arms of muscles crossing the knee or ankle). The scapula provides large moment arms for the scapulothoracic muscles. The Serratus Anterior is the main torque-generating muscle during elevation of the arm, whereas the Trapezius directs the clavicle and scapula towards the plane of elevation, and elevates the clavicle to allow the rotations of the scapula (van der Helm, 1994). The m. Serratus Anterior provides a latero-rotating moment. Adduction moments at the humerus are mainly generated by the tri-articular muscles like the m. Pectoralis Major (dependent on elevation angle) and m. Latissimus Dorsi. These muscles directly transfer force to the thorax, providing simultaneous adduction moments around the GH, AC and SC joint. There are only a few other adductors around the GH joint (m. Teres Major) and around the SC joint (m. Pectoralis Minor) present. When the arm is abducted, the effect of gravity will result in adducting moments around the GH and SC joints. This adducting moment presses the laterally rotated scapula against the thorax. In fact, this is a favorable position for the scapula, since the passive reaction forces between the thorax and scapula do not require metabolic energy. During forward flexion of the humerus, the gravitational forces will lift the scapula from the thorax. The Serratus Anterior and the Rhomboidei will press the scapula on the thorax, and provide a stable base for the humeral motions. This process is what is visible as the Scapulo Humeral Rhythm (SHR). The SHR has been shown to deviate from normal in subjects with impingement syndrome (Ludewig and Cook, 2000; McClure et al., 2004), but whether this is cause of, consequence of, or a contingent adaptation to the existing complaints is still under debate (McCully et al., 2005).

The coracoclavicular ligament is strong but not considerably stiff (stiffness ~103 N/mm; Harris et al., 2000)[3]. It forms a limitedly deformable link between the scapula and clavicle, scapular and clavicular motions, which allows for 8 (Harris et al., 2000) to 14 mm (Koh et al., 2005) elongation before failure, which is equivalent to about 20° of AC joint rotation. Since the clavicle is almost

[3]Woo et al. (1991) reported a stiffness for the anterior cruciate ligament of 240 N/mm and a maximum strength of 2160 N.

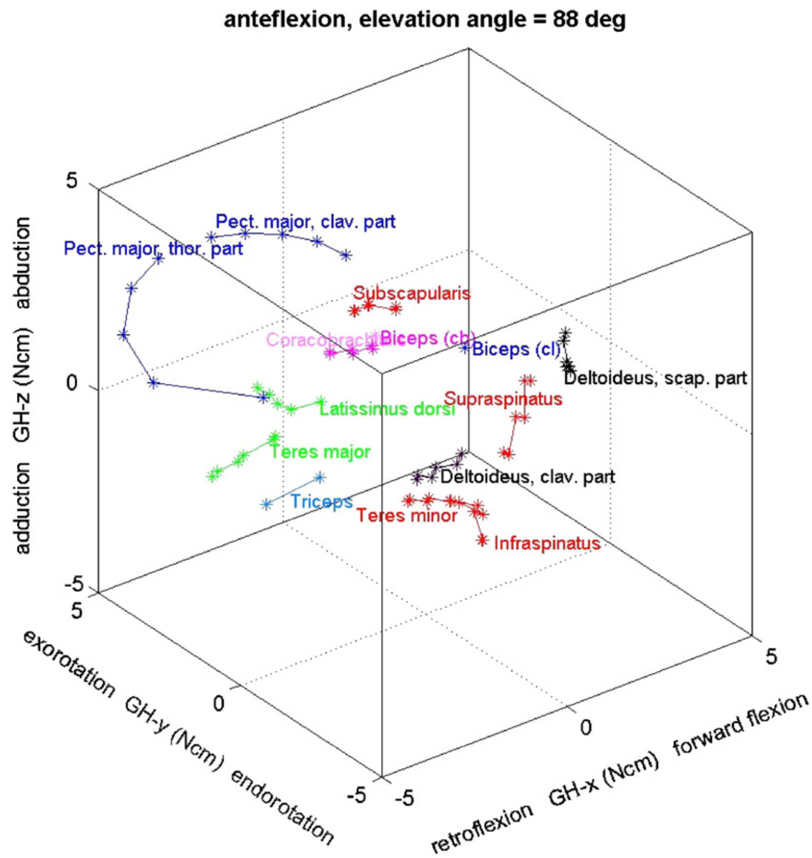

Fig. 4. Potential moment vectors (PMV) in arm forward flexion. Potential moment vectors are depicted along three axes: retroflexion–anteflexion and exorotation–endorotation on the horizontal axes and abduction–adduction on the vertical axis.

perpendicular to the scapular plane, the lateral rotation in the plane of the scapula is around the same axis as the axial rotation of the clavicle (van der Helm, 1994). Without the conoid ligament, the axial rotation of the clavicle would be induced by the weak AC capsule, which would likely result in faster degradation of the articular surface and possible capsule tears

3.2. Joint moment description

For three-dimensional structures such as the shoulder, it is difficult to describe the muscle function needed to obtain the desired joint moments. For example, m. Pectoralis Major provides a forward flexing moment around the GH joint, but also a moment around the vertical axis, moving the arm in a medial direction. The latter moment must be counteracted by, for instance, the m. Supraspinatus and m. Infraspinatus in order to preserve a pure forward flexion moment. Hence, these muscles have an important function for forward flexion!

x-, y- and z-components of the muscle moment arms are difficult to conceive, since the effect will also depend on the orientation of the bones. A description by the 'potential moment vector', **pmv**, combines the effect of moment arm $\boldsymbol{r}$ and force direction, unit vector $\boldsymbol{f}$:

$$\mathbf{pmv} = \boldsymbol{r} \times \boldsymbol{f},$$

$$\boldsymbol{r} = \boldsymbol{p}_{\text{insertion}} - \boldsymbol{p}_{\text{joint}},$$

$$\boldsymbol{f} = (\boldsymbol{p}_{\text{origin}} - \boldsymbol{p}_{\text{insertion}})/||\boldsymbol{p}_{\text{origin}} - \boldsymbol{p}_{\text{insertion}})||.$$

The **pmv** has the direction of the moment vector caused by the muscle. Multiplication with the actual muscle force will result in the muscle moment. The magnitude of the **pmv** is equal to the magnitude of the moment arm $\boldsymbol{r}$.

The **pmv** can point into any of the 8 quadrants around a joint (bi-sected by the frontal, transversal and sagittal planes). The (desired) external moment can also be shown in these quadrants. Since the summation of the muscle moments should be equal to the external moment (in a static situation), it can easily be seen which of the muscles are in the best position to generate the necessary moment, and which muscles are necessary to compensate for unwanted side-effects. Fig. 4 clearly demonstrates the complexity of muscle coordination around the glenohumeral joint.[4] It also illustrates that a large-scale musculoskeletal model of the multi-joint mechanism is necessary to determine the function of each of the muscles. In contrast to the traditional 'kinematic approach', as illustrated by the anatomical nomenclature, where the muscles were

[4]We included a simulation of the potential moment vector during abduction and anteflexion as on-line material. The movies are visible at: http://www.ifkb.nl/research/TA1/movies/anteflexion.avi and http://www.ifkb.nl/research/TA1/movies/abduction.avi.

named after the motion they can exert, e.g. flexors, abductors, etc., in fact all the necessary stabilizing functions should also be taken into account, to understand the disabilities resulting from muscle paralysis.

4. Stability

Stability (and instability) of the glenohumeral joint is a mechanically ill-defined notion. From a mechanical point of view, instability is the property that a joint will not return to its original position after a perturbation. In clinical terms this is similar to a dislocation of the joint. In clinical terms instability is synonymous with a too large displacement after force exertion on the humerus (see Soslowsky et al., 1997). In mechanical terms this would be considered as a compliant joint, which is still stable if the joint returns to the original position.

4.1. Joint articular surface

The joint congruency of the articular surfaces and the constraint area of the glenoid cavity have effect on the stability and translational stiffness of the GH joint (Anglin et al., 2000; Oosterom et al., 2003). If the curvature of the humeral head is smaller than the glenoid, the ‘‘joint translational stiffness’’ (defined as the gradient of the subluxation force with respect to the corresponding humeral head displacement) will be less, but the stability (~dislocation) does not change. Increasing the constraint angle increases the stability, but hardly affects the translational stiffness for less congruent joint configurations.

For joint stability the important parameter to consider is the percentage of enclosed curvature between articular surfaces, or the amount of surface that is covered by the glenoid. The enclosed curvature is an important trade-off factor to consider: a larger enclosed curvature will produce a more stable joint, but will allow larger reaction forces and increase the chances of a ‘‘rocking horse phenomenon’’ (Franklin et al., 1988) to occur, which could lead to loosening of the glenoid compartment of the implant. Smaller enclosed curvatures will be less stable intrinsically and, therefore, require more muscle control. This leaves the clinician with a ‘‘Catch-22’’: a larger curvature will produce a more stable joint, but also a higher risk of loosening, a smaller curvature will reduce the risk of loosening at the expense of joint stability and thus functionality. It also implies that implant model choices should vary with available muscle function and estimated future use.

4.2. Joint motion

Motions in the normal glenohumeral joint generally resemble kinematic ball-and-socket behavior, which is at least partially caused by this joint translational stiffness, or concavity compression (Lippitt and Matsen, 1993). This behavior implies the absence of large intra-articular translations and reasonable congruity between joint surfaces. Concavity compression has been used to describe the relationship between shear force, compression force and humeral head translation. The maximum allowable subluxation force will depend on the glenoid arc of enclosure ($66 \pm 12^{\circ}$ in anterior–posterior direction and $46 \pm 15^{\circ}$ in superior–inferior direction; McPherson et al., 1997), the depth of the glenoid cavity (5 ± 1 mm in AP view and 3 ± 1 mm in SI view; McPherson et al., 1997) and the compression force, as well as on the deformation of articular surface. Based on an in vitro study, Halder et al. (2001) concluded that the ratio between shear force and compressive force varied between 0.3 for anteriorly directed forces with the arm at the neutral position, and 0.6 in the inferior direction, in line with the geometric dimensions of the glenoid. Resection of the glenoid labrum led to a fairly small reduction of this ratio with approximately 10%, indicating the only minor mechanical effect of the labrum.

Since the study of Poppen and Walker (1976), there has been a dispute about the existence and the magnitude of translations in the GH joint. Translations can occur if the curvature of the humeral head is smaller than the curvature of the glenoid. Soslowsky et al. (1992) and van der Helm et al. (1989) measured the curvature, and both concluded that the mating humeral head and glenoid articular surfaces were quite congruent with radii of curvature within 3 mm Soslowsky et al. (1992). From these measurements and the existence of compressive forces mentioned earlier, it can be concluded that under non-pathological and outside extreme conditions, such as the late preparatory phase in throwing (Baeyens et al., 2001), the translations in the glenohumeral joints will be in the order of millimeters (Graichen et al., 2005), and in fact below the level of accuracy of electromagnetic or opto-electronic measuring techniques.

Considering the curvature of the articular surfaces implicitly assumes a rigid body approach. However, the subchondral endplate of the joint is relatively compliant with respect to the cortical bone (Frich et al., 1997). If the humeral head is compressed into the glenoid cavity, the glenoid is likely to deform, and two congruent curvatures will result. Two congruent curvatures with a small and constant joint gap makes sense when joint lubrication is considered. A constant fluid film between the articular surfaces will make almost frictionless motions possible. The pressure in the synovial fluid will be directly related to the joint reaction forces. In a constant joint gap, the intra-articular pressure will be almost constant, except at the end of the gap, where the pressure will be lower. A deformable flap like the labrum will reduce the drop of the intra-articular pressure, and thus improve the lubrication of the joint.

Negative intra-articular pressure has been mentioned as one of the stabilizing mechanisms of the GH joint (Fick, 1911; Gibb et al., 1991; Habermeyer et al., 1992; Itoi et al., 1998). Habermeyer et al. (1992) showed in a cadaver study that traction on the arm would produce a negative pressure, which was absent in the case of a labral tear or Bankart lesion. This negative pressure was shown to be capable of resisting a pulling force of about 22 N (plus the weight of the arm) before capsular stiffness collapsed (Gibb et al., 1991). The role of negative intra-articular pressure as a stabilizer can be assumed limited, since negative pressures only result from a net pulling force on the humeral head and can only sustain minor force levels. This is not likely to occur in a normal shoulder where muscle activity will compress the articular surfaces. If the negative intra-articular pressure plays a role, its stabilizing effect is rather small: Mcquade and Murthi (2004) showed that in relaxed subjects with their arm in a "closed-pack" or apprehension position, a translation of 10–22 mm can be obtained when the anterior drawer test is applied, whereas, as mentioned before, during active arm elevation intra-articular translations were only in the order of magnitude of 1 mm (Graichen et al., 2000). Habermeyer et al. (1992) suggested that intra-articular pressure might also play a role in the proprioceptive behavior of capsule and labrum, based on the effect of pressure sensors. This notion is supported by the general opinion that labral tears as in Bankart lesions, or SLAP lesions result in reduced joint stability (Gibson et al., 2004) while there is an absence of reflex deviations during intra-operative stimulation (Tibone et al., 1997). The consequence of a labral tear might thus be the loss of proprioception due to inadequate intra-articular pressure changes.

In general, the function of the labrum is not well understood. Some authors assumed that its role is that of a fender and thus mechanical (Howell and Galinat, 1989). Results of studies on the effect of labral defects on glenohumeral stability are mixed (Lazarus et al., 1996; McMahon and Lee, 2002), which is not surprising, taking into account that the labrum is easily deformable (Carey et al., 2000). It is more likely that an important function of the labrum lies in its role in joint lubrication. Studies on the acetabular labrum (Ferguson et al., 2003; Hlavacek, 2000) have shown that the labrum of the hip joint plays an essential role in joint lubrication and thus in the prevention of joint wear. In addition to its function as a washer, the labrum may function as a pressure sensor, whereas its mechanical properties are unlikely to add to joint stability.

4.3. Muscle function

Conceptually, the GH joint can be considered a 6 DOF joint, with three translational and three rotational DOF. Mostly, only the large joint rotations are taken into account. The translations perpendicular to the articular surface will be very small, limited by the visco-elastic properties of the cartilage and subchondral bone. Translations parallel to the articular surface can be larger, and can potentially lead to dislocations.

As concluded above, stability in the GH joint in the midrange of motion is mainly due to muscles. The GH joint can only dislocate if the resulting JRF vector (summation of muscle, ligamentous, gravitational and other external forces) at the center of the humeral head points outside the glenoid. The rotator cuff muscles (Fig. 3) are especially suitable to direct the JRF into the glenoid, since these muscles will pull the humerus into the glenoid, mainly based on their force direction and not on the exerted moment. It is advantageous to use muscles with a small antagonistic moment arm to reduce the contra-productive moment. Based on mechanical analysis one might conclude that the rotator cuff musculature, arranged in a half-circle around the GH joint, is very effective in directing the JRF (see Blasier et al., 1997). Prime movers with a large moment arm, like the m. Deltoideus, m. Pectoralis Major and m. Latissimus Dorsi, can also pull the humeral head into the glenoid, but action of these muscles will also result in large, possibly antagonistic moments.

Joint stabilization can be done by continuous co-contraction of muscles, or by the use of a control system based on short-latency and long latency reflexes. The first option is not likely to be the primary method, since this is metabolically expensive, while the rotator cuff muscles are not specially adapted to this, given the reported relatively low percentage type-I muscle fibres (Johnson et al., 1973).

4.4. Proprioception

For the preservation of stability by a control system based on reflexes a well-developed feedback system, including a sensor system, is a prerequisite. The most suitable place for sensors that signal joint force direction is in, or near the glenoid labrum. Yet, there is conflicting evidence about the existence of proprioceptors in the capsule and ligaments. Vangsness et al. (1995) report Pacini and Ruffini receptors in the middle, anterior and superior glenohumeral ligaments, as well as free nerve endings in the lower half of the labrum. Steinbeck et al. (2003) report Ruffini receptors in the humeral insertion of the inferior ligament. Gohlke et al. (1998) did not find receptors in the glenohumeral ligaments, but did find receptors in the peri-articular loose connective tissue.

It has to be concluded that at this point, there is (yet) no evidence for the existence of labrum sensors. In addition, it is almost inevitable that the sensors in the ligaments have a signaling function only in the end ranges of motion, as was shown for the cat's knee (Clark and Burgess, 1975). The rather long time delays between sensor activity and response make it unlikely that these sensors play an essential role in movement control. Jerosch et al. (1997) stimulated intra-operatively the anterior glenohumeral ligaments in humans and found time-delays between stimulation and EMG response in the order of 100–500 ms. If this time-delay is all due to transportation time along the nerves, it would mean a nerve conduction velocity of about 1.2–6 m/s, which is typical for Ruffini and Pacini sensors. Time-delays in the order of 100–500 ms are severe limitations to the effectiveness of the necessary proprioceptive feedback loop and do not agree with experimental results. Using a system identification approach and experimental data from in-vivo force perturbation studies, de Vlugt et al. (2002) showed that the measured behavior of the arm could be explained from responses of the muscles controlling the glenohumeral joint, based on feedback from muscle spindles and maybe also Golgi tendon organs, with a time-delay in the order of only 25 ms.

The multi-directional fiber orientation inside the glenohumeral capsule (Debski et al., 2003) gives rise to a second hypothesis related to the function of these sensors: it can be argued that due to the glenohumeral motion the orientation of the capsular fibers changes, and that this results in proprioceptive sensoric signals (Myers and Lephart, 2002). However, this hypothesis is not yet supported by any experimental results. On the contrary, Lephart et al. (2002) did not find a deterioration in joint position sense in patients after thermal capsulorraphy.

5. Future challenges

The special role of muscles for stabilization and the importance of propriocepsis makes it clear that biomechanical models should not only include all necessary parameters to correctly describe mechanical behavior, but should also include stabilization constraints and feedback and moreover, should focus on the relationship between reflexes and stability. The same applies for the study of shoulder function under pathological or 'newly created' morphological conditions, such as after tendon transfers, or joint reconstructions.

The second important challenge is understanding the importance of inter-individual differences for movement control and stability. Only if we understand the role of covariance in morphology, it will be possible to determine the necessary level of patient-specific modeling and the use of those models for decision making at the level of the individual patient.

6. Conclusions

(1) The large mobility of the shoulder is due to the simultaneous motions of the SC, AC and GH joints. Since the shoulder girdle is a closed chain, the motions of the SC- and AC-joint are coupled.
(2) A combination of mono-, bi- and tri-articular muscles control the motions of these joints. The effect of these muscles is highly coupled, and requires a highly tuned coordination.
(3) Glenohumeral joint stability is mainly due to active muscle control, directing the joint reaction force vector into the glenoid surface.
(4) Due to the non-rigid articular surfaces, translations in the GH joint are minimal.
(5) The main function of the labrum is likely to maintain the intra-articular fluid pressure.

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