



Shoulder biomechanics in normal and selected pathological conditions

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- The stability of the glenohumeral joint depends on soft tissue stabilizers, bone morphology and dynamic stabilizers such as the rotator cuff and long head of the biceps tendon. Shoulder stabilization techniques include anatomic procedures such as repair of the labrum or restoration of bone loss, but also non-anatomic options such as remplissage or tendon transfers.
- Rotator cuff repair should restore the cuff anatomy, reattach the rotator cable and respect the coracoacromial arch whenever possible. Tendon transfer, superior capsular reconstruction or balloon implantation have been proposed for irreparable lesions.
- Shoulder rehabilitation should focus on restoring balanced glenohumeral and scapular force couples in order to avoid an upward migration of the humeral head and secondary cuff impingement. The primary goal of cuff repair is to be as anatomic as possible and to create a biomechanically favourable environment for tendon healing.

Keywords: anatomy; glenohumeral instability; humerus; ligaments; rehabilitation; rotator cuff; scapula; therapeutic implications

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Introduction

The biomechanics of the shoulder are highly complex. First, it is composed of four joints (glenohumeral, acromioclavicular, scapulothoracic, and sternoclavicular). The glenohumeral joint has six degrees of freedom and is the most mobile joint in the human body, allowing the hand to reach a wide range of positions. This mobility can be

further enhanced by translation of the humeral head on the glenoid, but the consequence of this tremendous mobility is perhaps a predisposition to instability and impingements. Second, mobility is assumed by 18 muscles that act in synergy. Consequently, decoupling/isolating them is impossible, making precise kinematic analysis and clinical examination difficult. Third, the glenohumeral joint has the characteristics of an active non-weight-bearing joint, leading to major bony and muscular modifications and frequent tendon overuse.

When looking at the shoulder as a functional unit, it appears that several factors need consideration. To function normally, the shoulder needs all the anatomic structures to work in a chain. Form will allow function.¹ First, the central nervous system provides a signal to the muscle-tendon unit. By contracting, the muscle transmits its tension to the tendon, which then acts as a lever arm on the joint. To be efficient, such a system requires a stable fulcrum. The necessary stability is provided by static and dynamic factors such as bony contours, ligaments, labrum, capsule, etc.

The specificity of biomechanically relevant parameters, such as, for example, joint reaction forces, is that they cannot be measured *in vivo* without invasive procedures.² Our knowledge therefore mainly relies on experimental cadaveric studies³ or computational modelling.⁴ These simulations have become more sophisticated in recent years, allowing the inclusion of an increasing number of variables with the ability to adjust both pathology and patient-specific characteristics.⁵ This ongoing process will without doubt call into question prior assumptions and allow further insights into shoulder biomechanics.

It is crucial to understand the basic principles of shoulder biomechanics and their modifications in the most common pathologies encountered in daily practice. The goal

of this article is to provide an overview of normal glenohumeral biomechanics as well as the most common non-prosthetic shoulder disorders including instability and rotator cuff tears.

Instability

Static stabilizers

Static stability of the glenohumeral joint is provided by the capsulolabral structures as well as the bony anatomy of the glenoid. Historically, significant effort was placed on understanding the importance of the anterior capsulolabral structures, due to the fact that these structures are classically torn in the case of anterior shoulder instability.⁶ The glenohumeral ligaments are a thickening of the joint capsule and represent the primary static stabilizers. To allow a high degree of shoulder mobility they only become tight at the end-ranges of motion. The superior glenohumeral ligament is tight in adduction, the middle at 45 degrees of abduction and the inferior glenohumeral when the shoulder is brought to 90 degrees of abduction in external rotation.⁷ The inferior glenohumeral ligament is therefore considered the strongest and most important soft tissue stabilizer. Structurally it can be avulsed from the glenoid side resulting in an antero-inferior labral lesion, as well as from the humeral side resulting in the less-frequent humeral avulsion of the glenohumeral ligament (HAGL) lesion.^{8,9} The postero-inferior capsule and posterior inferior glenohumeral ligament are not as robust as their anterior counterparts,¹⁰ but it is often felt to be necessary to 'balance' both inferior ligaments during a soft tissue repair for instability. Laxity is a normal, physiologic and asymptomatic finding, that corresponds to translation of the humeral head in any direction to the glenoid.¹¹ Hyperlaxity is constitutional, multidirectional, bilateral and asymptomatic. Hyperlaxity of the shoulder is probably best defined as external rotation with the elbow at the side equal to or greater than 85 degrees.¹² This non-pathological finding is a risk factor for instability but does not by itself demand treatment unless there is clear pathological laxity. Pathological laxity of the inferior glenohumeral ligament is observed when passive abduction in neutral rotation in the glenohumeral joint is above 105 degrees, there is apprehension above 90 degrees of abduction, or if a difference of more than 20 degrees between the two shoulders is noted.^{13,14} Pathological laxity is often multidirectional and associated with a redundant capsule leading to an increased glenohumeral volume.¹⁵ Biomechanical studies have focused on evaluating the effectiveness of soft tissue procedures to reduce capsular volume. Cadaveric models created by stretching the capsule 10–30% beyond the maximal range of motion, revealed that 1 cm capsular shifts were effective to reduce capsular volume by an average 33.7% (range, 25.3% to

44.6%).^{16–18} Ponce et al further reported a linear relationship between the number of 1 cm stitches and capsular volume, each plication reducing the volume by approximately 10%.¹⁹ Lastly, while both capsular plication and rotator interval closure have been reported to be effective in restoring intact range of motion after capsular stretching, the addition of an interval closure has the benefit of better restoring humeral head translation at 60 degrees of abduction.^{18,20}

The osseous glenoid is relatively flat, the biomechanical role of the glenoid cartilage and labrum is to double the depth of the glenoid socket and therefore enhance the contact area with the humeral head.^{21–23} This is further believed to stabilize the joint by helping to centre the humeral head when compressed against the glenoid by the rotator cuff muscles (concavity compression mechanism). A complete loss of the anterior labrum has been reported to decrease the contact area by 7% to 15%, and increase the mean contact pressure by 8% to 20%.²⁴ A biomechanical study by Hara et al identified the antero-inferior labrum as being the weakest point, with a mean force necessary to cause a rupture of 3.84 ± 1.00 kg/5 mm.²⁵ Finally, it was postulated that an intact labrum could help create a negative intra-articular pressure (vacuum effect); this effect is, however, thought to be marginal when the rotator cuff muscles are contracted.^{26–28} Despite these important stabilizing effects, Itoi et al revealed that soft tissues alone play only a minor role in glenohumeral stability in mid-range of motion.²⁹

Glenoid bone defects and morphology

An important concept regarding glenohumeral joint stability is the concavity compression principle, which centres the humeral head on the glenoid. This centring mechanism is the result of the rotator cuff compressing the humeral head against the glenoid cavity, and is one reason why an anterior glenoid rim defect predisposes to recurrent anterior instability.³⁰ While there is some controversy, 15% to 20% glenoid bone loss seems to be the cut-off value for soft tissue repair.^{31,32} Shin et al demonstrated that in case of an anterior defect $\geq 15\%$, a soft tissue procedure (Bankart) is unable to restore normal shoulder kinematics and even leads to postero-inferior translation of the humeral head in abduction and external rotation.³² On the other hand, bone grafting (glenoidplasty) can successfully reconstruct glenoid curvature and depth and therefore restore stability.^{30,33} Another key point is the reduced contact area and increased articular contact pressure induced by bony glenoid defects.²⁴ While iliac bone graft (Eden-Hybinette), articular distal clavicle autografts and coracoid transfer (Latarjet or Bristow) can all restore normal values, the correct position and orientation of the bone graft is important.^{34,35} The Latarjet will, however, be limited by the amount of bone that can be harvested.

Young et al reported mean values of 26.4 ± 2.9 mm and 9.3 ± 1.4 mm for length and thickness respectively.³⁶ A graft placed in too lateral of a position will lead to an increased anterior-inferior peak contact pressure, whereas a recessed graft will lead to high edge loading. To avoid increased inferior contact pressure, the current evidence suggests orientating the coracoid bone graft in an inferior direction.³⁷ The congruent-arc modification of the original Latarjet technique further allows the reconstruction of larger defects by matching the shape of the graft to that of the glenoid.³⁸ The use of a distal tibial osteochondral allograft respects all these biomechanical principles and has been shown to be a valid alternative in the absence of reliable autograft.³⁹

During posterior shoulder dislocation, reverse Bankart lesions are only present in isolation in 51% of cases.⁴⁰ They are, however, sufficient to increase posterior translation and inferior translation of the humerus in the sulcus position by 86% and 31% respectively.⁴¹ Additionally, glenoid retroversion is more common in posterior instability and appears to predispose to posterior instability.⁴² Every five-degree increment of retroversion led to an additional posterior decentralization of the humeral head overall by (average \pm standard deviation) $2.0 \text{ mm} \pm 0.3$ in the intact and $2.0 \text{ mm} \pm 0.7$ in the detached labrum condition. Bony alignment in terms of glenoid retroversion angle plays an important role in joint centration and posterior translation, especially in retroversion angles greater than 10 degrees.⁴³ Labral injury from repetitive posterior loading or instability can range from a posterior labral tear to an incomplete, concealed avulsion of the postero-inferior labrum (also known as 'Kim lesion') to a reverse Bankart lesion. Glenoid retroversion beyond the average five degrees to 10 degrees has been shown to be a risk factor for developing subsequent posterior instability in a prospective study of healthy subjects. For every one degree increase in glenoid retroversion, the risk for posterior instability increase by 17%.⁴⁴

Humeral bone defects

A Malgaigne lesion⁴⁵ also called a Hill–Sachs lesion⁴⁶ describes the grooved defect of the humeral head. This frequently unrecognized complication of anterior dislocation of the shoulder joint is the result of compression of the posterolateral head upon the anterior glenoid rim. The presence of humeral bone loss has been linked with recurrent instability after open or arthroscopic shoulder stabilization.^{47,48} Cadaveric studies have revealed that humeral bone defects as small as 12.5% of the humeral head diameter will affect joint stability, which can be restored with allograft reconstruction. However, an isolated 25% bone loss was not shown to be sufficient to explain recurrent instability on its own.^{49–51} In other words, glenoid bone loss is required as well. Clinically, the more common

alternative to allograft reconstruction is the remplissage procedure, which insets the posterior capsule and infraspinatus tendon into the lesion. This procedure medializes the insertion of the posterior structures to prevent engagement and also decreases anterior translation of the humeral head. A recent review identified 10 biomechanical studies of which only one reported persistent engagement after a remplissage procedure in the presence of a 25% humeral head defect.⁵² The same study further compared the remplissage to the Latarjet and found that 84% of specimens (27 of 32 testing scenarios) stabilized after remplissage, and 94% of specimens (30 of 32 testing scenarios) stabilized after the Latarjet procedure. This was, however, not statistically significant and the authors concluded that both techniques are effective.⁵³ Nevertheless, at maximum external rotation at 60 degrees of abduction, remplissage altered the kinematics of the glenohumeral joint by shifting posteriorly and inferiorly the apex of the humeral head.⁵⁴ Moreover, while often described as an inset of the infraspinatus tendon, the procedure is in fact a capsulomyodesis of the infraspinatus and teres minor;⁵⁵ this has not only been proven in anatomic investigation, but also follows normal form as the tendon does not extend very far medially from its normal insertion.

For posterior instability, the McLaughlin procedure⁵⁶ using the detached subscapularis tendon has been described for locked posterior instability in presence of a reverse Malgaigne (Hill–Sachs) lesion. This technique has been subsequently modified as either a reverse remplissage⁵⁷ or an osteotomy of the lesser tuberosity with the attached subscapularis (Hughes and Neer method) to allow additional bone support to articular cartilage with satisfactory outcome both in acute and chronic setting.^{58,59}

Bipolar defects

Neither glenoid nor humeral head bone loss can be viewed individually. Just as they occur together at the time of injury, they interact in the risk of recurrent instability. The concept of the glenoid track has emerged as a way to understand this relationship. The concept was first proposed by Yamamoto et al, who used three-dimensional computed tomography (CT) scans to reveal that the normal glenoid track is $84\% \pm 14\%$ of the glenoid width.⁶⁰ Subsequently this was validated in live subjects where the value was determined to be 83%. This concept is in fact the continuation of the work by Burkhart and De Beer on engaging vs. non-engaging Hill–Sachs lesions.⁶¹ Di Giacomo et al further refined this to the on-track and off-track concept, stating that glenoid bone loss will result in a reduction in the width of the glenoid track.⁶² In the setting of glenoid bone loss, the glenoid track decreases. The glenoid track in the bone loss situation is determined by subtracting the width of the defect from 83% of the original glenoid width, which is thought to be the width in the

absence of a glenoid.⁶³ Then, the width of the Hill–Sachs defect from the origin of the infraspinatus to the most medial extent of the defect is measured and compared to the glenoid track to determine whether it exceeds the glenoid track ('off-track') or is less than the glenoid track ('on-track').

Dynamic stabilization (rotator cuff, conjoint tendon and long head of the biceps)

Dynamic stability of the glenohumeral joint is provided by the muscular structures during the mid-points of range of motion. As stated above, the rotator cuff is key to the concavity-compression concept in which it actively contributes to stability in opposition to the deltoid and pectoralis muscles (which tend to destabilize the joint superiorly and anteriorly).^{64,65} The cuff contributes to anterior (external rotators) and posterior (internal rotators) stability in cadaveric^{66,67} and electromyographic studies.⁶⁸ While all rotator cuff muscles contribute to anterior joint stability, the subscapularis seems to be the least effective at end-range of motion in opposition to the long head of the biceps.⁶⁹

In addition to the previously mentioned bony augmentation, the Latarjet procedure and its variant the Bristow combine (1) the ligamentous effect by augmentation of the coracoacromial ligament by the inferior glenohumeral ligament, (2) a muscular effect (hammock effect) by lowering the inferior part of the subscapularis, which is mainly efficient in mid-range motion (Fig. 1A and Fig. 1B),⁷⁰ as well as (3) a sling effect induced by the conjoint tendon forming an anterior rampart especially efficacious in end-range motion (Fig. 2). The two latter effects have often been confused in the literature.

According to a cadaveric study by Yamamoto et al, the hammock and sling effects appear to be the primary stabilizers and account for 51% to 62% of shoulder stability in mid-range of motion, and up to 76% to 77% at 90 degrees

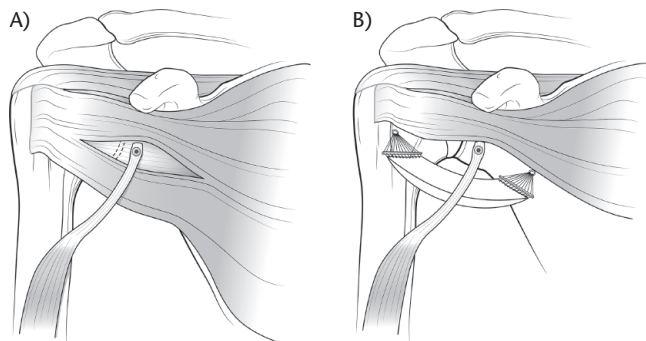


Fig. 1 (a) Anterior view of a left shoulder after dynamic anterior stabilization. (b) Lowering the inferior part of the subscapularis muscle done by biceps tendon in low-range motion is called 'hammock effect'. It represents a muscular effect.

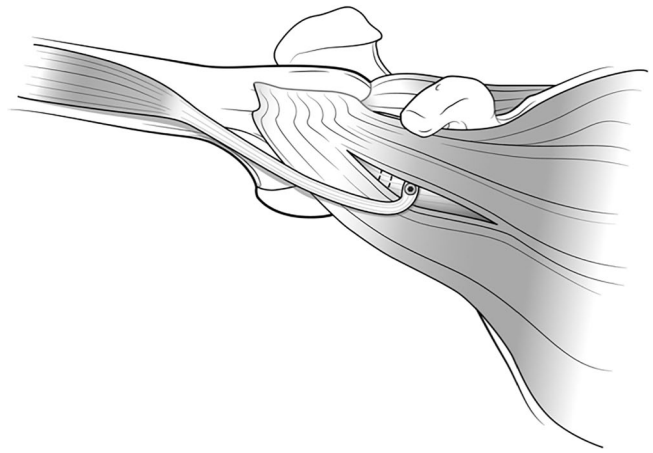


Fig. 2 Anterior view of a left shoulder after dynamic anterior stabilization. At higher range of abduction, the biceps tendon is more horizontal and does not lower the inferior part of the subscapularis muscle anymore. It forms a veritable sling in front of the shoulder, called the sling effect.

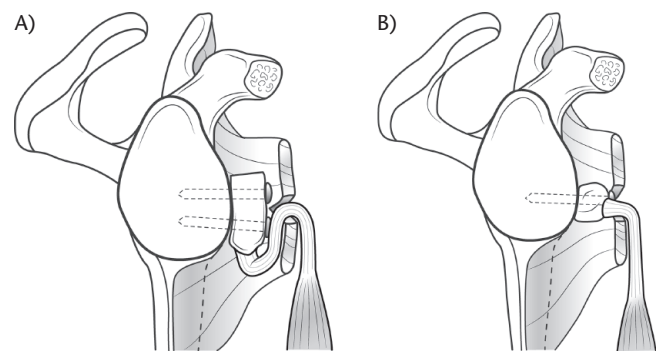


Fig. 3 Sagittal illustration of a right shoulder. Direction of the conjoint tendon in (a) the Latarjet and (b) Bristow procedure. Note that the conjoint tendon during Latarjet has to go around the inferior subscapularis (a). Contrarily, the conjoint tendon exits directly through the split during the Bristow procedure (b).

of abduction and maximal external rotation (end-range motion).⁷¹ The Latarjet technique further leads to an enhanced sling effect in comparison to the Bristow procedure due to the inferior graft position and subsequent conjoint tendon orientation and trajectory (Fig. 3).⁷²

These hammock and sling effects are also the central point of the recently developed dynamic anterior stabilization (DAS) procedure. In this technique the long head of the biceps, in place of the conjoint tendon, is transferred through a subscapularis split to the anterior glenoid margin.⁷³ The DAS results in decreased anterior glenohumeral translation depending on the glenoid defect conditions. As compared with isolated Bankart repair, DAS shows significantly less relative anterior translation in 10% glenoid defects at translation forces of 20 N (0.3 ± 1.7 mm vs. 2.2 ± 1.8 mm,

$P = .005$) and 30 N (2.6 ± 3.4 mm vs. 5.3 ± 4.2 mm, $P = .044$) and in 20% glenoid defects at all translation forces (20 N: -3.2 ± 4.7 mm vs. 0.8 ± 4.1 mm, $P = .024$; 30 N: -0.9 ± 5.3 mm vs. 4.0 ± 5.2 mm, $P = .005$; 40 N: 2.1 ± 6.6 mm vs. 6.0 ± 5.7 mm, $P = .035$).³¹ However, similar to previous biomechanical observations regarding isolated conjoint tendon transfer in 20% glenoid defects, DAS leads to a relevant posterior and inferior shift of the humeral head in the abduction external rotation (ABER) position and to a relevant increase in inferior glenohumeral translation and should consequently not be used for large bony defects.^{31,74} A recent comparative study on a subcritical bone model reported significantly improved peak resistance force to anterior displacement when augmenting labral repair with a transfer of the long head of the biceps compared to the conjoint tendon (54.1 ± 5.5 N vs. 46.5 ± 7.6 N; $P = .039$).⁷⁵ The DAS does not appear to limit postoperative rotational range of motion.³¹

Scapular morphology

Specific acromial morphology in the sagittal plane is significantly associated with the direction of glenohumeral instability. In shoulders with posterior instability, the acromion is situated higher and is oriented more horizontally than in shoulders with anterior instability. This acromial position may provide less osseous restraint against posterior humeral head translation. Posterior instability virtually never occurs with a steep 'Swiss chalet roof-type' acromion.⁷⁶

Restoration of stability

It is important to keep in mind that even if shoulder stabilization procedures are efficient to prevent recurrent macro-instability (defined as a recurrent shoulder dislocation), they seem inefficient in preventing micro-instability (defined as residual humeral head translation), which could be an explanation for persistent apprehension.⁷⁷

Rehabilitation

From a biomechanical point of view, rehabilitation protocols after glenohumeral instability should avoid excessive pressure and over tensioning on the repaired structures. Regarding pressure, humeral cartilage and labral compression evaluated by motion simulation only occurred in the superior half of the glenoid during exercises.⁷⁸ This indicates that postoperative exercises do not lead to important pressure changes on an inferior labral repair. Concerning soft tissue tension, rehabilitation should be performed in the scapular plane, which lies about 30 degrees anterior to the coronal plane of the body.⁷⁹ This position allows for decreased stress on the anterior capsular structures, optimized glenohumeral congruence and enhanced functional activity of the posterior cuff compared to the body plane.⁷⁹

As already mentioned, the rotator cuff acts as a key dynamic stabilizer, and if its force couples go unbalanced, the deltoid muscle will create an upward migration of the humeral head and secondary cuff impingement.⁸⁰ The same principle applies to the scapula, where the serratus anterior and trapezius act as the primary force couple stabilizing the scapula in abduction in the scapular plane.⁸¹ Rehabilitation should therefore focus on strengthening and careful balancing of these force couples. Regarding soft tissues repair, protection is best achieved by avoiding constraints to the antero-inferior capsule-labral complex. At 0 degree of abduction, Black et al found that the low-tension zone was around 45 degrees of external rotation, in case of anterior capsular shortening of only 2 mm this zone was reduced by an additional 20 degrees.⁸² Penna et al confirmed these findings, further reporting that combination of passive abduction and external rotation was responsible for a maximum measured force of 17.7 N on a capsule-labral repair.⁸³ While it seems reasonable to limit excessive stress on the capsule during early rehabilitation, residual capsular shortening on the other hand should be avoided as it alters physiologic glenohumeral head translation.⁸⁴

Rotator cuff

The physiologic state

The role of the rotator cuff is to work in conjunction with the deltoid to balance the force couples around the glenohumeral joint. In the horizontal plane, the cross-sectional area and force couples between the anterior (subscapularis) and posterior (infraspinatus and teres minor) rotator cuff are balanced.⁸⁵ The forces generated by the subscapularis, the supraspinatus, the infraspinatus and the teres minor are 53%, 14%, 22% and 10% respectively.⁸⁵ The subscapularis seems to be a key muscle for anterior forward flexion,⁸⁶ while the infraspinatus prevents superior and anterior translation of the humeral head.⁸⁷

The rotator cable, first described by Burkhart⁸⁸ as a thick bundle of fibres perpendicular to the supraspinatus, is of major biomechanical importance (Fig. 4).⁸⁹ It is mandatory to have a good understanding of the anatomy surrounding the rotator cable as well as the close relationship between the insertion of the supraspinatus and infraspinatus tendons as well as the coracohumeral ligament. The rotator cable outlines the rotator crescent which is a relative avascular lateral portion of the supra and infraspinatus tendons. The anterior cable inserts in close relation to the coracohumeral ligament into the anterior greater tuberosity and upper lesser tuberosity, representing fibres of the anterior supraspinatus. The posterior cable insertion will be located at the junction between the infraspinatus and teres minor.^{89,90} Thus, a tear involving all of the infraspinatus disrupts the posterior cable while disruption

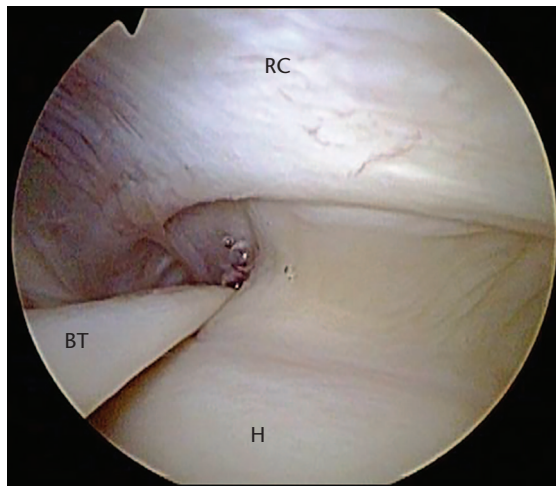


Fig. 4 Right shoulder viewed through a posterior portal. Arthroscopic view of crescent configuration of the rotator cuff (RC). The cable surrounds the crescent.

Note. BT, biceps tendon; H, humeral head.

of the anterior cable requires a tear involving the upper half of the subscapularis tendon. The function of the cable is frequently compared to that of a suspension bridge which transmits the forces of the cuff through the span to its pillars. This mechanism could explain why function is preserved in tears involving only the rotator crescent (Fig. 4) and why partial cuff repairs with restoration of the pillars can restore good function.^{89,91}

Further, anatomical pseudoparalysis (defined as the inability to actively forward elevate the arm > 90 degrees with complete passive anterior forward elevation) was shown to be the consequence of the disruption of at least one rotator cable attachment, subsequently leading to insufficient equilibrium in the vertical plane and resulting in altered kinematics.⁹² Bouaicha et al recently introduced the concept of the shoulder abduction index (SAM), which is basically a ratio of the lever arm of the rotator cuff and deltoid as an anatomic predictor to the appearance of pseudoparalysis.⁹³ According to their work, a SAM < 0.77 (odds ratio 11) in the presence of a massive rotator cuff tear is predictive of pseudoparalysis.

Rotator cuff tear repair

It appears preferable to restore the anatomy of the rotator cuff after a tear whenever possible to restore load transmission from tendon to bone. This can, however, be challenging when facing large and retracted tear patterns, particularly chronic tears. A medially non-anatomic reinsertion significantly reduces the compressive glenohumeral joint reaction forces, the glenohumeral stability and the supraspinatus moment arm, especially in abduction.⁹⁴ Consequently, medialization of the supraspinatus should be limited to 10 mm as it does not seem to limit shoulder

range of motion by internal impingement.^{95,96} Denard et al reported that subscapularis footprint medialization by up to 4 to 7 mm is also functionally acceptable.⁹⁷

Articular-sided rotator cuff tears are thought to be the equivalent of superior capsular rupture and a physiological adaptation in the throwing athlete allowing enhanced external rotation and anterior humeral translation.^{98,99} However, biomechanical studies have shown that a partial-thickness tear will lead to altered strain patterns in the remaining cuff and therefore enhance the risk of tear propagation.^{100,101} A trans-tendon repair of articular-sided partial-thickness rotator cuff tears was shown to reduce glenohumeral contact pressure and contact area during internal impingement but also subacromial contact pressure.¹⁰² The latter assumes that the repair is done without overtensioning.

The coracoacromial arch

Another important point is that contact between the rotator cuff and the coracoacromial arch is not per definition a pathologic state and can be seen under physiologic conditions.¹⁰³ While acromion shape has been the source of extensive research, an increased critical shoulder angle (38 degrees) has been pointed out as a source of increased load to the supraspinatus tendon at lower degrees of abduction.¹⁰⁴ This led to the suggestion to perform a lateral acromioplasty instead of anterior subacromial decompression as an adjunct to rotator cuff repair.¹⁰⁵ This further has the advantage of preserving the acromial insertion of the coracoacromial ligament which, when resected, allows anterosuperior humeral head translation.¹⁰⁶

Surgical possibilities in case of irreparable rotator cuff lesions

When facing impaired shoulder function in the presence of an irreparable postero-superior cuff tear, several surgical options have been proposed. Tendon transfers, commonly using the latissimus dorsi and more recently the lower trapezius can both significantly enhance shoulder function. While the main goal of the tendon transfer is to restore external rotation, recent biomechanical data favours the use of lower trapezius tendon transfer to the infraspinatus insertion because of both stronger abduction and external rotation moment arms.¹⁰⁷ The development of arthroscopic surgery led to an increased awareness and subsequently better understanding of the superior capsule, which is closely related to the undersurface of the supraspinatus and infraspinatus tendons and resists superior migration of the humeral head.¹⁰⁸ Subsequent research showed that a double-layer repair with inherent approximation of the superior capsule leads to improved biomechanical properties of the construct.¹⁰⁹ In the setting of an irreparable cuff, superior capsular reconstruction (SCR) using either an autograft (tensor fascia lata),¹¹⁰ a dermal allograft¹¹¹ or the long head of the biceps¹¹² recreates a passive restraint to superior

and anteroinferior translation.¹¹³ Therefore, adding a static stabilization like the SCR to a dynamic stabilizer like a tendon transfer may ultimately enhance articular stability at the low to mid ranges of abduction.¹¹⁴ Finally, SCR is a promising procedure that remains, however, relatively new and is subject to further research regarding optimal graft choice and surgical technique to avoid excessive strain on the construct during activities of daily living.^{115,116}

The last proposed solution trying to restore glenohumeral contact pressures is the implantation of a balloon spacer in the subacromial space. In a recent cadaveric study, this procedure was shown to efficiently lower the humeral head, increase deltoid load and normalize articular contact pressure at most abduction angles.¹¹⁷ While the use of a biodegradable balloon may be questionable regarding long-term outcomes in the setting of an irreparable tear, it could on the other hand be a suitable adjunct to rotator cuff repair by reducing peak pressure and wear on the repair, potentially avoiding a re-tear.¹¹⁸

An irreparable isolated subscapularis tear implies not solely a tendon failure, but also rupture of the underlying anterior capsule and ligaments, leading to subsequent altered shoulder kinematics. The biomechanical specificity being that both a dynamic and static stabilizing force is impaired, consequently increasing anterior and inferior humeral head translation.¹¹⁹ Treatment options include tendon transfer of the pectoralis major or latissimus dorsi tendon and/or anterior capsule reconstruction.¹²⁰ An *in vitro* study by Konrad et al reported increased restoration of humeral head translation when the pectoralis tendon was transferred behind the conjoint tendon, allowing better restoration of the line of action of the subscapularis tendon.¹²¹ This led to further anatomic studies favouring an anterior transfer of the latissimus dorsi tendon.¹²² A variety of options have been proposed for anterior capsule reconstruction including autografts (tensor fascia lata, hamstrings), tendon allograft, or human dermal allograft.¹²³ A recent cadaveric study by Komperda et al revealed that anterior capsular reconstruction was superior to pectoralis major tendon transfer to restore anterior and inferior humeral head translation.¹²³ Further, the addition of an anterior latissimus dorsi tendon transfer to an anterior capsular reconstruction did not enhance antero-inferior humeral head stability.¹¹⁹

Rehabilitation

The primary goal of cuff repair is to be as anatomic as possible and to create a biomechanically favourable environment for tendon healing. Rehabilitation protocols must logically be adapted to the strength of the repair and tissue quality. Basic science research has mainly focused on the effect of mechanical loading on tendon-to-bone repair during the acute phase of healing using rat models.¹²⁴ While some authors reported improved tendon-to-bone

healing with immobilization,^{124,125} others have found that limited early (during the first six weeks after a repair) tensile load is beneficial for viscoelastic tendon properties.^{126,127} However, uncontrolled tensile load (as seen with open chain exercises, eccentric muscle activation and motion beyond repair elasticity), leads to impaired tissue healing and can predispose to re-tear or repair tissue elongation.^{128–130} Excessive compressive loads, typically increased by postoperative scapular protraction,¹³¹ do further impair tissue healing.^{124,132} Lastly, Sonnabend et al, in a primate model, reported that while eight weeks after cuff repair the tissue appeared macroscopically healed, mature healing with Sharpey fibres started at 12 weeks, therefore supporting a 12–15 week rehabilitation programme.¹³³ Further studies are needed to provide guidelines for rehabilitation based on tear size and type of repair.

Conclusions

The shoulder is a complex biomechanical entity with close relationships between anatomical structures and the biomechanical consequences of the different pathologies encountered. Soft tissue stabilizers, bone morphology and dynamic stabilizers such as the rotator cuff and long head of the biceps tendon all interact to ensure shoulder stability. Balanced glenohumeral and scapular force couples are mandatory to preserve or restore shoulder function. Further, a thorough knowledge of the anatomy and biomechanical properties of the rotator cuff, underlying joint capsule, rotator cable and coracoacromial arch is essential when performing a rotator cuff repair. The huge potential of the human body to cope and adapt to the different pathologies can make it sometimes challenging to differentiate between an anatomical or pathological variant. The wide range of pathologies encountered as well as the even higher number of proposed anatomic and non-anatomic surgical solutions make it a very interesting subject for further research. The understanding of the discussed biomechanical principles should therefore be of great help to the surgeon treating these pathologies.

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