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Recent advance

Biomechanical bases for tendon transfers at the shoulder

Bases biomécaniques des transferts tendineux à l'épaule

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ABSTRACT

Paralysis of the muscles around the shoulder is a debilitating condition that continues to be a very challenging problem. It leads to an inability to position one's hand in space. This greatly compromises the function of the upper limb and can lead to chronic shoulder pain due to inferior glenohumeral subluxation. Management of these complex problems has two main objectives: (i) stabilize the glenohumeral joint to decrease pain related to inferior glenohumeral subluxation; (ii) restore active range of motion in external rotation, abduction, and internal rotation. All the shoulder muscles contract in a coordinated and complex manner to allow the shoulder to move through a complete range of motion. Understanding how the different muscle groups coordinate their contractions and the basic biomechanical principles of tendon transfers is paramount before considering doing a tendon transfer around the shoulder. To function properly, a tendon transfer should have a similar line of pull (similar moment arm), similar tension and similar excursion to that of the muscle it replaces; one tendon transfer should replace only one function and the donor (transferred) muscle should have normal muscle strength (at least M4).

Mots-clés:
Transfert musculo-tendineux
Biomécanique
Epaule
Paralysie du plexus brachial
Rupture de la coiffe des rotateurs
Epaule paralytique

RÉSUMÉ

La paralysie des muscles de l'épaule est un problème très invalidant et difficile à prendre en charge. Elle entraine l'incapacité à positionner la main dans l'espace, ce qui diminue considérablement la fonction du membre supérieur et entraine des douleurs chroniques de l'épaule secondaires à une subluxation scapulo-humérale inférieure. La prise en charge de ces problèmes complexes doit avoir deux objectifs principaux: 1) stabiliser l'articulation scapulo-humérale pour réduire les douleurs liées à la subluxation scapulo-humérale inférieure; 2) restaurer les mobilités actives en rotation latérale, en abduction et en rotation médiale. Les muscles de l'épaule se contractent de façon coordonnée et complexe pour permettre les mouvements harmonieux de l'épaule. La compréhension de la contraction coordonnée des différents groupes musculaires et des principes biomécaniques élémentaires des transferts tendineux est indispensable avant de pouvoir envisager un quelconque transfert tendineux à l'épaule. Ainsi, pour fonctionner, un transfert tendineux doit avoir: 1) la même ligne d'action (même bras de levier), 2) une même tension, et 3) une même excursion que le muscle qu'il remplace; 4) un transfert tendineux doit avoir pour but de ne réanimer qu'une seule fonction; 5) le muscle donneur (transféré) doit avoir une force musculaire normale (au moins M4).

1. Introduction

Paralysis of the shoulder muscles is a highly debilitating condition that is difficult to treat [1,2]. Patients are unable to position their hand in space, which greatly compromises the function of the upper limb and brings about chronic shoulder pain

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secondary to inferior glenohumeral subluxation. The treatment of these complex problems has two main objectives: 1) stabilize the glenohumeral joint to reduce pain related to its inferior subluxation; 2) restore active motion in external rotation, abduction, and internal rotation.

There are two options to accomplish these two objectives: tendon transfer or glenohumeral arthrodesis. While the latter will reliably stabilize the glenohumeral joint, the procedure is irreversible, with moderate gains in mobility through the use of the scapulothoracic joint [3–5] and relatively high complication rates (pain, nonunion [3–5]). Hence, tendon transfers are always preferable over arthrodesis [6,7] if there are transferable functional muscles around the shoulder, particularly when scapulothoracic mobility is limited.

Tendon transfers in the shoulder were initially described to treat the sequelae of brachial plexus palsy; however, their indications have expanded considerably and now apply to any reconstructive shoulder surgery. Transfers are now indicated for the treatment of:

- nerve pathologies in the shoulder: sequelae of brachial plexus palsy, including isolated axillary nerve paralysis; isolated paralysis of the long thoracic nerve or the external branch of the accessory nerve (accessory spinal nerve),
- irreparable rotator cuff tears, posterosuperior or isolated subscapularis tears.

2. Anatomical considerations

Shoulder mobility requires the interaction of three joints (glenohumeral, acromioclavicular and sternoclavicular), the scapulothoracic synarthrosis and the subacromial gliding plane. The glenohumeral joint is responsible for 70% of the shoulder's mobility while the scapulothoracic junction is responsible for the other 30% [8,9]. In all, 14 muscles are involved in shoulder movement and stability. Among them, eight are muscles that bridge the glenohumeral joint (pectoralis major, supraspinatus, infraspinatus, teres minor, deltoid, subscapularis, teres major) while the other six muscles act on the scapulothoracic joint (serratus anterior, levator scapulae, rhomboid major, rhomboid minor, trapezius, pectoralis minor). All the glenohumeral muscles (other than the pectoralis major) originate on the scapula and terminate on the humerus. All the scapulothoracic muscles originate on the spine or rib cage and terminate on the scapula. The shoulder muscles contract in a complex and coordinated manner to move the shoulder through its full range of motion.

3. Biomechanical considerations

Goldner [6] divided the shoulder muscles into four functional units: movement initiators (deltoid and clavicular head of pectoralis major), stabilizers (supraspinatus, infraspinatus, subscapularis), depressors (latissimus dorsi, teres major, pectoralis major, long head of biceps brachii, long head of triceps brachii) and accessory scapular stabilizers (pectoralis minor, serratus anterior, trapezius, rhomboids, levator scapulae). In case of paralysis, the various clinical presentations will be linked to the group in which the affected muscles belong and the function of the remaining muscles.

In case of isolated deltoid paralysis, the shoulder stabilizer muscles (supraspinatus, infraspinatus, subscapularis) and the movement initiators (clavicular head of pectoralis major) remain functional. Normal mobility is preserved (Fig. 1) [10] although some instances of isolated deltoid palsy can be associated with limited mobility.

In case of isolated palsy in the stabilizing muscles (massive irreparable rotator cuff tear), movement initiation is possible through the action of the deltoid and clavicular head of the pectoralis major. Conversely, if the stabilizer muscles are inactive, arm elevation is impossible because of anterosuperior humeral head subluxation resulting in pseudoparalysis of the shoulder (Fig. 2). However, in certain cases, especially when the teres minor and the lower portion of the subscapularis are intact, normal mobility may be preserved despite a massive irreparable rotator cuff tear [11]. In case of paralysis of the movement initiators and stabilizers, no shoulder movement is possible (Fig. 3).

Tendon transfers for reconstruction purposes must focus on the movement initiators and shoulder stabilizers. However, it is essential to also consider the scapular stabilizers.

To evaluate the functional contribution of each muscle, its moment arm and strength must be determined. The moment arm (d) is defined as the perpendicular dropped from the joint's center of rotation to a muscle's line of pull (Fig. 4). A muscle's strength (F) is proportional to its cross-sectional area. The product of these two values is a muscle's moment of force ($M_F = d \times F$), which is its aptitude or more simply, its efficiency, at moving the shoulder. Thus the longer the moment arm, the less force is needed is carry out a movement. These calculations were used to determine that the contribution of the supraspinatus was only 14% during abduction versus 32% for the combined infraspinatus and teres minor and 52% for the subscapularis [12,13]. This shows the essential role of the force couples that make up the anterior and posterior stabilizer muscles in the rotator cuff at maintaining transverse balance in the shoulder to carry out movements effectively [11]. Not surprisingly, the contribution of the

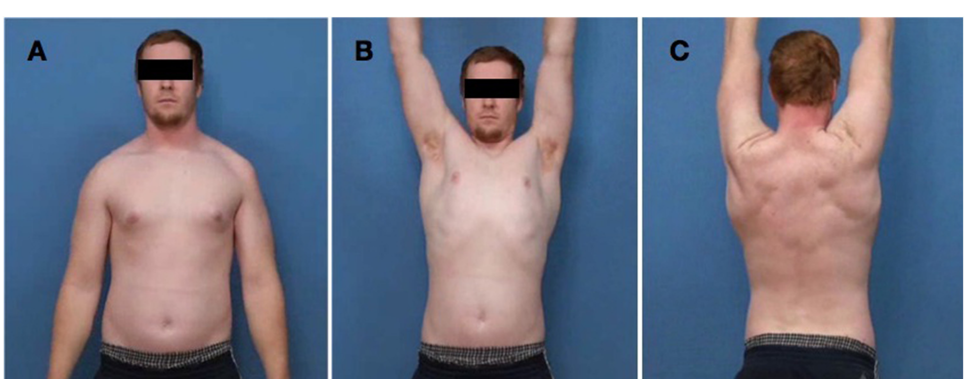

Fig. 1. Isolated paralysis of the left deltoid (visible atrophy) (a). The shoulder stabilizer muscles are still functional, which means that normal mobility is preserved on the front (b) and the back (c).

Fig. 2. Massive irreparable rotator cuff tear in the right shoulder. The stabilizer muscles cannot be activated. This leads to anterosuperior subluxation of the humeral head resulting in pseudoparalysis of the shoulder.

Fig. 3. Paralysis of the deltoid and rotator cuff in the right shoulder. No movement is possible.

infraspinatus and teres minor is 45% in external rotation and that of the subscapularis is 42% in internal rotation [13].

Tendon excursion corresponds to a muscle's ability to move a joint that it crosses. It mainly depends on the length and orientation of its muscle fibers. Analysis of tendon excursion of the rotator cuff muscles show that it is much less than that of the deltoid during abduction and elevation movements. This confirms their essential role as glenohumeral joint stabilizers, which consists of resisting the upward traction placed on the humerus when the deltoid contracts. In fact, in the shoulder, muscles function as couples. A couple describes a rotational movement achieved by two muscle groups exerting an identical force in two opposite directions at a given distance from one another [14]. Thus, this couple concept applies to:

- the external (lateral) tipping movement of the scapula with the superior component by the descending part of the trapezius and the inferior component by the ascending part of the trapezius,
- the internal (medial) tipping movement of the scapula with the superior component by the rhomboids and the superior digitations of the serratus anterior, and the inferior component by the latissimus dorsi,
- anterior elevation and abduction movements of the shoulder with a superior component by the deltoid and an inferior component by the rotator cuff muscles [15].

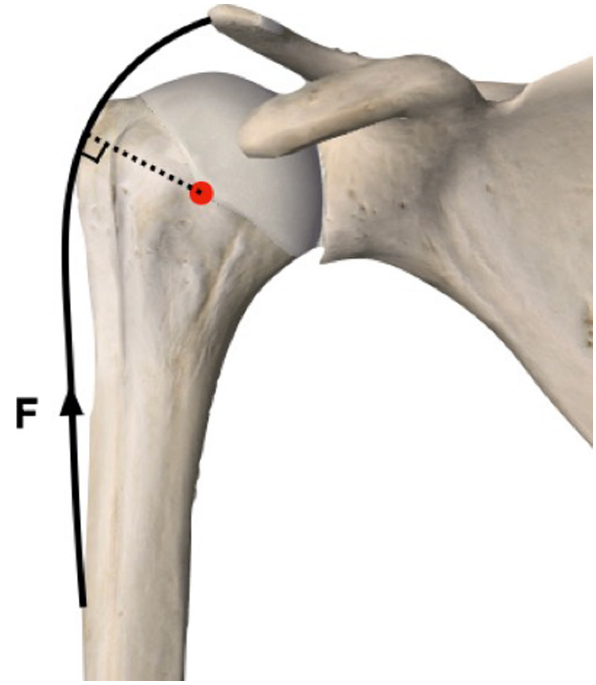

Fig. 4. The moment arm (*dotted line*) is perpendicular between the line of pull (F) of a muscle and the joint's center of rotation (*red dot*).

Kronberg et al. [16] analyzed the electromyographical activity of the various shoulder muscles during eight distinct movements: abduction, adduction, flexion, extension, external rotation, internal rotation, horizontal flexion, horizontal extension. They confirmed the essential role of the deltoid, since it is activated during all eight analyzed movements, and the rotator cuff, since it is activated in six of the eight movements. This demonstrates its role as a dynamic stabilizer of the humeral head across from the glenoid cavity. Lastly, this study also confirms the essential role of the subscapularis as a stabilizer, since it even contracts during the external rotation movement, which confirms its role as an anterior stabilizer.

In-depth understanding of the coordinated contraction of the various muscle groups and the force couple concept is absolutely necessary before considering doing any type of tendon transfer in the shoulder.

4. Tendon transfers

Like in the hand, tendon transfers in the shoulder must comply with five basic principles. Thus, to function properly, a tendon transfer must

- have the same line of pull (same moment arm) as the muscle it is replacing,
- have the same tension as the muscle it is replacing,
- have the same excursion as the muscle it is replacing,
- only replace one function,
- and the donor (transferred) muscle must have normal muscle strength (at least M4 [17]).

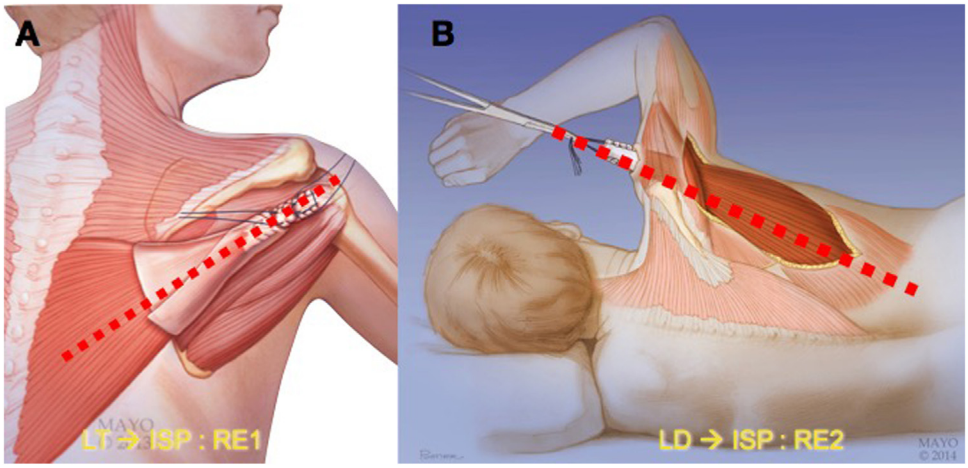

Fig. 5. Analysis of the lines of pull for the transfer of the ascending portion of the trapezius (left) and latissimus dorsi (right). This explains why the ascending portion of the lower trapezius is more effective with elbow at the side and why the latissimus dorsi is more effective in 90° abduction.

In the shoulder, these principles are extremely difficult to apply, as this joint allows movements in all three anatomical planes. Thus it is impossible to achieve a perfect match in terms of excursion, tension, and line of pull between the transferred muscle and the muscle being replaced. However, it is vital to take these different aspects into consideration to obtain the most effective transfer possible. A similar line of pull between the lower trapezius and the infraspinatus could explain the effectiveness of this transfer in external rotation with elbow at the side, while the similar line of pull between the latissimus dorsi and the teres minor explains the effectiveness of this transfer for rotation in 90° abduction [18] (Fig. 5). Similarly, the differences in the line of pull between the pectoralis major and the subscapularis could explain the inconsistent results of pectoralis major transfer for restoring internal rotation [19]. Herzberg et al. [20] measured the potential excursion and muscle force intensity of all the shoulder muscles by dividing the multipennate muscles into different muscle bodies. This study, essential for planning tendon transfers, shows that rotator cuff muscles and the deltoid muscle have a relatively small tendon excursion but generate high muscle force. The latissimus dorsi, which is often used to restore external rotation, has lower muscle strength but a large excursion.

Several biomechanical studies have been done [18,21,22] to determine the effectiveness of various tendon transfers and to determine the most effective transfer for each indication. However, it is crucial to keep in mind that these studies only provide information about the moment arm and tendon excursion, and do not provide insight into the tension to place on the transfer.

5. Conclusion

When considering doing a tendon transfer in the shoulder, the same reasoning as a transfer in the hand can be used. Thus, a surgeon must ask the following questions:

- Which muscle(s) or function(s) is(are) lost?
- What is the priority function to re-establish?
- Which muscles are available?
- Among the available muscles, which ones have:
  - o an adequate excursion?
  - o an adequate tension?
  - o an adequate line of pull?

Conflicts of interest

The authors have no conflicts of interest to declare.

Ethical approval

Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

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