J Shoulder Elbow Surg (2017) ■■, ■■–■■

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

ORIGINAL ARTICLE

Bipolar pedicled teres major transfer for irreparable subscapularis tendon tears: an anatomic feasibility study

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Background: Subscapularis (SSC) tendon tears are a challenging problem because they can significantly alter shoulder mechanics and function. Tendon retraction and advanced fatty degeneration associated with a chronic tear may make it irreparable. Tendon transfers options for such tears are viable, but results in the setting of associated glenohumeral instability are inconsistent. With the potential to recreate the SSC line of pull, the teres major (TM) may be a viable option for transfer. This cadaveric study investigated the feasibility and outlined the steps of a bipolar, pedicled TM transfer for irreparable SSC tendon tears.
Methods: Eight fresh frozen cadaver torsos from 4 women and 4 men (average age, 84 years; range, 68-96 years) were dissected. Anatomic details comparing TM to SSC were examined, including muscle width, length, thickness, and line of pull in the scapular plane. In addition, a surgical technique was described for implementing the pedicled TM transfer.
Results: Measurements between the TM and SSC were comparable, with the exception of muscle belly width, which was significantly greater in the SSC. With transfer of the TM, there was no impingement or tension on the brachial plexus or the neurovascular pedicle of the TM. The line of pull of the TM relative to the SSC had a difference of 9°.
Conclusions: This study demonstrates that a bipolar TM tendon transfer is an anatomically feasible option for reconstruction of an irreparable SSC tendon tear. Further clinical studies are necessary to understand its outcome in in vivo conditions.
Level of evidence: Anatomy Study; Cadaver Dissection

Keywords: Teres major; irreparable; subscapularis; tear; transfer; bipolar

Irreparable subscapularis (SSC) tendon tears are a challenging problem. Unlike older or less active patients with arthritis, arthroplasty is not an option for young, active patients without glenohumeral joint pathology.[10,11,21,26] Primary repair of the SSC is preferred, but the tendon retraction and advanced fatty degeneration associated with a chronic tear may render it irreparable, with poor outcomes after

The Mayo Clinic Institutional Biospecimen Review Committee approved the protocol (study number: 17-004495/Bio00015382).

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https://doi.org/10.1016/j.jse.2017.11.024

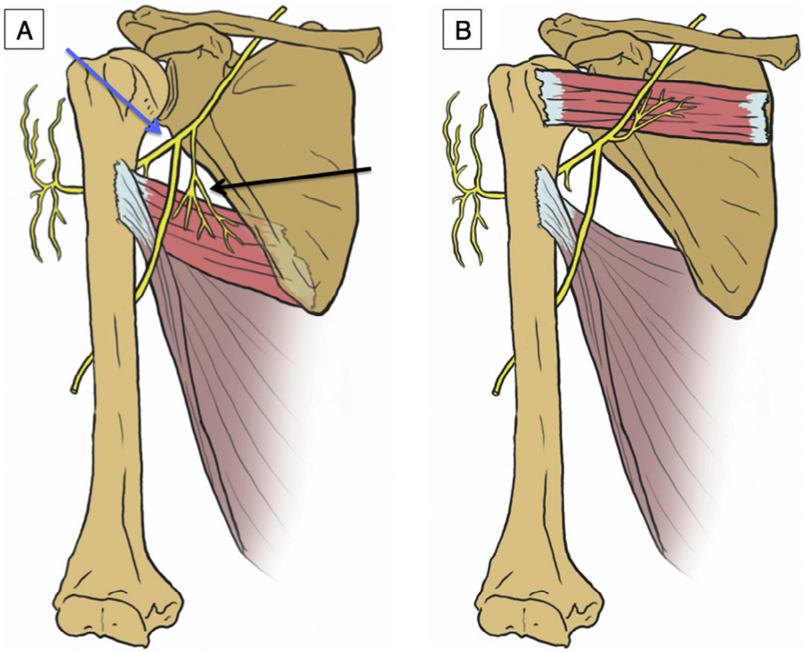

Figure 1 (**A**) Drawing shows the technique representing the teres major muscle in its native anatomic position with the direction of the anterior clamp (*blue arrow*), which is passed anterior to the humeral head and posterosuperior to the axillary nerve and the brachial plexus, and the direction of the posterior clamp (*black arrow*), which is passed anterior to the scapula and posterior to the thoracic wall. (**B**) Once transferred, the teres major muscle is positioned in the subscapularis fossa, superior to the axillary nerve and posterior to the brachial plexus.

fixation.[13,14,19] Chronicity of the tear and fatty infiltration of the SSC muscle belly have been shown to negatively correlate with successful repair.[9]

Biomechanically, the SSC serves as the anterior half of the transverse force couple that controls humeral head motion. Loss of this anterior restraint can lead to significant rotational and translational disturbances of the shoulder joint, and reconstructive options are necessary to stabilize the joint.[18,30]

Reconstruction options for an irreparable SSC tendon include static capsular reconstruction with allograft or dynamic reconstruction with tendon transfers. The Achilles tendon, iliotibial band, and semitendinosus tendon have been used as allografts for static stabilization of the anterior capsule. Outcomes of these grafts, however, have been variable.[16,31] Dynamic reconstruction options with muscle tendon transfers include the pectoralis major (PM), pectoralis minor, upper trapezius, and latissimus dorsi (LD) muscle tendons.[6,17,22,24] The PM is the most common of these transfers, with continued pain relief and function at 10-year follow-up.[20] Success, however, has been inconsistent in patients with a concomitant irreparable SSC tendon and associated anterior instability of the glenohumeral joint.[8]

Failure of these dynamic stabilizers can be partly attributed to a different muscle line of pull. Principles of tendon transfer include (1) an expendable donor, (2) a donor of adequate excursion, (3) a donor of adequate strength, (4) a straight line of pull, (5) synergistic muscle function, and (6) a single function per transfer.[25] The teres major (TM) muscle potentially meets the criteria relative to the SSC: it is expendable, and as a pedicled muscle, it can have adequate strength and excursion, a correct line of pull, and synergistic action as an internal rotator of the shoulder joint. Biomechanical and anatomic studies of the TM have been described in different applications, including flaps for soft tissue defect coverage and active, functional unipolar or bipolar transfers.[4,5,27-29,32]

This study presents the anatomy, discusses the feasibility, and outlines the steps of a bipolar, pedicled TM transfer for irreparable SSC (TM-SSC) tendon tears (Fig. 1). Our hypothesis is that the TM-SSC is an anatomically feasible transfer capable of functioning in place of an irreparable SSC tear.

Materials and methods

We performed a cadaveric study on 8 fresh frozen torsos from 4 women and 4 men with an average age of 84 years (range, 68-96 years). Before dissection, fluoroscopic examination confirmed a nontraumatic, intact glenohumeral joint without significant osteoarthritis or rotator cuff arthropathy.

Anatomic measurements

TM measurements were obtained with a slide caliper with an accuracy to 0.1 mm (Mitutoyo, Kawasaki, Japan), and all angles were measured with a goniometer. Dimensions of the TM muscle were measured before and after tendon transfer. Before the transfer, measurements included width of the tendon at its insertion, musculotendinous junction, and muscle belly at the level of the pedicle in addition to the maximum muscle thickness. The TM-SSC transfer was then conducted using the technique described below.

After the transfer, the skin, deltoid, and pectorals muscles were excised to evaluate the TM-SSC proximity to the posterior cord of the brachial plexus and axillary neurovascular bundle as well as the TM and SSC muscle relation to each other. Measurements of SSC tendon width at its insertion, musculotendinous junction, and muscle belly at the level of the pedicle were also obtained.

Bipolar, pedicled TM transfer for irreparable SSC tears

Each cadaver was placed into lateral decubitus with the upper extremity free, providing wide access to the shoulder girdle. Three incisions were needed to perform this transfer: anterior, axillary, and posterior.

The first incision was the anterior incision. This incision accessed the SSC tendon through a standard deltopectoral approach. The axillary nerve was identified at the inferior edge of the SSC tendon and protected (Fig. 2). Blunt dissection was used to release soft tissue adhesions under the coracoid from lateral to medial, along the anterior surface of the SSC tendon and muscle belly to release it from the thorax.

The second incision was the axillary incision. This incision accessed the TM and was located posterior and lateral, between the inferior angle of the scapula and the axillary fold. With the arm abducted and internally rotated, the TM was easily palpated and identified. The main neurovascular pedicle could be identified along the anterior surface of the muscle belly, sometimes with accessory pedicles (Fig. 3).[5] After the muscle was identified, it was released from its origin and insertion. From its origin medially, the muscle was elevated with a part of the infraspinatus muscle fascia and a part of the periosteum of the lateral scapular border. With internal rotation of the humerus, the insertion of the TM was easily identified and often coalesced into a conjoint tendon with the LD.

The third incision was the posterior incision. This incision posteromedially accessed the SSC fossa and was longitudinal, located along the medial border of the scapula just inferior to the scapular spine. The lower trapezius was identified and retracted superiorly, and 3 cm of the rhomboid major and serratus anterior insertions were subperiosteally dissected from the scapula to expose the SSC fossa.

After the donor muscle was harvested around its pedicle and the recipient bed prepared, the bipolar pedicled TM was ready to be transferred. A long Kelly clamp was advanced from the anterior incision to the axillary incision, hugging close to the medial humerus to avoid impingement of the brachial plexus, which was retracted anteriorly. This clamp was attached to the TM insertion. A second clamp was introduced into the posterior incision, passed anterior to the scapula and posterior to the thoracic wall, within the subscapularis fossa, and exited in the axillary incision. This second clamp was attached to the TM origin. Gentle traction was applied on both ends of the clamps so that the TM insertion was retrieved from the anterior incision and the origin was retrieved from the posterior incision (Fig. 4). To prevent axillary nerve entrapment, the nerve was retracted anteriorly during the transfer, along with the brachial plexus. Before final fixation, the TM muscle was directly visualized from the axillary incision, ensuring that there were no twists in the tendon.

Posterior fixation of the transfer was performed first, followed by anatomic fixation of the serratus anterior and rhomboid major muscles (Fig. 5). Next, the posterior and axillary incisions were closed. Lastly, the TM insertion was fixed to the humeral head. In living conditions, this would allow avoiding any traumatic mobilization of the transfer during closure and at the same time controlling its tension by positioning the distal insertion point onto the humeral head. Without passive tension in cadaveric tissues, the optimal insertion point or optimal arm position (ie, internal, neutral, or external rotation) could not be determined; however, anterior fixation onto the lesser tuberosity was possible in all cases. Furthermore, in this cadaveric study, tendon-to-tendon fixation was achieved at both ends of the transfer using strong nonabsorbable sutures. However, tendon-to-bone or bone-to-bone fixation onto the humeral head may be used in vivo for stronger fixation, as previously described.[8,20] Similarly, harvesting a scapular bone chip with the origin of the TM would be feasible to achieve a stronger bone-to-bone proximal fixation of the transfer onto the medial border of the scapula.

Muscle line of pull

To evaluate the muscle lines of pull, the scapulohumeral girdle was removed from the torso after the TM-SSC transfer. The line of pull

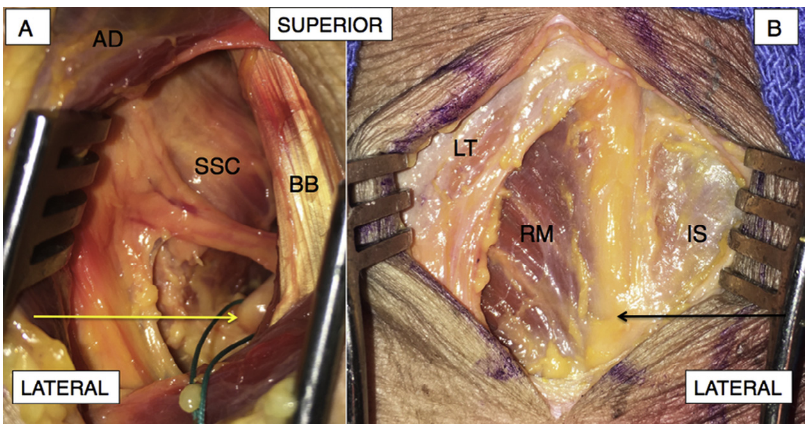

Figure 2 Anatomic dissections show (**A**) the first incision (ie, anterior), with the axillary nerve tagged (*yellow arrow*), and (**B**) the third incision (ie, posterior), inferior to the lower part of the trapezius muscle, showing the medial border of the scapula (*black arrow*). *AD*, anterior deltoid muscle; *SSC*, subscapularis muscle; *BB*, biceps brachii muscle; *LT*, lower trapezius muscle; *RM*, rhomboid major muscle; *IS*, infraspinatus muscle.

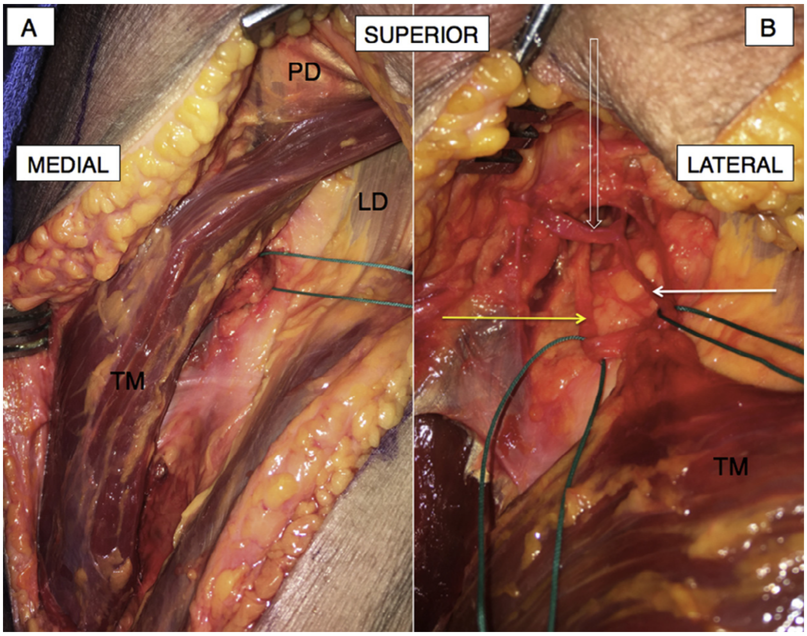

Figure 3 (**A**) Anatomic dissections show the second incision (ie, axillary), allowing for satisfactory exposure of the teres major (*TM*) muscle and its pedicle. (**B**) Further dissection of the pedicle demonstrated that the nerve (*yellow arrow*) was a branch of the thoracodorsal nerve, and the artery (*white arrow*) was issued from the circumflex scapular artery (*open arrow*). *PD*, posterior deltoid muscle; *LD*, latissimus dorsi muscle.

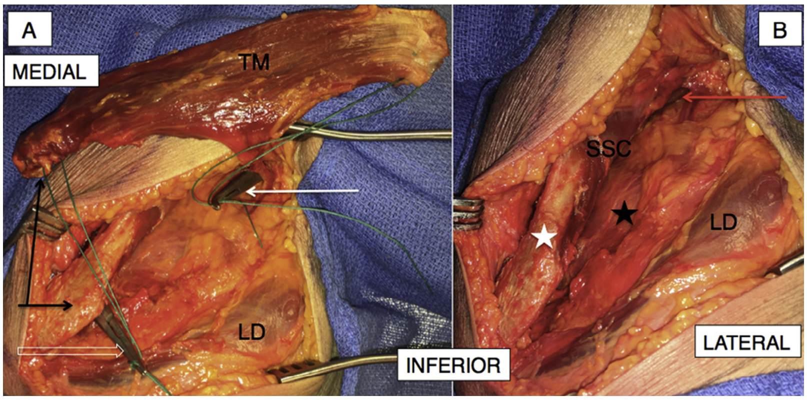

Figure 4 (**A**) Anatomic dissections show the teres major (*TM*) muscle elevated on its pedicle, with its scapular origin proximally (*black arrow*) and humeral insertion distally. (**B**) Two clamps, coming from the deltopectoral (*white arrow*) and posteromedial (*open arrow*) incisions, allow proper positioning of the transfer (*red arrow*) in the subscapularis fossa, between the scapula posteriorly (*white star*) and the thoracic cage anteriorly (*black star*). *SSC*, subscapularis muscle; *LD*, latissimus dorsi muscle.

angle of the transferred TM and original SSC was defined in the scapular plane as the angle between the longitudinal axis of the muscle and the superior border of the scapula, where the greater the measured angle, the more vertical the line of pull (Figs. 6 and 7).

Statistical analysis

The Shapiro-Wilk test was used on all continuous data and excluded their normal distribution. For continuous measurements, Wilcoxon signed rank tests were used for comparisons between TM and SSC measurements. Results are presented as a mean ± standard deviation (range). The level of significant was defined as $P < .05$ for all tests. Computerized statistical analysis was performed using SPSS 22.0 software (IBM, Armonk, NY, USA).

Results

Bipolar pedicled TM

The TM muscle was readily identified in all cadavers and separated from the teres minor superiorly and the LD inferiorly. Its main neurovascular pedicle was located anteriorly at a mean distance of 63.8 ± 8.3 mm (range, 49.1-74.0 mm) from its

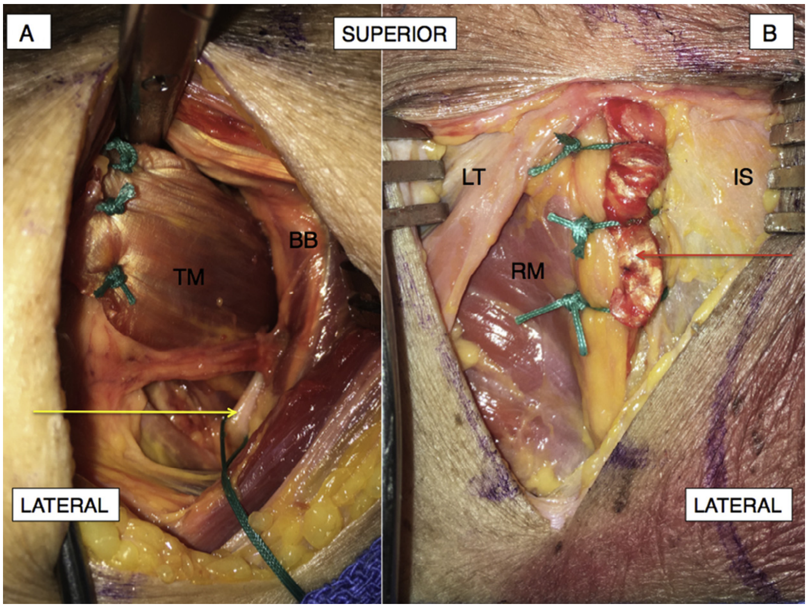

Figure 5 Anatomic dissections show the (**A**) distal and (**B**) proximal tendon-to-tendon fixations of the transfer (*red arrow*). (**A**) Please note the absence of tension on the axillary nerve after transfer (*yellow arrow*) and the complete coverage of the subscapularis tendon. *TM*, teres major muscle; *BB*, biceps brachii muscle; *LT*, lower trapezius muscle; *RM*, rhomboid major muscle; *IS*, infraspinatus muscle.

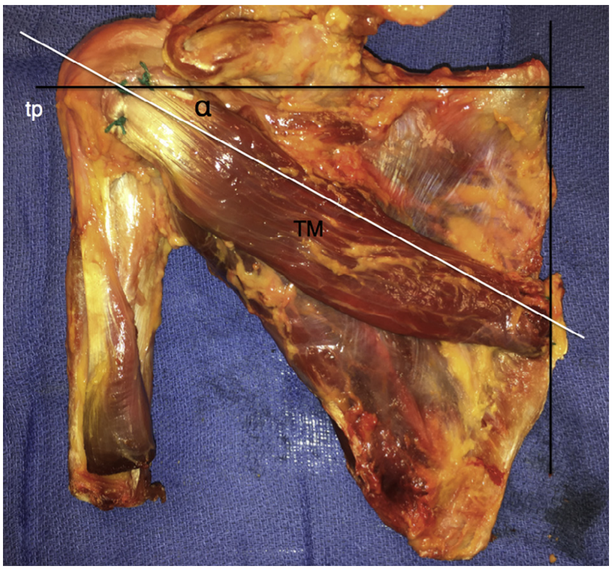

Figure 6 Anatomic dissection modeling the transferred teres major (*TM*) muscle line of pull (*white line*). The TM midaxis was first determined between the 2 midpoints of its proximal and distal fixations; then, the transverse plane (*tp*) was approximated with the line normal to the medial border of the scapula. The angle (α) between the TM midaxis and the transverse plane (*tp*) represents the line of pull angulation of the TM in the scapular plane.

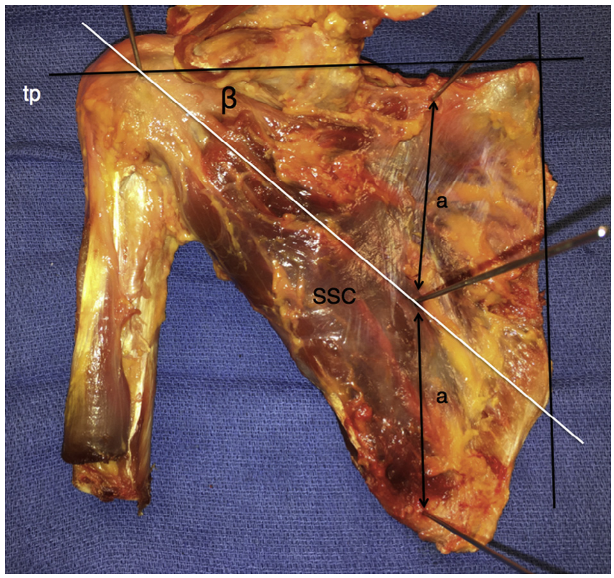

Figure 7 Anatomic dissection modeling the subscapularis (*SSC*) muscle line of pull (*white line*). The SSC muscle midaxis was first determined between the 2 midpoints of the SSC muscle belly and insertion; then, the transverse plane (*tp*) was approximated with the line normal to the medial border of the scapula. The angle (β) between the SSC midaxis and the transverse plane (*tp*) represents the line of pull angulation of the SSC in the scapular plane.

humeral insertion. From the axillary incision, dissection of TM was technically feasible in all cases.

Neurovascular anatomy

As a result of the short distance of the transfer, no constraints were noted on the TM pedicle once positioned into the SSC fossa. After the transfer, the posterior cord of the brachial plexus and its branches and terminal divisions were lying anterior to the TM-SSC construct, without tension or compression. The nerve to the TM muscle branched off of the thoracodorsal nerve in 5 shoulders and the lower subscapular nerve in other 3, with an average length of 68.4 ± 15.6 mm (range, 48.4-89.7 mm). The main vascular pedicle arose from

Table I Cadaveric measurements*

Measurements	Teres major	Subscapularis	*P* value
Dimensions, mm			
Width			
Tendon	31.5 ± 3.8 (24.7-37.1)	22.9 ± 3.1 (19.0-27.2)	<.01
MTJ	33.0 ± 4.1 (26.3-39.7)	31.4 ± 2.6 (27.3-35.0)	.11
Belly	35.5 ± 4.3 (29.2-42.9)	145.0 ± 13.3 (127.6-168.9)	<.01
Length			
Tendon	26.7 ± 4.0 (21.1-32.2)	34.6 ± 5.6 (27.1-42.8)	.01
Belly	134.8 ± 11.9 (120.6-152.1)	138.6 ± 12.9 (119.9-162.9)	.06
Total	161.5 ± 15.0 (143.9-184.3)	173.2 ± 15.7 (153.2-201.0)	.02
Thickness	9.9 ± 2.0 (7.2-12.3)	10.5 ± 1.8 (7.7-13.1)	.31
Line of pull,°	30 ± 5 (23-41)	39 ± 7 (30-49)	.04

MJT, musculotendinous junction.
* All measurements are presented as mean ± standard deviation (range).

the circumflex scapular artery in 5 shoulders and from the thoracodorsal artery in the remaining 3. The mean artery length was 33.7 ± 6.9 mm (range, 22.3-41.8 mm). Distal accessory pedicles arising from the circumflex scapular artery were identified in all but 1 shoulder, entering the TM muscle belly close to its scapular origin.

Comparison of the TM and SSC muscle dimensions

Numeric comparison of the TM and SSC muscles are detailed in Table I. The width of the SSC tendon at its insertion onto the lesser tuberosity averaged 22.9 ± 3.0 mm (range, 19.0-27.2 mm), and the TM tendon insertion averaged 31.5 ± 3.8 mm (range, 24.7-37.1 mm; $P < .01$). Because the TM tendon was larger, there was complete coverage of the SSC insertion in all cases.

The mean width of the SSC belly was significantly greater than the mean width of the TM belly, with a discrepancy of more than 10 cm (Table I).

Although there was no difference between TM and SSC muscle belly length, the mean length of the SSC tendon was greater than the mean TM tendon length, resulting in a longer total mean muscle length of 173.2 ± 15.7 mm (range, 153.2-201.0 mm) for the SSC compared with 161.5 ± 15.0 mm (range, 143.9-184.3 mm) for the TM ($P = .02$). The maximal thickness of the SSC muscle was slightly larger than for the TM muscle, but the difference was not significant ($P = .31$). The TM line of pull was slightly more horizontal than the SSC line of pull, with a mean discrepancy of 9° ($P = .039$).

Discussion

In this anatomic study, we demonstrate the feasibility of a bipolar, pedicled transfer of the TM to the SSC fossa as a potential reconstructive option for irreparable SSC tears. Going from its anatomic position posterior to the scapula and anterior to the proximal humeral shaft to a position anterior to the scapula and glenohumeral joint, the pedicled TM-SSC transfer appears to fulfill the criteria for tendon transfer because it recreates the SSC muscle line of pull by using an expendable muscle.

Neurovascular anatomy

This study confirms previously reported characteristics of TM that make it a potential donor for muscle transfer, including its reliable vascular pedicle and innervation.[32] In an anatomic study of 11 shoulders, Wang et al[29] described the vascular configuration of the pedicle, surgical approach to the muscle through a posterior approach, and the redundancy in function, thus making it an expendable muscle. More recently, Dancker et al[5] confirmed this vascular pattern and added a precise description of TM innervation. Our study agrees with the reported neurovascular anatomy; as previously outlined, the limiting factor for a TM pedicled transfer would be the artery, which was much shorter than the nerve (ie, 33.7 ± 6.9 mm vs. 68.4 ± 15.6 mm, respectively).[5] However, as a result of the minimal displacement of the muscle belly that is required in this transfer, we observed that the pedicle had enough excursion in all cases. Similarly, this bipolar transfer reroutes the transfer superior to the axillary nerve, thus preventing compression or traction, or both, on this nerve as it was outlined in a unipolar fashion.[7,12]

Comparison of TM and SSC muscle dimensions

Similar anatomic measurements of the TM relative to the SSC also make this a convenient choice for tendon transfer. The dimensions of the TM insertion are similar to those of the SSC insertion onto the lesser tuberosity. Thus, in addition to its potential as a dynamic anterior joint stabilizer, the TM transfer will function as a static reinforcement of the anterior glenohumeral articular capsule, similar to previously described repairs.[16,31]

The TM muscle belly thickness was similar to the SSC belly thickness. This is crucial information in this transfer configuration because space in the scapulothoracic joint is limited. In fact, the bulkiness of the transfer, especially during active muscle contraction, may compress its own pedicle or limit the scapulothoracic motion. In addition, considering the proximity of the posterior cord, extra muscle bulk may be a cause for impingement of the brachial plexus or its branches.[12] Because the indication for this transfer is in the setting of SSC dysfunction, the SSC is most likely to be atrophic and no longer filling the SSC fossa; if necessary, it may also be partially excised through the axillary incision to place the pedicled TM transfer in an empty SSC fossa, thus preventing impingement.

TM length was statistically significantly inferior to the SSC length by approximately 2 cm, but no limitation was noted during the transfer. This may be explained by the position of the transfer, which was more horizontal than the SSC midaxis and thus decreased the working length of the tendon needed. Also, cadaveric tissue lacks passive tension and has increased extensibility. This might appear as a limitation or an increased risk factor for loss of external rotation from a tenodesis effect in an in vivo situation. However, previous studies have shown the TM is stretched an additional 47% to insert onto the greater tuberosity for posterosuperior rotator cuff tears reconstruction (ie, from a mean original length of 13.7 cm to 19.2 cm once transferred),[3] without a tenodesis effect preventing internal rotation.[2,4,32] Thus, the TM muscle length is likely able to tolerate elongation while functioning adequately and should not be a limiting factor in this anterior configuration.

Biomechanical rationale

Ackland and Pandy[1] demonstrated the significant differences between the lines of actions of the upper PM and the SSC. In both the scapular and transverse planes, the upper PM acts as a "destabilizer" of the glenohumeral joint, whereas the SSC, with a favorable ratio between compressive and shear forces, acts as a primary glenohumeral "stabilizer".[1] With the TM positioned to mimic the SSC, with a medial scapular border origin, passing through the SSC fossa, and progressing laterally to insert onto the SSC footprint, this scapulohumeral TM transfer is integrated in the scapular plane and recreates the SSC muscle line of pull; subsequently, similar biomechanical actions should be achieved. The clinical significance of a 9° difference in line of pull between 2 muscles in the same plane (ie, scapular plane) that we outlined in this study is unknown.

Our muscle belly measurements show that the difference between the TM and the SSC muscles in volumes and physiologic cross-sectional areas (PCSA) may be significant. Holzbaur et al[15] confirmed this in a magnetic resonance imaging study among 10 young and healthy individuals, which showed that the mean volume and PCSA of the SSC muscle were more than 5-times greater than the TM muscle. Because the volume and PCSA of a muscle correlates with its work capacity, the TM muscle may not be sufficient to recreate full SSC function, especially after transfer where loss of work of power is commonly observed.[25] However, the distal insertion of the transfer onto the lesser tuberosity will result in an increase of the internal rotation moment arm of the TM.[18] Furthermore, the preload of the TM muscle fibers will be increased once transferred, as demonstrated by the necessary elongation of the TM muscle to be distally fixed onto the lesser tuberosity. Such characteristics will provide a mechanical advantage to the transferred TM that might compensate for this shortcoming.

Stand-alone transfer?

Elhassan et al[7] recently reported the anatomic feasibility of a LD transfer to reconstruct the SSC muscle, and Kany et al[17] reported the early radioclinical outcomes of this procedure, performed arthroscopically in 5 patients, which appeared to be very encouraging. Nonetheless, the bipolar TM transfer described in our study, if done in association to the LD transfer, may contribute to further static and dynamic stabilization of the glenohumeral joint in the scapular plane, which the inferior line of pull of the LD transfer does not provide. In addition, the LD muscle could theoretically compensate for the smaller muscle mass of the TM transfer. Electromyographic studies have shown the LD and TM have similar synergistic functions, findings that were confirmed by the clinical success of this double transfer in other indications.[2,23] Furthermore, in patients without an available LD muscle for transfer (eg, failure of a previous LD-SSC transfer, LD muscle already used in another indication, or paralyzed or paretic LD muscle), this bipolar TM transfer appears to be a reasonable alternative.

Limitations

This study has inherent limitations. First, this is an anatomic feasibility study performed in cadavers. This limits our ability to predict in vivo clinical outcomes and nuances with such a transfer, particularly considering the esthetic cost due to the 3 different incisions, the partial dissection of the rhomboid major and serratus anterior muscles, the increased risk of sutures failure due to the bipolar fashion of this transfer, and the extensive scapulothoracic detachment that is needed to position the transfer, which may increase the risk for postoperative adhesions and subsequent limited range of motion.

Another significant limitation is the lack of resting muscular tension, which increases the extensibility of muscle tissues. If this may have biased our cadaveric measurements, this also limits our ability to propose a particular position for the arm during reinsertion in an in vivo scenario, because this will mainly depend on the tension of the transfer the operator will observe intraoperatively. However, passive intraoperative tension should not limit external rotation and, at the same time, provide a tenodesis effect that spontaneously positions the arm 20° internally rotated (ie, starting from neutral rotation). Patients should be immobilized postoperatively with a sling in internal rotation, such as after SSC direct repairs, to obtain a tensionless setting of the transfer that allows satisfactory healing of the sutures.[9]

Lastly, considering our small sample size, type 2 errors may have occurred in cases without statistical significant differences (eg, muscle belly thicknesses and lengths).

Conclusions

With a similar line of pull, functional expendability, close proximity, and similar tendon measurements, the bipolar pedicled TM transfer appears to fulfill the criteria as an option for reconstruction in irreparable SSC tendon tears. This study also demonstrates that this is an anatomically safe transfer relative to the surrounding neurovascular structures. Further clinical studies are necessary to assess its outcome in in vivo conditions.

Acknowledgments

The authors thank the Mayo Clinic Anatomy Laboratory for ensuring the availability of the specimens for this study.

Disclaimer

The authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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