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Biomechanics of lower trapezius and latissimus dorsi transfers in rotator cuff–deficient shoulders

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Background: Irreparable posterosuperior rotator cuff tears cause pain and impaired shoulder function. Latissimus dorsi (LD) transfer has been proven to improve shoulder function, but lower trapezius (LT) transfer has recently been proposed as an alternative. This study aimed to compare the biomechanics of LD and LT transfers and how they are affected by different insertion sites.
Methods: The Newcastle shoulder model was used to investigate the biomechanics of these 2 tendon transfers. Computed tomography data sets from 10 healthy subjects were used to customize the model, and virtual LD and LT transfers were performed on supraspinatus, infraspinatus, and teres minor insertion sites. Muscle moment arms and lengths were computed for abduction, forward flexion, and external rotation.
Results: The LT yields greater abduction moment arms compared with the LD when it is transferred to the native supraspinatus and infraspinatus insertion sites. However, they become adductors when transferred to the native teres minor insertion. Both muscles show strong external rotation moment arms, except for the LT with a supraspinatus insertion. Resting muscle strains were 0.21 (±0.03), 0.12 (±0.02), and 0.06 (±0.03) for the LD and 0.70 (±0.15), 0.61 (±0.13), and 0.58 (±0.13) for the LT for the supraspinatus, infraspinatus, and teres minor insertions, respectively.
Conclusions: LT provided better abduction and external rotation moment arms when transferred to the infraspinatus insertion. LD performed better when transferred to the supraspinatus insertion. Overall, LT transfer showed a biomechanical advantage compared with LD transfer because of stronger abduction moment arms. However, significantly larger muscle strains after LT transfer necessitate a tendon allograft to prevent muscle overtensioning.
Level of evidence: Basic Science Study; Computer Modeling

Keywords: Tendon transfer; computer shoulder model; moment arm; rotator cuff tear; biomechanics; latissimus dorsi; lower trapezius

Rotator cuff tear (RCT) is a common shoulder injury that causes pain and loss of function and can eventually lead to arthropathy.[15] Massive RCTs involving tendon retraction and fatty infiltration are generally considered irreparable, and attempted repair is associated with high rates of retear.[6] For patients with irreparable RCTs, several surgical

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options exist, including tendon transfer,[5,8,11] shoulder arthroplasty,[14] and partial repair.[2] Tendon transfer involves the detachment of a nearby muscle from its anatomic insertion and reattachment at the rotator cuff insertion site on the humeral head. The tendon transfer aims to approximate the muscle function of the irreparable rotator cuff and to improve shoulder function.

Latissimus dorsi (LD) transfer is the most common tendon transfer for posterosuperior RCTs and has been used for several decades. The main goal of LD transfer is restoration of external rotation, which is compromised after posterosuperior RCT. Several studies have demonstrated the success of this technique in providing pain relief and improved shoulder function.[9,10] However, LD transfer can increase the risk for shoulder subluxation[19] and requires strong deltoid function during shoulder elevation to overcome the antagonistic-adduction forces from the LD after transfer.[19]

Lower trapezius (LT) transfer was recently proposed as an alternative to LD transfer.[4,5] The line of action of the LT, once transferred, better mimics that of the infraspinatus compared with the LD.[17] It is also less likely to require additional deltoid force during shoulder elevation because the LT does not exert as much of an adduction force compared with the LD. However, a downside of LT transfer is the need for a bridging tendon allograft because of the large distance of the LT's native insertion from the humeral head.[18] The effectiveness of LT transfer has been demonstrated in those with brachial plexus injuries[16]; however, clinical[5] and biomechanical[9,14] studies involving RCTs are limited.

Cadaveric studies have shown that LT transfer provides more efficient external rotation when the arm is in adduction and better restores native glenohumeral joint reaction forces compared with LD transfer.[11,17] However, these cadaveric studies have several limitations because they have simplified or omitted scapulothoracic motion and used static models, which limits their translation to clinical practice. Scapulothoracic motion is a significant component of shoulder joint movement, and because both the LT and LD originate from the thorax, lines of action, muscle lengths, and muscle forces would all be dependent on scapulothoracic dynamics. In addition, the cadaveric models were able to evaluate LT and LD transfers only in limited static conditions and only the rotational moment arms. Both tendon transfers can affect the rotational and abductive-adductive moment arms. Therefore, it is essential to evaluate their function throughout the full range of motion and in multiple planes to better understand how they can restore shoulder function and the ability to complete dynamic activities of daily living. Given the various experimental limitations that exist, an essential tool to explore the complex biomechanics of tendon transfers is computational modeling and simulation. In the past, similar biomechanical models were used to investigate how muscle moment arms and glenohumeral joint contact forces are affected on a shoulder with massive posterosuperior RCTs.[13] The same studies also showed the effectiveness of LD and teres minor transfers during standardized activities[12] and activities of daily living.[13]

The purpose of this study was to compare the biomechanical properties of LD and LT transfers using an established computational musculoskeletal model of the upper extremity. The first aim of the study was to determine moment arms of the muscles around the shoulder after LD and LT transfers to 3 different insertion sites on the proximal humerus. The second aim was to determine the muscle lengths of the LD and LT transfers. We hypothesized that LT transfer would provide greater external rotation and abduction moment arms but would be limited by its relatively short muscle length.

Materials and methods

This is an in silico study that used a shoulder model and a medical imaging data set to investigate the moment arm of LT and LD tendon transfers in massive RCT shoulders.

Shoulder biomechanical models

A 3-dimensional (3D) biomechanical model of the upper extremity, the Newcastle shoulder model, was used in this investigation. The model represents a normal shoulder and elbow and includes the thorax, clavicle, scapula, humerus, radius, and ulna. The skeletal geometry of the original model is based on a single cadaver and derived from the reconstruction of the Visible Human data set. The model includes the sternoclavicular, acromioclavicular, and glenohumeral joints and simulates the 3D scapula and clavicle kinematics, which are computed from formulations derived from healthy subjects.[3]

The model includes 31 muscles and 3 ligaments of the upper extremity that are divided into 90 lines of action representing the anatomic muscle division into fascicles. These lines of action are modeled as elastic strings that wrap around the bone geometry (Fig. 1). The LD muscle is modeled with 5 lines of action, and the trapezius muscle is modeled with 16 lines of action (Fig. 2). The model can compute the length and moment arm of any muscle over a predefined motion using the tendon excursion method.[1]

Model customization—computed tomography and 3D reconstruction

The study used additional computed tomography (CT) data sets from 9 nonarthritic subjects with no prior history of shoulder surgery (mean age, 61 $\pm$ 14 years; 5 men, 4 women) to customize and to create an additional 9 models. All CT scans were taken under settings of 100 to 240 mA, 100 to 140 mVs, with 0.5- to 1-mm slice thickness and 512 $\times$ 512 pixels per slice (resulting in a mean pixel size of 0.4 $\pm$ 0.1 mm). The CT data sets were uploaded to Mimics software (Materialise, Leuven, Belgium) for segmentation and reconstruction of thoracic, scapular, and humeral

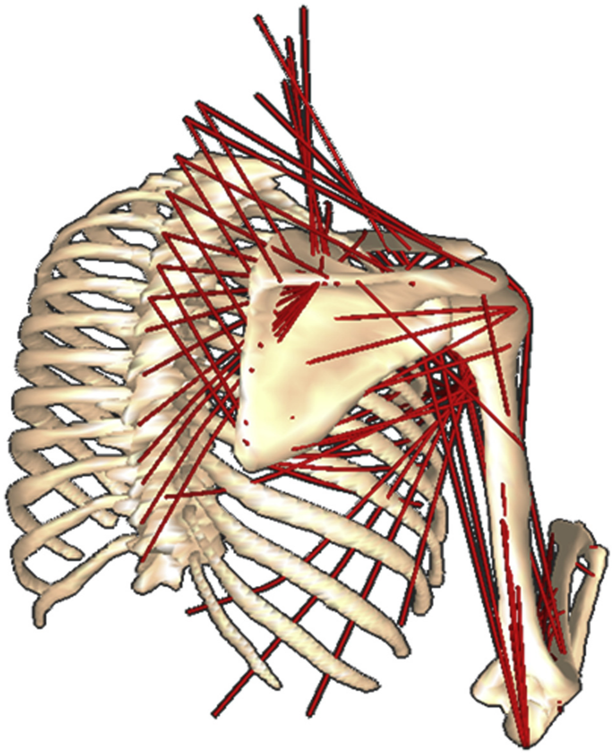

Figure 1 The Newcastle shoulder model. The latissimus dorsi is modeled with 5 lines of action, and the trapezius is modeled with 16 lines of action.

geometries. Automatic gray-value thresholding with a minimum value of 226 Hounsfield units allowed initial segmentation of bone materials from other tissues. Manual segmentation was used to refine and to finalize the boundaries of the scapular, humeral, and thoracic geometries. All the necessary International Society of Biomechanics anatomic landmarks of the thorax, clavicle, and scapula were identified from the CT scans to define the joint and to segment coordinate systems according to the original model.[3,20] The only missing landmarks were the medial and lateral humeral epicondyles (CT scans extended inferiorly to mid humerus only), but they were estimated according to the methodology of Amadi et al.[1] The muscles' origins and attachments were identified for each model by an orthopedic fellow and reviewed by a qualified shoulder surgeon.

LT and LD tendon transfers—model configurations

This study modeled the tendon transfers as they are described in clinical practice and previous biomechanical studies.[8,9] First, the LD and LT anatomic origins and insertions were identified for each subject. Virtual tendon transfers were then simulated by transferring the LD and LT insertions to various sites within the rotator cuff footprint on the greater tuberosity of the humerus. For the LT transfer, the 9 inferior lines of action (originating from the 4th to the 12th thoracic vertebrae) were selected for transfer, and their insertions were reattached to a single point on the greater tuberosity (no attachment tendon width). This attachment method was chosen to model the use of a tendon allograft, which is often used in clinical practice during LT transfer. For the LD transfer, all 5 lines of action of the muscle were selected, and their insertions were reattached to the greater tuberosity, maintaining the native tendon footprint (Fig. 2) as is done in clinical practice.

The study investigated the LD and LT after the transfer of each to the insertion sites of the supraspinatus, infraspinatus, and teres minor. Hence, 6 models and tendon transfers were created for each of the 10 subjects (LD-supraspinatus, LD-infraspinatus, LD–teres minor, LT-supraspinatus, LT-infraspinatus, LT–teres minor; Fig. 3).

Kinematic data and simulations and data outcomes

Four standardized activities were simulated in this study:

- Humeral elevation in the (1) frontal (abduction) and (2) sagittal (forward flexion) planes. All activities were modeled from 0° to 150° of humeral elevation.
- Humeral external rotation with the arm at (3) 20° abduction and (4) 90° abduction. The external rotation was simulated by starting the arm at 80° of internal rotation and rotating it externally to 80° of external rotation (total external rotation arc of motion = 160°).

Scapular kinematics was simulated during all activities. Muscle-tendon paths were specified, and muscle moment arms were computed throughout each motion using the tendon excursion method.[1] For the 2 humeral elevation motions (abduction, forward flexion), positive moment arm values indicate an abductive moment arm; negative values indicate an adductive moment arm. For the 2 external rotational motions, negative moment arm values indicate an externally rotating moment arm; positive values indicate an internally rotating moment arm. Muscle lengths were also computed, and muscle strains were defined as the ratio of muscle elongation (after tendon transfer) over the anatomic resting length of the muscle. The muscle strain data were calculated to highlight only the muscle elongation after the tendon transfer and are not related to tension.

Statistics

Repeated-measures analysis of variance with Bonferroni pairwise comparison was performed in SPSS software (IBM, Armonk, NY, USA) to compare the variances of the moment arms during each motion for each tendon transfer model. Statistical significance was assumed when $P < .05$.

Results

Moment arm analysis

Moment arms for the LD and LT, after tendon transfer, are summarized in Figures 4 and 5. During abduction, the LT showed larger abduction moment arms compared with the LD ($P < .05$) for the first 65°, 150°, and 120° of abduction for the supraspinatus, infraspinatus, and teres minor

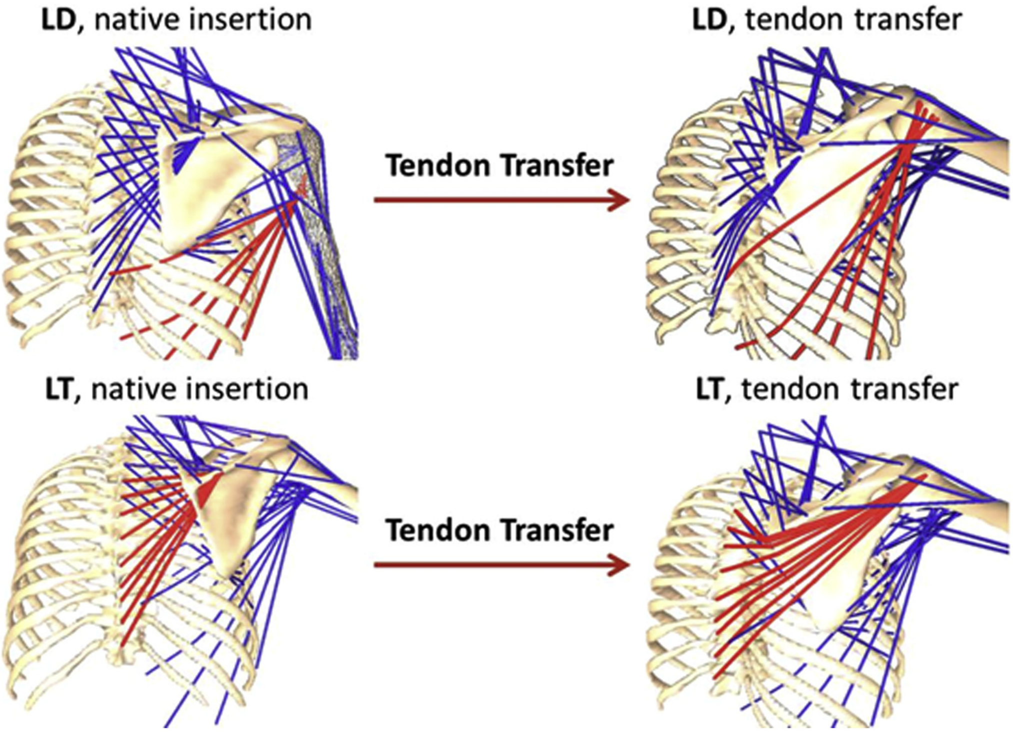

Figure 2 Latissimus dorsi (*LD*) and lower trapezius (*LT*) transfers were simulated by transferring the insertions of the corresponding muscle lines of action to the new locations.

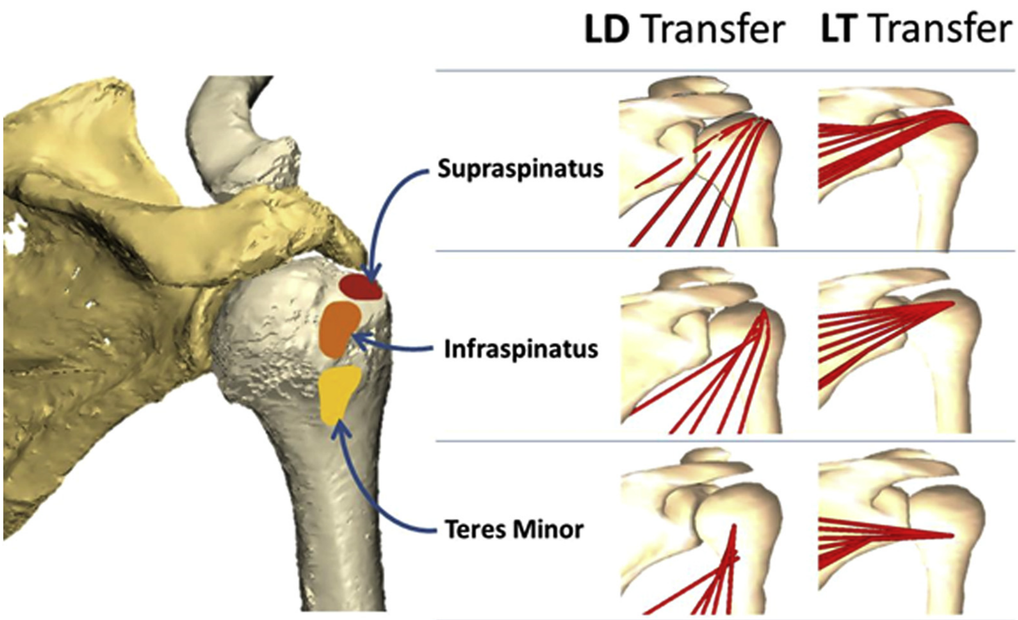

Figure 3 Both latissimus dorsi (*LD*) and lower trapezius (*LT*) were transferred from their anatomic cites to the insertion of supraspinatus, infraspinatus, and teres minor.

insertions, respectively. The LT moment arms had positive values throughout the motion for the supraspinatus and infraspinatus insertions (maximum values of +14.5 mm ± 11.2 mm and +18.0 mm ± 3.6 mm, respectively). For the teres minor insertion, the LT moment arms ranged from −9.9 mm ± 2.9 mm (at 0° of abduction) to 10.6 mm ± 5.3 mm (at 150° of abduction). The LD moment arms were lower and ranged from negative to positive values for all the

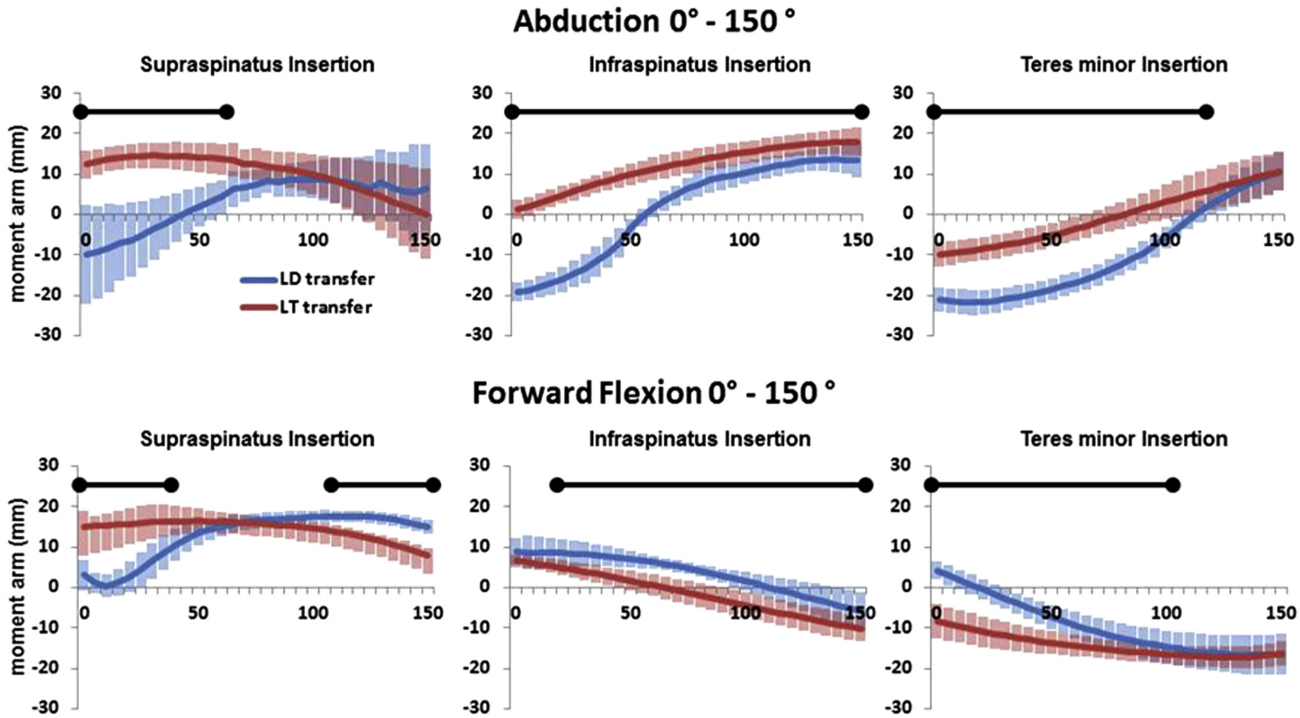

Figure 4 Lower trapezius (*LT*) and latissimus dorsi (*LD*) moment arms during abduction and forward flexion motions (*horizontal bars* indicate significant differences between the data, $P < .05$). The *error bars* indicate standard deviation.

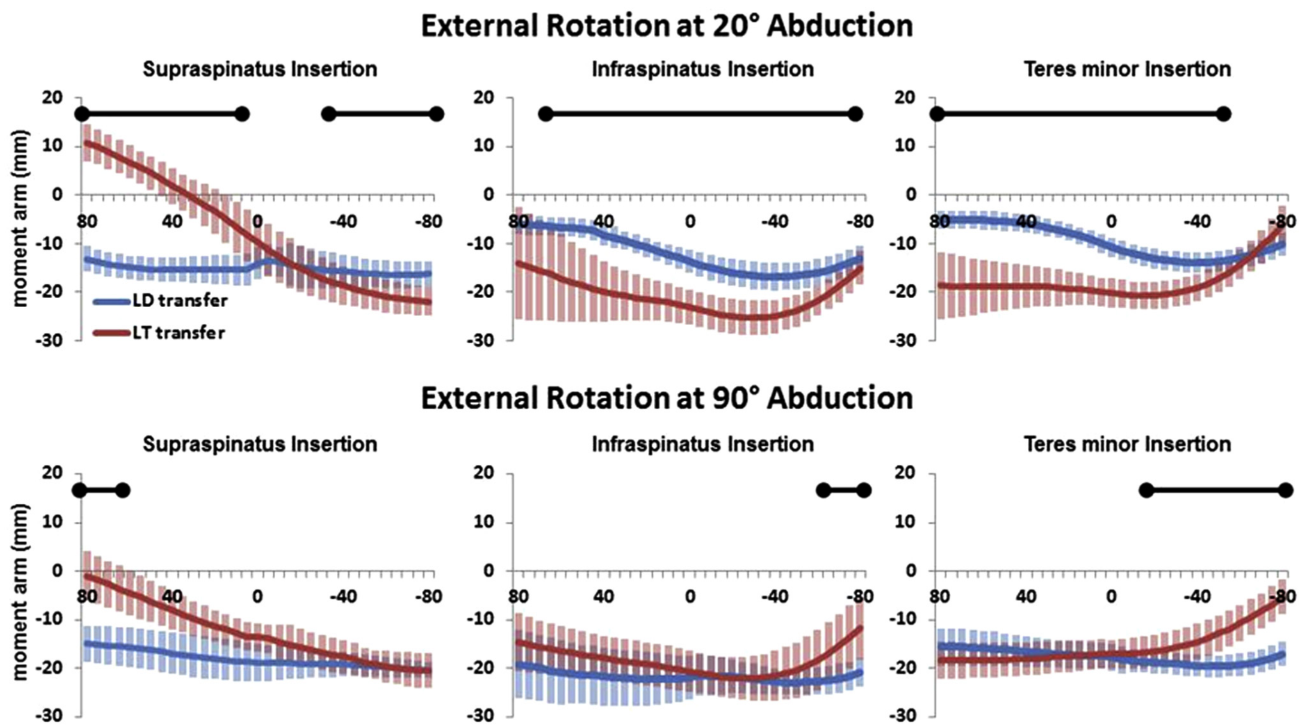

Figure 5 Lower trapezius (*LT*) and latissimus dorsi (*LD*) moment arms during external rotation motion at 20° and 90° of abduction. Rotation (*horizontal axis*) ranges from 80° of internal rotation (positive) to 80° of external rotation (negative). Negative moment arm values indicate an externally rotating moment arm; positive values indicate an internally rotating moment arm (*horizontal bars* indicate significant differences between the data, $P < .05$). The *error bars* indicate standard deviation.

insertions (−9.9 mm ± 3.0 mm to +8.6 mm ± 12.4 mm for supraspinatus, −19.3 mm ± 2.2 mm to +13.6 mm ± 4.2 mm for infraspinatus, and −21.8 mm ± 2.5 mm to +10.6 mm ± 4.9 mm for teres minor). There were significant differences also for the forward flexion motion between the LD and LT transfers, but they were smaller than for abduction. The LD had on average larger forward flexion moment arms, except for the first 40° of forward flexion for the supraspinatus insertion ($P = .003$). The supraspinatus insertion provided the largest forward flexion moment arms for both the LD and LT (maximum values of +17.6 mm ± 4.5 mm and +16.4 mm ± 7.1 mm, respectively), but those were at different parts of the motion (maximum was at 115° ± 10° of forward flexion for the LD and at 40° ± 15° of forward flexion for the LT).

Both LD and LT tendon transfers showed strong external rotation moment arms when attached to the infraspinatus and teres minor insertions. The LT showed on average larger magnitude external rotation moment arms compared with the LD for external rotation at 20° adduction (−25.3 mm ± 2.6 mm vs. −16.9 mm ± 1.9 mm [$P = .003$] for infraspinatus insertion and −20.7 ± 2.8 mm vs. −13.9 mm ± 1.7 mm [$P = .001$] for teres minor insertion). For external rotation at 90° of abduction, there were significant differences between the 2 transfers, with the LD providing slight external rotation advantage at the end range of external rotation for the infraspinatus and teres minor insertions (final 15° [$P < .001$] and final 60° [$P < .001$] of external rotation, respectively). However, the LT external rotation moment arms decreased significantly when attached to the supraspinatus insertion, becoming on average smaller than the LD, especially when the arm was internally rotated (first 75° of rotation at 20° of abduction [$P < .001$] and first 20° of rotation at 90° of abduction [$P < .001$]).

Muscle length analysis

Muscle elongation lengths for the LT transfers were significantly larger than for the LD. The maximum strain with the arm at rest was 0.21 (±0.03), 0.12 (±0.02), and 0.06 (±.03) for the LD transfers compared with 0.70 (±0.15), 0.61 (±0.13), and 0.58 (±0.13) for the LT transfers to the supraspinatus, infraspinatus, and teres minor insertions sites, respectively ($P < .001$ for all pairwise comparisons). However, the maximum values of strain were observed during the external rotation motion at 90° of abduction; the LT transfer yielded muscle strains of 0.74 (±0.18), 0.77 (±0.20), and 0.79 (±0.17), whereas the LD transfer yielded muscle strains of 0.51 (±0.09), 0.46 (±0.08), and 0.40 (±0.07) for the supraspinatus, infraspinatus, and teres minor insertions sites, respectively. The strain values between the different insertion sites were not statistically significant ($P > .081$ for all pairwise comparisons).

Discussion

The data showed statistically significant differences between the 2 tendon transfers. One of the main objectives of the LD and LT tendon transfers is to restore external rotation function to subjects with posterosuperior RCTs. In that respect, the results suggested that both tendon transfers can generate an external rotation moment arm in any of the 3 insertion sites. However, when the LT tendon is attached to the supraspinatus footprint, its external moment arm is significantly reduced when the arm is in a neutral to internally rotated position. This can be explained by the line of action of the LT tendon, which generates more compression rather than an externally rotating moment arm when it is attached to the supraspinatus (Figs. 5 and 6). This is in contrast to the LD transfer, which maintains an external rotation moment arm for each insertion point. The compressive action of the LT transfer (compared with LD transfer) was also shown by the cadaveric work of Omid et al,[17] which showed reduced glenohumeral translations in shoulders treated with LT transfer compared with LD transfer.

The moment arm results showed that the LT is a more effective external rotator than the LD when the arm is at 20° of abduction and the tendon is attached to the infraspinatus or teres minor insertions (Fig. 5). However, this advantage is eliminated when the arm is at 90° of abduction. The LD, compared with the LT, provided equivalently high external rotation at 90° when attached to the infraspinatus and teres minor insertions. In fact, at the end range of motion (external rotation >50°), the LD transfer generated more external rotation in this scenario. This agrees well with a previous cadaveric study,[11] which showed that LT transfer can generate more external rotation when the arm is at 0° abduction. However, the investigators showed that the LD can be a stronger external rotator when the arm is abducted to 90°.

Even if the LD transfer can generate external rotation because of its line of action, it also tends to generate an adductive moment that would need to be counteracted by the deltoid muscle to elevate the arm. The results of this study indeed showed large adductive moment arms for the LD transfers. The effect was reduced only when the LD was attached to the supraspinatus site, which yielded the smallest range of adductive moment arm values during the abduction motion. In contrast, the LT transfer performed much better for the supraspinatus and infraspinatus insertions, where it generated abductive moment arms throughout the abduction range of motion. Only the teres minor insertion resulted in the LT's resisting humeral abduction by generating adductive moment arms.

The results of this study showed that both tendon transfers have advantages and disadvantages that are affected by their attachment site. Considering all the results and tradeoffs, an infraspinatus insertion would be favored

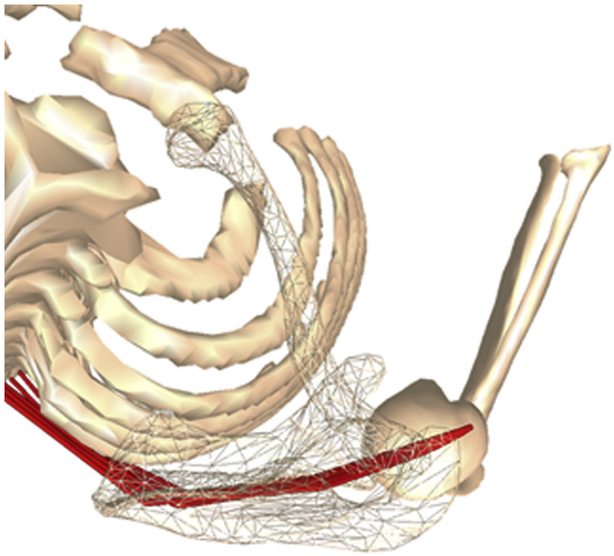

Figure 6 The line of action of the lower trapezius when it is attached to the supraspinatus insertion exerted a more compressive action that reduced its ability to externally rotate the arm.

for the LT transfer because it is not counterproductive during humeral abduction and can also provide sufficient external rotation moment arms when the arm is both abducted and adducted. In contrast, a supraspinatus insertion should be considered for the LD transfer because an infraspinatus or teres minor insertion would result in larger adductive resistance during abduction.

However, the LT transfer poses a different clinical challenge because its reattachment needs to be combined with an interposition tendon allograft.[9] In our study, the tendon transfer was simulated as a simple transfer of the lines of action of the LT to the new attachment point. This is a limitation of this study as it is not an accurate representation of the LT tendon transfer. In clinical practice, the LT is typically unable to be extended to reach the humerus, and a graft is used to bridge the gap. The length-strain results of the study indeed showed that even in the resting position, the lines of action of the LT were stretched up to 70.1% (±14.7%) when it was attached to the supraspinatus insertion. This translates to 113.1 mm (±45.4 mm) of muscle elongation from its resting length, which is impossible to achieve without a tendon allograft. In contrast, the LD tendon transfer did not exceed 21.2% (±3.1%) for any of the insertion points and therefore would not likely require a tendon allograft.

This study has several limitations to be considered. Modeling muscles with elastic lines of action that wrap around the bones is challenging and may not completely represent the complex biomechanics that occur in vivo. In the model, each muscle had to be represented with multiple lines of action to simulate the many anatomic fascicles and large origin points. However, the modeled lines of action behaved independently, not always acting as a cohesive muscle. It is difficult to simulate allograft augmentation in this type of muscle modeling. More sophisticated finite element volumetric muscle models can overcome those limitations, but they are computationally heavy and difficult to implement in large-scale biomechanical models. However, the type of muscle modeling used in this study has been validated in multiple studies against cadaveric models and has shown close agreements for moment arm and length calculations.[3,7]

This study considered scapula kinematics, but the data were derived from healthy subjects. This might be unrealistic and a limitation of this study because pathologic shoulders often show abnormal scapula motion. However, even if scapula kinematics might be underestimated in this study, the authors believe that it is a better approximation compared with previous cadaveric studies in which the scapula was fixed. That is because both LD and LT are triarticular muscles, and it is important to understand how they act on the glenohumeral joint during a dynamic motion of the shoulder girdle. Another limitation of the study is that the models simulated the motions without taking into account glenohumeral translation, which usually happens in these types of tendon transfers.

Future studies are needed to perform dynamic analysis of the LT and LD transfer shoulder models to determine how the altered anatomy affects muscle and joint contact forces. This next step in the biomechanical investigation of LT and LD transfers is necessary to further evaluate the clinical feasibility of these tendon transfers in restoring a patient's ability to perform activities of daily living.

Conclusions

The study showed significant differences between the 2 tendon transfers. When the LT is attached to the supraspinatus and infraspinatus insertion sites, it generates abduction moment arms throughout a normal range of motion and thereby mimics the intact supraspinatus. For teres minor insertion, both muscles create an adduction moment arm that requires increased deltoid force to counteract their action when the arm is being elevated. The results suggest that both tendon transfers can produce external rotation, but this is compromised when the LT is transferred to the supraspinatus insertion. Considering the tradeoffs, an infraspinatus insertion would be favored for LT transfer because it would offer external rotation without resisting humeral abduction, whereas a supraspinatus insertion would be favored for LD transfer because it will provide maximal external rotation with minimal resistance to humeral abduction. The results also suggest that LT transfer has a slight biomechanical advantage compared with LD owing to better abduction moment arms. However, the length results show that LT is very elongated after the tendon transfer, which suggests that a tendon allograft is required to bridge the gap to the insertion site.

Disclaimer

Lawrence V. Gulotta is a paid consultant and speaker for Zimmer Biomet.

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