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Review article

Tendon transfers in reverse total shoulder arthroplasty: A systematic review and descriptive synthesis of biomechanical studies

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ABSTRACT

Background: The role of tendon transfer and ideal insertion sites to improve axial rotation in reverse total shoulder arthroplasty (RTSA) is debated. We systematically reviewed the available biomechanical evidence to elucidate the ideal tendon transfer and insertion sites for restoration of external and internal rotation in the setting of RTSA and the influence of implant lateralization.
Patients and methods: We queried the PubMed/MEDLINE, Embase, Web of Science, and Cochrane databases to identify biomechanical studies examining the application of tendon transfer to augment shoulder external or internal rotation range of motion in the setting of concomitant RTSA. A descriptive synthesis of six included articles was conducted to elucidate trends in the literature.
Results: Biomechanics literature demonstrates that increasing humeral-sided lateralization optimized tendon transfers performed for both ER and IR. The optimal latissimus dorsi (LD) transfer site for ER is posterior to the greater tuberosity (adjacent to the teres minor insertion); however, LD transfer to this site results in greater tendon excursion compared to posterodistal insertion site. In a small series with nearly 7-year mean follow-up, the LD transfer demonstrated longevity with all 10 shoulders having > 50% ER strength compared to the contralateral native shoulder and a negative Hornblower's at latest follow-up; however, reduced electromyography activity of the transferred LD compared to the native contralateral side was noted. One study found that transfer of the pectoralis major has the greatest potential to restore IR in the setting of lateralized humerus RTSA.
Conclusion: To restore ER, LD transfer posterior on the greater tuberosity provides optimal biomechanics with functional longevity. The pectoralis major has the greatest potential to restore IR. Future clinical investigation applying the biomechanical principles summarized herein is needed to substantiate the role of tendon transfer in the modern era of lateralized RTSA.
Level of evidence: IV; systematic review.

1. Introduction

While alleviation of pain and overall restoration of shoulder function can be reliably achieved with reverse total shoulder arthroplasty (RTSA) [1–3], restoration of active axial (external and internal) rotation can be more challenging to consistently attain. Internal rotation (IR) is critical to patients' ability to perform activities of daily living (ADLs), which include perineal hygiene, reaching their back pocket, washing their back, and fastening a bra. Similarly, external rotation (ER) is crucial to position the hand in space and to perform ADLs such as eating, facial grooming, and holding a phone to the ear [4,5]. Poor IR is often attributed to a torn or unrepaired subscapularis, whereas poor ER is attributed to an atrophied or incompetent infraspinatus and teres minor. Given that loss of axial rotation can occur in either ER or IR, tendon transfers performed during RTSA have been proposed as a solution to correct rotational deficits with generally positive but often inconsistent results [6–10].

Several tendon transfers and insertion sites on the proximal humerus have been described to restore both IR and ER. However, there is no consensus on the optimal tendon and transfer site to maximize either ER or IR in patients with rotational deficiency.

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While clinical reports have been published describing the clinical outcome of tendon transfer during RTSA [11–17], the majority is non-comparative and has limited patient samples. Moreover, the influence of implant lateralization on the biomechanics of tendon transfer is seldom considered.

The purpose of this study was to systematically review the available biomechanical evidence informing the ideal tendon transfer and insertion site for restoration of axial rotation in the setting of RSA and the influence of implant lateralization.

2. Materials and methods

This systematic review was performed in accordance with the guidelines for Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [18].

2.1. Eligibility criteria

We included original biomechanical studies written in English and published prior to November 2022 evaluating the application of tendon transfers to augment shoulder range of motion in the setting of concomitant RTSA. A study was considered biomechanical in nature if it assessed the mechanics (e.g., moment arm, line of action) or muscle properties (e.g., activation patterns) after tendon transfer. Studies were excluded on the basis of being:

- duplicate;
- non-English text;
- review or meta-analysis;
- case report/series reporting < 5 patients;
- commentary or editorial;
- pure radiographic, solely concerned on surgical technique, or non-human;
- no RTSA implantation with concomitant tendon transfer;
- allograft-prosthetic composite reconstruction.

2.2. Search strategy

We searched the PubMed/MEDLINE, Embase, Web of Science, and Cochrane databases for articles that had been published through November 2022, using the following terms: “tendon”, “transfer”, “l’Episcopo”, “teres”, “latissimus”, “pectoralis”, “reverse”, “inverted”, “shoulder” (Appendix A for database-specific search strategies). After excluding duplicates, titles and abstracts were examined, and studies that obviously violated eligibility criteria were excluded; when questionable, we erred on the side of inclusion. Subsequently, full-texts of the remaining articles were reviewed and eligibility criteria were applied. Of note, studies were excluded for being clinical rather than biomechanical during full-text screening, but not title and abstract screening. This process was performed by two authors (KAH and KMH); disagreements were resolved by discussion between the two authors until consensus was reached. In addition, a single author (KAH) reviewed the reference lists of included studies for additional articles meeting eligibility criteria.

2.3. Synthesis

Meta-analysis was not performed because of the inherent heterogeneity of biomechanical data and the laboratory and testing conditions utilized. Instead, a descriptive qualitative synthesis was performed.

3. Results

3.1. Search results

The search returned 394 publications, of which 199 were found to be unique following duplicate exclusion. We excluded 167 articles during title and abstract screening, leaving 32 articles for full-text review. We excluded 26 articles during full-text screening, initially yielding six articles for inclusion. No additional studies were identified from cross-referencing and hand searching. Fig. 1 illustrates the selection process for included studies, which are tabulated in Table 1.

3.2. Implant lateralization

Chan et al. [19] implanted a custom onlay RTSA that allowed for varying humeral-sided lateralization into eight cadaveric shoulders to assess the influence of humeral lateralization on rotational torque after latissimus dorsi (LD) and lower trapezius transfers for ER and pectoralis major transfer for IR. LD and lower trapezius transfers were inserted to the posterolateral greater tuberosity (GT) adjacent to the footprint of the teres minor. The pectoralis major was transferred to the most anterior aspect of the lesser tuberosity (Fig. 2A). In shoulder adduction, the authors found that the lower trapezius transfer generated on average 1.6 ± 0.2 nm more torque than the LD transfer ($p < 0.001$). Furthermore, the moment arms of all tendon transfers were optimized with greater humeral component lateralization.

3.3. Optimal LD transfer insertion site for ER

Favre et al. [20] implanted an RTSA using the anatomical shoulder replacement system (Zimmer Inc, Warsaw, IN) with 20° of humeral retroversion and neutral baseplate version in a single cadaver. The authors compared the ER moment arm for the transferred LD at three different insertion sites: anterior to the GT in the bicipital groove, posterolateral (PL) to the GT, and posterodistal (PD) to the GT (Fig. 2B). The humerus was positioned in 90° of scapular plane elevation (53° glenohumeral elevation and 37° scapular lateral rotation) and changes in the axial rotation moment arms were recorded as the humerus was externally rotated from 0 to 90°. Additionally, ER moment arms were measured when the arm was positioned for eating and combing. From 20–90° of ER and for both ADLs, the insertion site PL to the GT (adjacent to the teres minor insertion) provided the greatest ER moment arm. At this site, the authors estimated the LD could generate a 7- and 9-times greater ER moment arm during eating and hair combing compared to the teres minor.

Nicholson et al. [21] utilized the Newcastle Shoulder Model to simulate implantation of a Delta III (DePuy, West Chester, PA, USA) RTSA (medialized glenoid, medialized humerus) and LD transfer to the three sites previously described by Favre et al. [20] previously (Fig. 2C). In shoulder adduction, the PL site had a 5–10 mm greater ER moment arm from 10–90° of ER compared to anterior and PD insertion sites. When abducted to 90°, anterior and PL insertion sites produced ER moment arms 10–15 mm greater from 0–90° ER compared to the PD site. Additionally, despite low force generation from the transferred LD, their model predicted that the required posterior deltoid force generation for ER in the absence of the teres minor would dramatically decrease with LD transfer versus without ($p < 0.001$); a greater reduction was seen for anterior and PL insertion sites compared to PD ($p = 0.023$ and $p = 0.021$, respectively). However, anterior (40.9 ± 2.9 mm, $p < 0.001$) and PL (13.0 ± 6.8 mm, $p = 0.035$) also significantly elongated the LD tendon, whereas transfer to the PD site retained the native tendon length ($p = 0.689$).

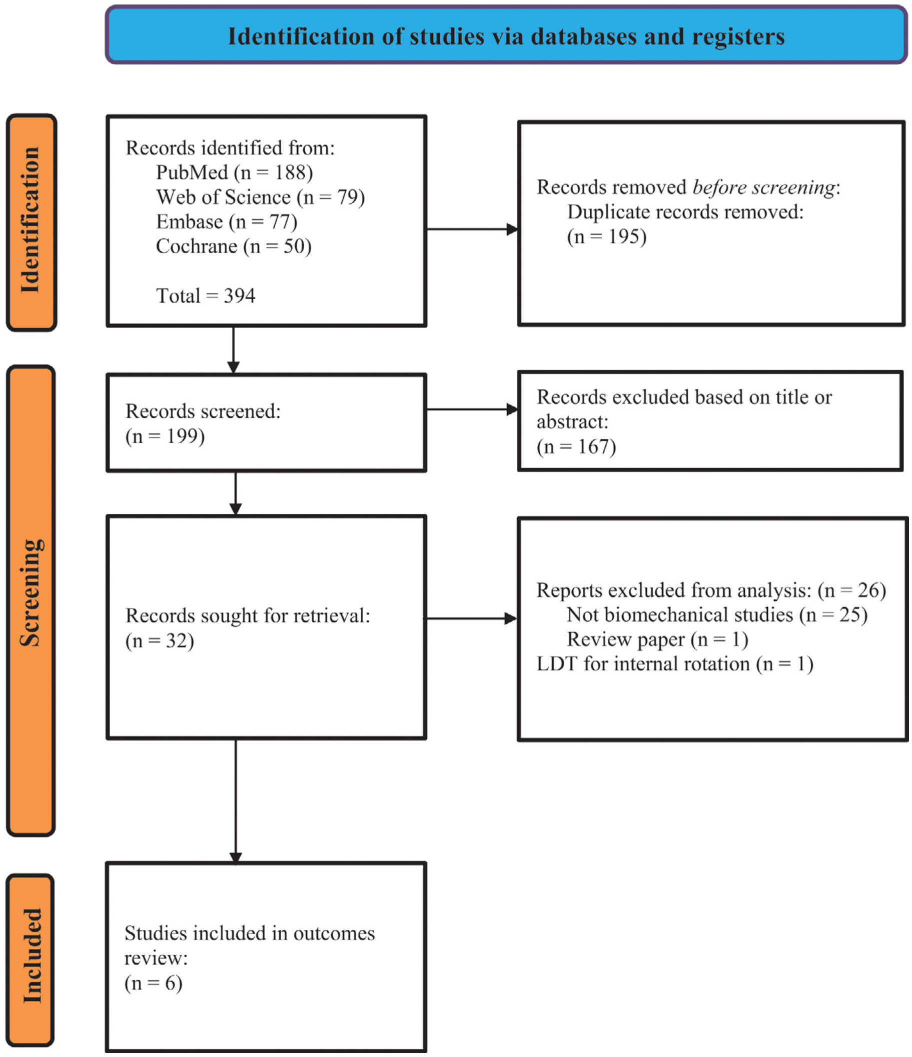

Fig. 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram depicting article identification, subsequent exclusion, and analysis.

Table 1
Included studies.

Author (year)	Title	Journal	Study design
Chan et al. (2020)	Latissimus dorsi tendon transfer in reverse shoulder arthroplasty: transfer location affects strength	*JSES International*	Cadaveric ($n = 8$)
Alonso-Rodriguez Piedra et al. (2022)	Reverse total shoulder arthroplasty with latissimus dorsi and teres major transfer: biomechanical and electromyographical outcomes	*European Journal of Orthopaedic Surgery & Traumatology*	Clinical biomechanics ($n = 10$)
Werthel et al. (2021)	Biomechanical effectiveness of tendon transfers to restore active internal rotation in shoulder with deficient subscapularis with and without reverse shoulder arthroplasty	*Journal of Shoulder Elbow Surgery*	Cadaveric ($n = 6$)
Chan et al. (2022)	The biomechanical effectiveness of tendon transfers to restore rotation after reverse shoulder arthroplasty: latissimus versus lower trapezius	*Shoulder & Elbow*	Cadaveric ($n = 8$)
Nicholson et al. (2022)	Biomechanical comparison of 3 latissimus dorsi transfer sites for reverse total shoulder arthroplasty in the absence of teres minor	*Journal of Shoulder Elbow Surgery*	Computer model; Newcastle Shoulder Model
Favre et al. (2008)	Latissimus dorsi transfer to restore external rotation with reverse shoulder arthroplasty: a biomechanical study	*Journal of Shoulder Elbow Surgery*	Cadaveric ($n = 1$)

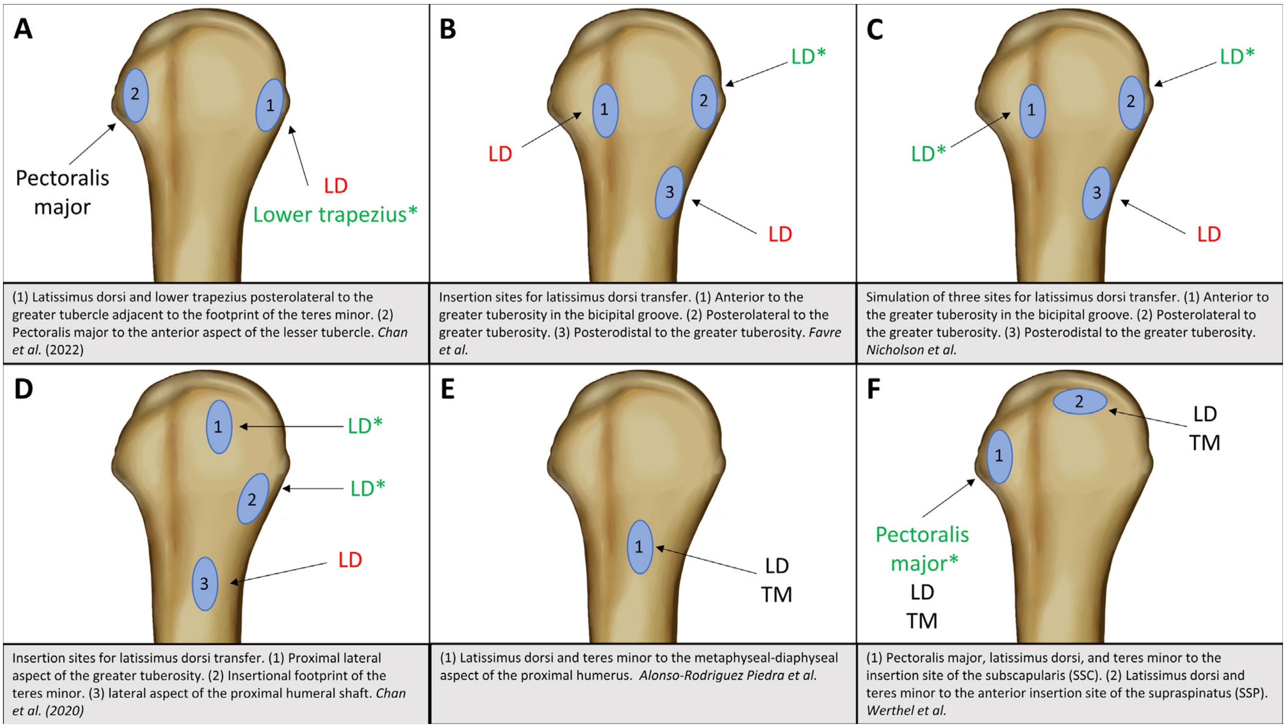

Fig. 2. Tendon transfer insertion sites described in the six included biomechanical studies. When comparisons between transfers were made by studies, the best tendon and transfer site are denoted by green text and an asterisk while its comparator is denoted in red text. Black text indicates no comparisons were made. LD: latissimus dorsi; TM: teres major.

Chan et al. [22] implanted a custom RTSA that allowed for varying humeral-sided lateralization into eight cadaveric shoulders to assess the influence of LD insertion site on ER torque (Fig. 2D). They found significantly greater ER torque when inserted at the proximal lateral aspect of the GT and insertional footprint of the teres minor compared to the lateral aspect of the proximal humeral shaft (across from the native insertion site of the LD). Additionally, lateralization of the humeral component increased the ER torque for all insertion sites.

3.4. Muscle adaptation after tendon transfer

Alonso-Rodriguez Piedra et al. [23] reviewed 10 RTSAs with concomitant LD and teres major (TM) transfer for combined loss of active elevation and external rotation (CLEER) pathology and assessed bilateral shoulder rotation strength and performed fine needle electromyography (EMG) of the LD and TM (Fig. 2E). At a mean follow-up of 81 months (range, 42–136 months), all patients had ER strength > 50% of the contralateral native shoulder and negative Hornblower's test and ER lag signs. EMG of the LD and TM did not differ between treated and untreated shoulders, suggesting that both muscles adapt to their new function. However, the LD in the treated shoulder showed greater activation in its native function (i.e., backward flexion) than in its acquired function (ER).

3.5. Comparison of tendon transfers and insertion sites for internal rotation

Werthel et al. [24] evaluated the IR moment arm of five tendon transfer pairs with and without implantation of a lateralized humerus/lateralized glenoid RTSA (comprehensive; Zimmer-Biomet, Warsaw, IN, USA) without subscapularis repair (to simulate deficiency) in six cadavers. Tendon transfer pairs evaluated were pectoralis major (PM) to the insertion site of the subscapularis (SSC), LD to the anterior insertion site of the supraspinatus (SSP) tendon on the GT, LD to the subscapularis insertion, TM to the anterior insertion site of the SSP, and TM to subscapularis insertion (Fig. 2F). The IR moment arms differed significantly between the native shoulder and after RTSA. In shoulder adduction after RTSA, the PM-SSC had a significantly greater IR moment arm compared to other transfers ($p < 0.001$ for all). In 90° of shoulder abduction after RTSA, the IR moment arm was significantly greater for the PM-SSC, LD-SSP, and TM-SSP compared LD-SSC and TM-SSC ($p < 0.001$ for all). These results demonstrated that biomechanical results of tendon transfers performed in native cadaver studies (i.e., without RTSA) cannot be applied to shoulders with RTSA. The authors concluded that transfer of the PM is the most efficient to restore IR in the setting of lateralized humerus/lateralized glenoid.

4. Discussion

Results of the six included articles demonstrated that increasing humeral-sided lateralization optimized tendon transfers performed for both ER and IR. The reported optimal LD transfer site biomechanically for ER is posterior to the greater tuberosity (adjacent to the teres minor insertion). However, transfer to this site resulted in greater tendon excursion compared to posterodistal insertion site. In a small clinical series with nearly 7-year mean follow-up, the LD transfer to a site lateral and distal (Fig. 2E) demonstrated longevity with all 10 shoulders having > 50% ER strength compared to the contralateral native shoulder and negative Hornblower's; however, EMG differences were noted between the transferred and contralateral native LD. In the setting of lateralized RTSA, pectoralis major transfer to the subscapularis insertion site has the greatest biomechanical potential to restore IR.

The indications to perform concomitant tendon transfer are frequently debated and lack consensus. While the original Grammont-style RTSA demonstrated poor restoration of ER [13], modern lateralized RTSA have demonstrated improved ER leading some surgeons to believe that adequate tensioning of the posterior deltoid and remaining posterior rotator cuff as well as increased impingement-free range of motion with a lateralized construct is sufficient to provide a functional range of ER [25,26]. Berglund et al. [25] retrospectively reviewed patients that underwent lateralized RTSA (reverse shoulder prosthesis, DJO surgical) without LD transfer with combined loss of active elevation and ER either secondary to rotator cuff tear arthropathy (CLEER group; $n = 24$) or a post-traumatic etiology (non-CLEER group; $n = 9$). The authors found significant improvement in ER in both CLEER and non-CLEER groups from pre- to postoperative assessment at a mean 43.4 months (range, 24 to 77 months) follow-up (CLEER: -21° to 28°, $p < 0.001$; non-CLEER: -19° to 26°, $p < 0.001$). The mean Goutallier classification for included patients in the CLEER and non-CLEER groups were 3.6 ± 0.7 and 2.6 ± 1.3 for the infraspinatus and 2.2 ± 1.4 and 0.6 ± 1.0 for the teres minor, respectively. While these results are promising, given the significant pathology of the posterior rotator cuff and relatively short-term follow-up of this report, the longevity of ER restoration after lateralized RTSA alone may potentially be shorter-lived compared to the longevity of ER after RSA with tendon transfer given the demonstrated function and muscle adaptation reported by Alonso-Rodriguez Piedra et al. [23] However, longer-term follow-up is needed to substantiate this hypothesis.

Young et al. [26] reported the 2-year clinical results of 22 patients with CLEER that were randomized to receive either a RTSA alone (either Zimmer Trabecular Metal Reverse Shoulder System or Biomet Comprehensive Reverse Arthroplasty System) or RTSA with LD-TM tendon transfer. The teres minor was torn in 67% of patients receiving RTSA alone and 81% of patients undergoing RTSA with LD-TM transfer ($p = 0.620$). CLEER was diagnosed in patients that had loss of active shoulder elevation above 110°, a positive Hornblower sign, and teres minor fatty infiltration of grade 2 or higher. A positive Hornblower sign was specifically defined as the inability of the patient to actively hold the arm in abduction and ER for 3 seconds, and the test result was considered positive if the arm dropped more than 30°. The primary outcome was the activities of daily living which require ER (ADLER) score at 2-year follow-up, which was 29.5 in both the 12 patients that underwent RTSA with LD-TM transfer and 10 patients that underwent RTSA alone ($p = 0.863$). Active ER at 2-year follow-up was reported for 12/22 patients; the median active ER in 5 patients that received RTSA with LD-TM transfer was 80° (interquartile range, 45–90°) versus 70° (60–90°) in the seven patients that received RSA alone ($p = 0.373$). Although this study provides compelling data, it has significant limitations. The ADLER score has not been validated, has no previously defined minimal clinically important difference (MCID), and the authors arbitrarily chose a 20% difference in its score for the power analysis. Additionally, the sample size was very small, only 50% of the RTSA with LD-TM transfer had 2-year follow-up, patients were not blinded to treatment, and Hamada scores differed between groups. In a letter to the editor, Boileau et al. [27] further pointed out limitations related to patient selection, statistics, and interpretation of results; these authors concluded they will continue performing RTSA with LD-TM transfer in CLEER patients with no teres minor. A counter-response to this letter was written by Young et al. [28]. A further consideration not discussed in these correspondences is the influence of implant design; while the 0 mm lateralized offset variations of the included prostheses were reportedly used, the Zimmer Trabecular Metal Reverse Shoulder System is a medialized glenoid/medialized humerus design whereas the Biomet Comprehensive Reverse Arthroplasty System is a lateralized glenoid/lateralized humerus design per Werthel et al. [29]. There is no description in the study about which prostheses patients in each arm received and patients were operated on by three different surgeons. This heterogenous clinical data makes it difficult to formulate accurate clinical indications for using tendon transfers in RTSA.

Both Berglund et al. [25] and Young et al. [26] have provided important clinical insight. However, our review of the biomechanical literature performed herein provides further clarity on how ER in RTSA may be best restored. Studies by Chan et al. [19,22] suggest that in contrast to the historical use of a medialized RTSA when concomitant tendon transfer is performed, additional humeral-sided lateralization may improve the moment arm of the tendon transfer. Although demonstration clinically is needed, improvement in the ER torque may translate to improved ER in these patients. A recent meta-analysis performed by Hones et al. [30] found no difference in both postoperative ER and pre- to postoperative improvement in ER based on use of a medialized versus lateralized RTSA and whether the LD was transferred alone or together with the TM. However, limitations inherent to meta-analysis are important to consider, and thus we believe further investigation is warranted. An additional consideration is that while greater humeral-sided lateralization might intuitively provide a more favorable moment arm for torque generation from a transferred tendon, lateralization may alter the line of pull or increase tendon excursion thereby reducing the efficiency of the transferred tendon (i.e., fall off of the Blix curve) [31]. Increased tendon excursion from implant lateralization may be compounded by insertion to the posterolateral greater tuberosity, which biomechanical studies reviewed herein demonstrate provides the ideal ER moment arm but requires greater tendon excursion compared to insertion at the posterodistal site on the humerus. We propose the following critical question: how does restoration of ER in patients with CLEER compare when treated with lateralized RTSA alone versus medialized RTSA with tendon transfer (either LD alone or with concomitant TM) versus lateralized RTSA with tendon transfer? Until this question is answered clinically, both lateralized RTSA alone and RTSA with tendon transfer appear to be reasonable options to restore ER and are both supported in the literature.

The limitations of biomechanical studies should be considered. Cadaveric studies comparing different tendon transfers can quantify moment arms but do not account for differential force-generating capacities of involved muscles, which are not equal. Common to all cadaveric studies, the data are representative of time-zero effects; natural soft tissue adaptation that occurs in vivo is not accounted for. Different techniques and RTSA implants were used in the biomechanical studies, which may influence findings; however, we did not note any disagreements among included studies. Experimental laboratory conditions simplified the line of pull for the tendons evaluated; however, many of the muscles evaluated have broad origins and thus their function in vivo may not be accurately replicated. This is also a limitation of in silico studies, which represent muscles using sets of elastic lines with defined paths to constrain their location in space. Other limitations of in silico studies include representation of a single subject's anatomy, which may not extrapolate uniformly to individuals of different size and sex. Additionally, the influence of the posterior deltoid muscle as an external rotator was not addressed in any studies. While some included studies evaluated the influence of glenoid and humeral lateralization, none evaluated the influence of humeral version and thus we could not comment on its influence on rotation after RSA. However, prior clinical studies have demonstrated that modifications to humeral component version have little influence on shoulder rotation after RSA [32–34].

5. Conclusion

Increasing humeral-sided lateralization optimizes the moment arm of tendon transfers performed for both ER and IR. The optimal LD transfer site for ER is posterior on the greater tuberosity, although at the cost of greater tendon excursion. One small study demonstrated that functional longevity of the LD transfer is possible, although reduced EMG activity between transferred and native LD was noted. The pectoralis major has the greatest potential to restore IR in the setting of lateralized RTSA. Given the recent clinical controversy regarding the potential for lateralized RTSA alone to restore ER in preoperatively deficient patients, future clinical investigation applying the biomechanical principles summarized herein is needed to determine the role of tendon transfer in the modern era of lateralized RTSA.

Disclosure of interest

Mr. Hao is a paid consultant for LinkBio Corp. Dr. King is a consultant for Exactech, Inc. and LinkBio Corp. Dr. T. Wright is a paid consultant and receives royalties from Exactech, Inc. Dr. Schoch receives royalties from Exactech, Innomed and Responsive Arthroscopy. The other authors, their immediate families, and any research foundations 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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Authors' contribution

Study conception was performed by KAH, KMH, and BSS. Articles were screened for inclusion by KAH and KMH. The initial draft of the manuscript was written by KAH and KMH. All authors edited the initial manuscript draft and have approved the final article.

Artificial intelligence statement

No artificial intelligence was used for the writing of the submitted work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.otsr.2024.103903.

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