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The effect of humeral version on teres minor muscle moment arm, length, and impingement in reverse shoulder arthroplasty during activities of daily living

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Background: External rotation can be compromised after reverse total shoulder arthroplasty (RTSA). A functional teres minor (TM) is relatively common in patients with posterosuperior tears of the rotator cuff, and its function should be enhanced for better postoperative results. The aim of this study was to investigate how the version of humeral fixation can affect the TM rotational moment arm and muscle length as well as impingement after RTSA.
Methods: A 3-dimensional shoulder model was used to describe RTSA. Four humeral fixation versions were tested: +20°, 0°, −20°, and −40° (+, anteverted; −, retroverted). TM rotational moment arm and length as well as impingement-free range of motion were calculated for a set of 3 simple clinical motions: (1) scapula plane abduction (0°-150°); (2) internal/external rotation with the arm in adduction; and (3) internal/external rotation with the arm in abduction. Six common activities of daily living were also evaluated.
Results: An anteverted fixation maximized TM moment arms, but it also resulted in very short muscle length (compared with normal) and increased inferior impingement. In contrast, 40° humeral retroversion resulted in the longest TM muscle length, but it also showed the smallest moment arms and increased anterior impingement in some of the activities of daily living.
Conclusions: Even if TM external rotation moment arm is higher in RTSA than in a normal shoulder, the decreased length could impair its force generation. The 0° and 20° retroversion was the optimum compromise between sufficient TM length and moment arm with minimum impingement.
Level of evidence: Basic Science, Computer Modeling.

Keywords: Reverse shoulder arthroplasty; teres minor; humeral version; external rotation; moment arm; muscle length

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Reverse total shoulder arthroplasty (RTSA) is gaining popularity in the treatment of rotator cuff arthropathy.[21] Clinical data have shown that RTSA can relieve pain and improve arm function by restoring flexion and abduction.[4,8] However, several studies have also shown that external rotation can be compromised after RTSA.[5,19,20] This loss of external rotation may limit the patient's ability to perform common activities of daily living (ADLs) that require combined abduction and external rotation, such as eating or combing hair. Thus, the outcome of RTSA is influenced by the integrity of the external rotators, specifically the teres minor (TM).[21]

According to Grammont[9] and Boileau,[5] a potential solution to improve active external rotation is to increase humeral retroversion to improve the mechanical advantage of the TM, when it is present. However, no studies have focused on the ability of the TM to externally rotate the shoulder after RTSA. Biomechanical studies have investigated the effect of the humeral version (HV) on impingement-free range of motion (ROM),[11,14,15] and their results vary.

The purpose of this study was to evaluate TM rotational moment arms and muscle lengths after RTSA. Furthermore, we aimed to determine how changes in HV affected these variables and how they compared with a normal shoulder. Testing conditions consisted of standardized, arbitrary motions of the shoulder as well as more complex motions that were designed to simulate ADLs. Our hypothesis was that the muscle length of the TM and moment arm would be reduced after RTSA compared with the normal, native shoulder. We also hypothesized that these deficits could at least be partially corrected by increasing the retroversion of the humeral component of the prosthesis. This is clinically important because maximizing the function of the TM will improve the external rotation strength needed to perform ADLs.

Methods

Biomechanical computer model

A 3-dimensional (3D) biomechanical model, the Newcastle Shoulder Model,[6] was used for this investigation. The model represents a normal shoulder and includes 6 rigid segments (thorax, clavicle, scapula, humerus, radius, and ulna). The skeletal geometry of the segments derived from the reconstruction of the Visible Human data set.[22] 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.[1,16] These lines of action are modeled as elastic strings that wrap around standard shapes (e.g., cylinders and spheres) corresponding to the bone geometry (Fig. 1). Specialized software (SIMM; MusculoGraphics Inc, Santa Rosa, CA, USA) was used for the model visualization and muscle wrapping. The model that also includes the sternoclavicular, acromioclavicular, and glenohumeral joints can simulate the 3D scapula and clavicle

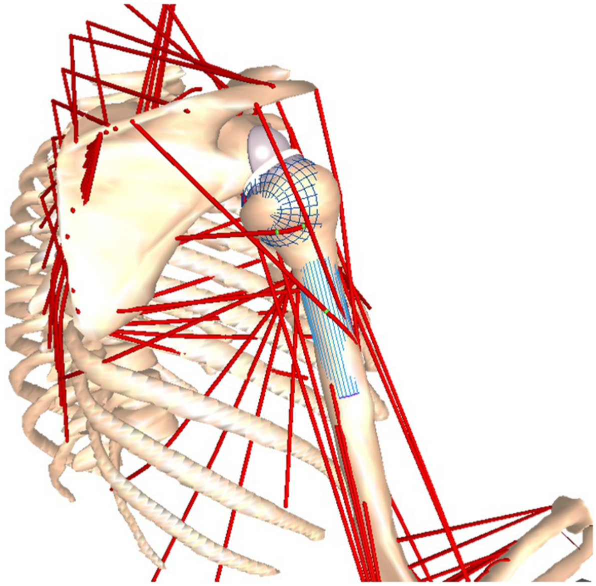

Figure 1 The Newcastle Shoulder Model representing an RTSA. The only active rotator cuff muscle in the model is the TM, which wraps around the humeral head.

kinematics and can compute the length and moment arm of any muscle over a predefined motion by the tendon-excursion method.[1,2]

For the current study, an adapted version of the Newcastle Shoulder Model that resembles the geometry of a commercially available reverse shoulder prosthesis (Delta III; DePuy Synthes, Lyon, France; Fig. 1) was also used as it was described by Kontaxis and Johnson.[18] The RTSA model was created by simulating a virtual surgery on the original Newcastle Shoulder Model by using all the appropriate surgical tools and following the standard surgical guidelines as they are described by the manufacturer. All the rotator cuff muscles were excluded from the RTSA model with the exception of the TM.

The shoulder model also uses a contact detection algorithm that can evaluate implant to bone or bone to bone impingement. There are a few studies to show how HV affects impingement in RTSA. In the current investigation, impingement was evaluated to understand how the change in HV can affect both TM function (moment arm and muscle length) and impingement.

Model setup and kinematic inputs

To understand how RTSA and humeral fixation can affect the biomechanical properties of the TM, its rotational moment arm and length were calculated and compared for different versions of the humeral component. Those values were also compared with normal anatomy to investigate how the RTSA geometry can affect the biomechanical properties of TM. The version angle was defined with the help of the epicondylar axis as shown in Figure 2. To simulate a retroverted fixation, the stem was implanted with a clockwise rotation, and vice versa. The different version setups that were tested in the study were +20° HV, 0° HV, −20° HV, and −40° HV (+, anteverted; −, retroverted).

The TM rotational moment arm and length data were computed for a set of kinematic profiles:

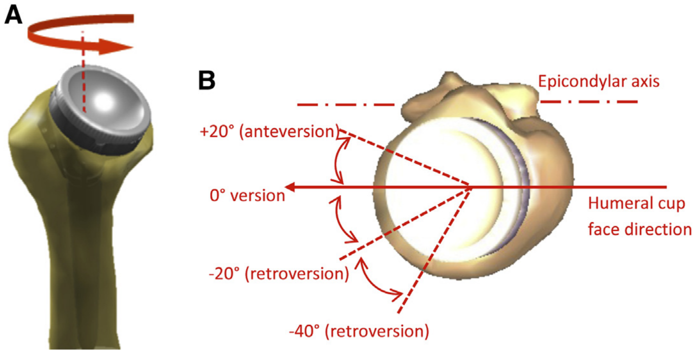

Figure 2 For the right humerus, the change of the version was achieved by rotating the implant along its long-stem axis. Clockwise rotation will result in retroverted fixation. The 0° version of the humeral fixation was defined in relation to the epicondylar axis.

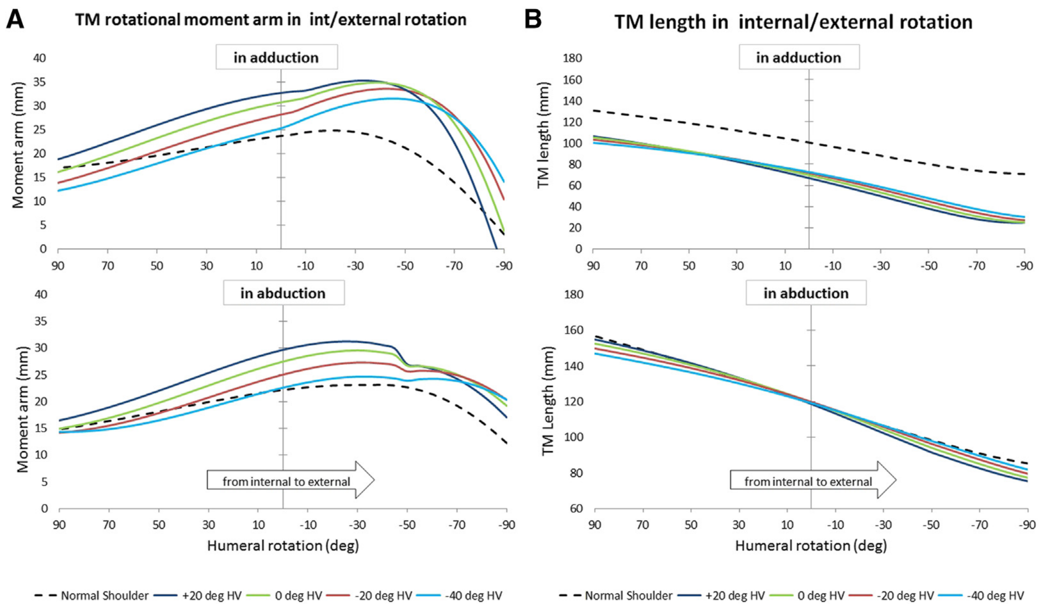

Figure 3 TM rotational moment arm (**A**) and muscle length (**B**) in the normal shoulder and in RTSA with different degrees of humeral version, during external rotation in adduction and abduction.

Standardized simple motions that represent typical clinical tests:

- Humeral abduction in scapular plane from 0° to 150° (humerothoracic angles)
- Rotation in adduction: with the arm elevated only 20° in the frontal plane, the humerus rotates from +90° internal rotation to −90° external rotation (− indicates external rotation, + indicates internal rotation)
- Rotation in abduction: with the arm elevated 90° in the frontal plane, the humerus rotates from +90° internal rotation to −90° external rotation

ADLs:

- Task 1: reaching the contralateral shoulder
- Task 2: reaching opposite side of neck
- Task 3: drink from a mug
- Task 4: talking on the phone
- Task 5: combing hair
- Task 6: reaching overhead

The kinematic profiles of the ADLs were extracted from a larger kinematics database that was originally used to compare kinematic differences between normal controls and RTSA subjects.[17] The kinematics were recorded by a motion analysis system (8 cameras, VICON 512; VICON Motion Systems Ltd, Oxford, UK) and performed by healthy individuals. Reflective markers were attached on the torso (xiphoid, manubrium, seventh cervical vertebra, and eighth thoracic vertebra), humerus (cluster of 3 medially), and forearm (cluster of 3 distally), and anatomic landmarks and coordinate definitions were determined according to the recommendations of the International Society of Biomechanics.[26]

Results

Moment arm

For the simple standardized motions (rotations in adduction and in abduction), results showed that RTSA increases the rotational moment arm of the TM (Fig. 3, *A*). The increase was bigger for rotation in adduction than for rotation in

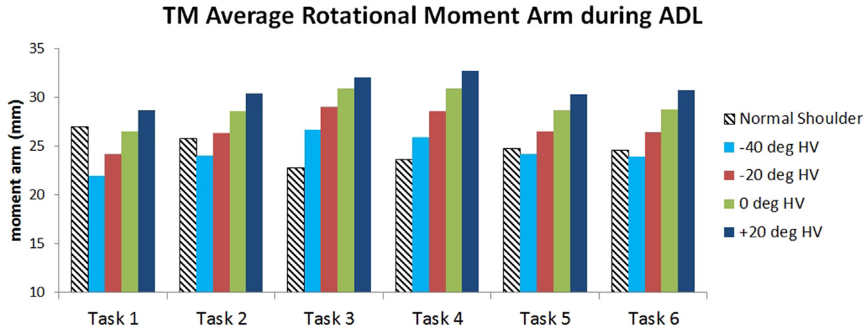

Figure 4 Average TM moment arm results for the normal shoulder and RTSA with −40°, −20°, 0°, and +20° HV.

abduction. The TM moment arm averaged 19.4 mm for rotation in adduction for the normal shoulder, whereas for RTSA, it was 23.0 mm, 24.8 mm, 26.1 mm, and 26.5 mm for −40°, −20°, 0°, and +20° HV, respectively. For rotation in abduction, the TM in the normal shoulder was 19.6 mm; for RTSA, it was 20.5 mm, 22.1 mm, 23.6 mm, and 24.9 mm for −40°, −20°, 0°, and +20° HV, respectively.

The degree of HV influenced the magnitude of the TM moment arm in the RTSA. During external rotation with the arm in adduction, the moment arm reached its highest values when the humeral component of the prosthesis was placed at 20° of anteversion (35.1 mm, at 35° of external rotation). Whereas 0° of HV had a similar peak value (34.9 mm, at 40° of external rotation), −20° and −40° of HV showed smaller maxima (33.6 mm and 31.5 mm, respectively) at 45° of external rotation. The moment arm values were constantly decreased after the peak value (and as the humeral external rotation was increasing), but a more rapid drop was observed for the +20° HV fixation compared with the other HVs (Fig. 3, *A*).

During the complex motions of the ADLs, the TM moment arms differed between the RTSA and the normal shoulder, but the relationship varied. For two of the ADL motions, "reaching the contralateral shoulder" and "drinking from a cup," the moment arm curves in the RTSA group started at higher values compared with the normal shoulder but then dropped to smaller values throughout the remainder of the cycle of motion (Supplemental Fig. 1). For the rest of the ADL motions, the RTSA had an increased TM moment arm, but the difference was highly dependent on the degree of HV. The greatest moment arm in every complex motion tested for the RTSA was achieved when the humeral component was placed in 20° of anteversion and the lowest for 40° of humeral retroversion (Fig. 4). The average difference between each version was 7.4% (biggest increase was noted between −40° and −20° HV with 9.1%, followed by −20° to 0° HV with 7.6%, followed by 0° to +20° HV with 5.7%). Compared with a normal shoulder, the average TM moment arm was increased in tasks 3, 4, 5, and 6 when RTSA was placed in +20°, 0°, and −20° of HV. For −40° of HV, the average moment arm was smaller than in the normal shoulder in 4 of the 6 ADLs (tasks 1, 2, 3, and 4). For task 1 only, RTSA +20° HV achieved a larger average TM moment arm compared with the normal shoulder (Fig. 4).

Length

The RTSA had an effect on TM length compared with the normal shoulder because its insertion was moved medially (by 26 mm) and distally (by 18 mm). For the simple motion "scapula plane abduction" and with the arm at the side (0° humeral abduction, TM resting length), the length of the TM was more than 20% shorter than in the normal shoulder and was reduced from 105 mm to 80 mm (RTSA; Fig. 5). However, as the arm was elevated, the length of the TM in RTSA increased at a higher rate compared with the normal shoulder. At 90° of humeral elevation, the TM had the same length for the normal shoulder and RTSA, whereas at the end of the motion (150° of humeral elevation), the RTSA length was 7.5% longer. HV in RTSA did not affect the TM length much for this motion (average difference of 1.1 mm between all HVs).

For the 2 rotational tasks (rotation in adduction and abduction), the patterns of the results were similar. The shortest TM length for the normal shoulder was observed in 90° of external rotation in adduction (71 mm; Fig. 3, *B*). The equivalent value for RTSA ranged from 25 mm (RTSA +20° HV) to 31 mm (RTSA −40 HV°). This is an average of 62% reduction of TM length compared with the normal shoulder. For the task "rotation in abduction," the length of the TM in RTSA was close to that of the normal shoulder (Fig. 3, *B*). The version of RTSA had a small effect on the TM length, with the −40° HV having the highest values in external rotation (8 mm longer compared with +20° HV).

During the ADLs, the length of the TM in the RTSA ranged within the maximum and the minimum length of the TM in the normal shoulder but varied with the version of the humeral stem (Table I). However, the shortest length of TM for +20° HV was 80 mm, which is 24% lower than the resting length and 10% shorter than the −20° and −40° HV. In every ADL motion tested, the biggest decrease in length of the TM between the RTSA and the normal shoulder was found with use of +20° HV; the smallest was found with

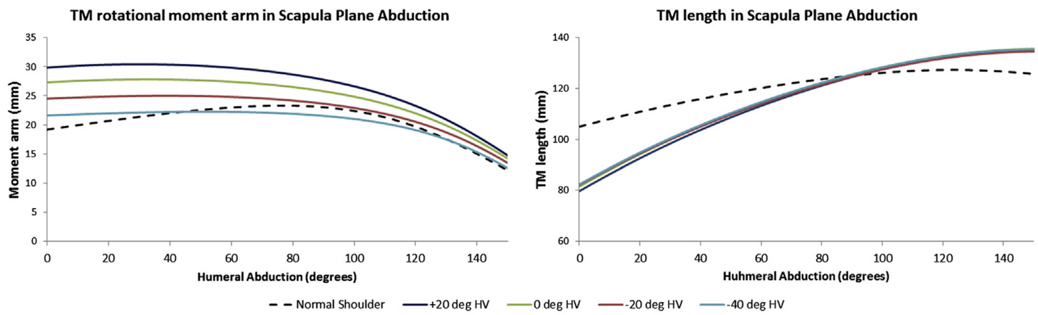

Figure 5 TM rotational moment arm and length in the normal shoulder and in RTSA with different degrees of humeral version in the task ''scapula plane abduction''.

Table I Minimum and maximum values of TM muscle length during ADLs

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
	Minimum TM length values (mm)					
Normal shoulder	105	105	108	108	106	110
+20° HV	80	81	93	92	83	91
0° HV	85	85	95	95	85	93
−20° HV	87	87	97	96	87	94
−40° HV	89	89	98	96	88	94
	Maximum TM length values (mm)					
Normal shoulder	147	137	117	114	132	131
+20° HV	143	137	111	102	133	136
0° HV	143	138	113	104	134	137
−20° HV	142	138	115	106	135	137
−40° HV	140	137	115	107	134	137

TM, teres minor; *HV*, humeral version; +, anteverted; −, retroverted. Task 1: reaching the contralateral shoulder; task 2: drinking from a cup; task 3: combing hair; task 4: talking on the phone; task 5: brushing teeth; task 6: reaching overhead.

use of −40° HV. On average and during every motion of the ADLs, the decrease of TM length between normal and RTSA shoulders was 5.0% (SD, 2.0), 5.3% (SD, 2.2), 6.2% (SD, 2.5), and 7.8% (SD, 2.9) for −40°, −20°, 0°, and +20° HV (standard deviation [SD] across all tasks; Fig. 6). The most noticeable difference was observed during the task of talking on the phone and for −40° HV, in which the TM length was on average 13.2% shorter compared with the normal shoulder.

Impingement

The impingement results for the task ''scapula plane abduction'' showed that ROM was limited by the contact of the humeral cup with the scapula inferior border (inferior impingement) and the contact of the humerus with the acromion (superior impingement). RTSA with −40° HV had the larger ROM, and the +20° HV had the smallest (Table II).

In the 2 rotation tasks (in adduction and abduction), the impingement-free ROM was limited only by the contact of the cup to the scapula, either to the anterior or to the posterior border of the glenoid vault (there was no contact of the humerus to the acromion). On average, rotation in adduction had smaller ROM than rotation in abduction (65° vs 153°, *red* vs *blue* in Fig. 7, *A*). The results showed that maximum ROM was achieved at −20° HV for both motions (71° and 169° ROM for adduction and abduction, respectively). In general, increased retroversion increased external rotation and decreased internal rotation (and vice versa).

For the ADL tasks, there was contact of the humeral cup with either the inferior scapula border (named inferior impingement) or with the anterior-superior border of the glenoid (named anterior impingement). The contact detection algorithm calculated the percentage of inferior and anterior impingement during each cycle of ADLs. The average results (all ADLs) showed that anteversion (+20° HV) decreased the anterior impingement, whereas retroversion (−40° HV) decreased the inferior impingement (Fig. 7, *B*). The total impingement (inferior and anterior) was minimum for 0 and −20° of HV, but the ratio of inferior to anterior impingement was different for those fixations (Fig. 7, *B*).

Discussion

The TM is one of the essential muscles to externally rotate the arm in patients who have undergone RTSA.[5] Functional external rotation is necessary to perform many ADLs, whereas TM deficiency has been associated with lower postoperative Constant scores.[21]

RTSA changes the biomechanics of the shoulder joint and provides the deltoid with a larger moment arm by medializing the center of the glenohumeral rotation.[14,18,24] However, RTSA can also adversely affect the performance of the other muscles crossing the glenohumeral joint that are responsible for rotational movements, such as the TM. In the normal shoulder, the humeral shaft axis lies close to the rotational center of the glenohumeral joint (center of humeral head). However, in RTSA, this relationship changes because the humeral axis is farther away from (lateral of) the center of rotation (center of glenoid

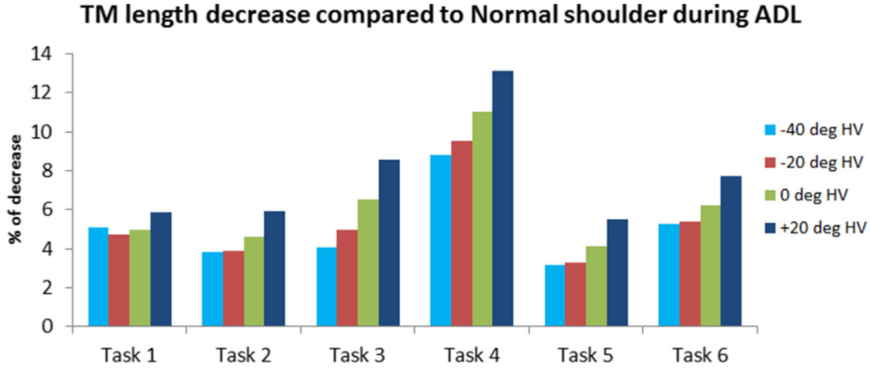

Figure 6 The average percentage decrease of TM length from normal to RTSA during ADLs. In general, retroverted fixation (−40° HV, *light blue*) had the longest overall TM length and thus showed the smallest decrease compared with normal.

Table II Impingement results for the motion "scapula plane abduction"

	Scapula plane abduction			
	−40° HV	−20° HV	0° HV	+20° HV
Impingement (degrees)				
Inferior	16	20	25	33
Superior	137	131	127	128
Range	121	111	102	95

As the humerus elevates (humerothoracic elevation from 0° to 150°), inferior impingement is the lowest value of humeral elevation (in degrees) at which the cup does not contact the scapula border. Superior impingement is the highest value of humeral elevation (in degrees) at which there is no contact between the humerus and the acromion.

sphere). A simple humeral rotation in RTSA results in the humeral shaft axis moving in an arc, the size of which depends on the geometry of the reverse prosthesis (e.g., size of sphere, neck-shaft angle, poly insert thickness). This change in geometry explains the larger values of TM moment arm compared with the normal shoulder. This effect was bigger when the humerus was in low degrees of elevation.

The mechanism is explained in Figure 8: because of the RTSA geometry, a change in the HV means that the cup has to adapt to a different position on the sphere to satisfy the kinematic constraints (center of cup and sphere are coincident). This affects the moment arm of the TM muscle (the line of action of the muscle is closer or farther away from the center of rotation). For example, with the arm at rest, 20° of humeral retroversion will result in a more anterior placement of the cup and humerus. This shifts the action of the muscle closer to the center of rotation and as a result reduces the TM moment arm (Fig. 8). However, this effect varies by the humeral position.

Muscle capability after RTSA is influenced by the possibility of maintaining good muscle tension. Muscle behavior is explained by the concept of a length-tension curve first presented by Blix in 1894.[3] The optimal muscle length yields maximum force output; shortening of a muscle will decrease the force capacity of the muscle over a given ROM.

This study analyzed the TM rotational moment arms and muscle lengths after RTSA with use of different HVs and compared them with the TM in a normal shoulder. To our knowledge, this is the first study on this topic. Other authors[10,15] analyzed how RTSA changes muscle moment arms and origin to insertion distance, but they did not focus on the role of the HV. Herrmann et al[15] used a combined in vitro/in silico approach to calculate moment arms for the subscapularis and TM and explained the clinically observed impaired external and internal rotation. However, the study was performed only with the humeral component implanted with 10° of retroversion. In the study of Greiner et al,[10] the preservation of rotational moment arms and muscle pretension after lateralized RTSA was investigated by setting the humeral angle to 10° in all specimens. Some biomechanical studies investigated the relationship between HV and impingement-free ROM along with muscle forces in abduction and intrinsic stability.[7,11,14,23] However, no study has considered TM moment arms and lengths during shoulder rotation. Moreover, this study investigated TM moment arm and length during ADLs together with the effect of HV on impingement.

The performance of a muscle during a complex, multiplane movement can be variable, depending on the position of the arm in space. To have a complete picture of how the TM moment arm changes under different HVs, this study analyzed standardized as well as ADL kinematics data that were previously recorded from a motion capture system. This allowed a more realistic evaluation of the performance of RTSA in terms of TM muscle moment arm in external rotation compared with a general analysis of standardized, one-plane activities alone.

RTSA increases TM external rotation moment arms compared with a normal shoulder. Such increase is less pronounced in high degrees of arm abduction. At the same time, because of humeral medialization, RTSA decreases TM length, especially in low degrees of humeral abduction. Herrmann et al[15] showed different results regarding TM

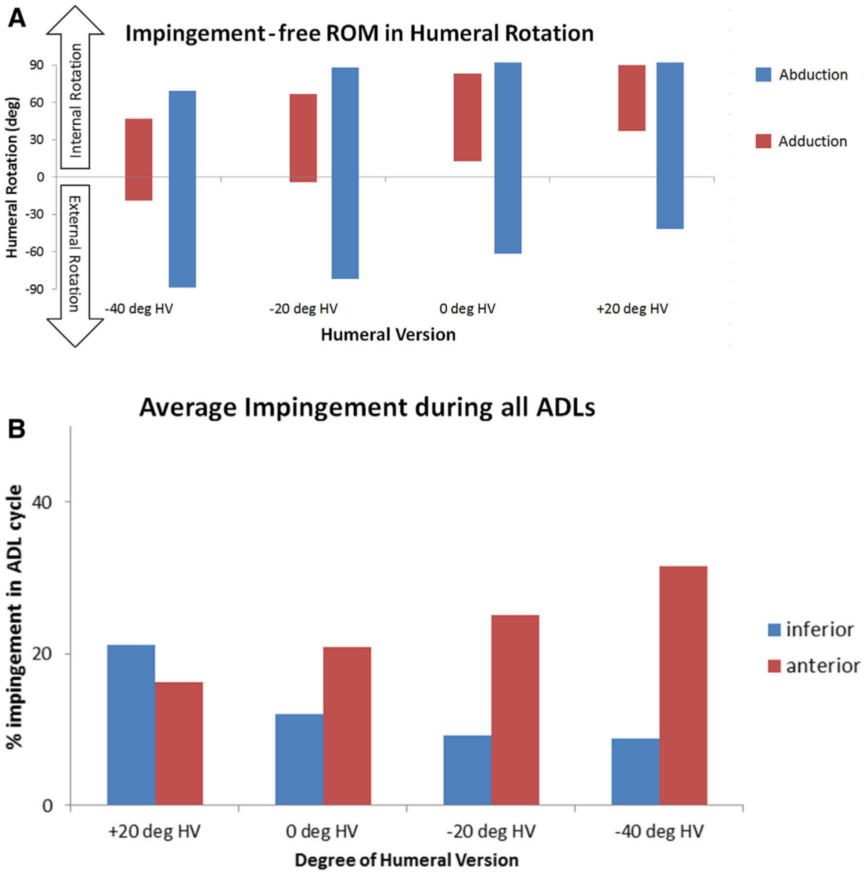

Figure 7 (**A**) Impingement-free rotational range of motion in abduction and in adduction for various degrees of HV. (**B**) Average inferior and anterior range of motion across all ADLs for various degrees of HV.

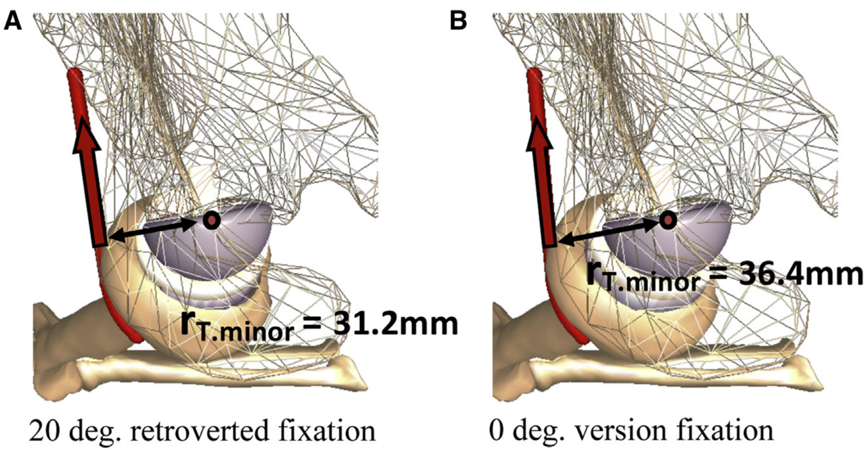

Figure 8 The version of the stem fixation can affect the rotational moment arm of the teres minor. For example, with the arm at rest, a 20° retroverted fixation (**A**) places the cup and the humerus in a more anterior position, decreasing its moment arm and increasing its length compared with 20° anteversion (**B**). However, this effect varies by the humeral position.

rotational moment arms. They used 3D models of the shoulder derived from computed tomography scans of 7 cadaveric specimens. They compared preoperative and postoperative TM rotational moment arms at various degrees of abduction (15°, 30°, 45°, and 60°). They found no difference at 15° of abduction and significantly smaller values with increasing abduction in the postoperative group. The discrepancy with our findings might be related to the prosthetic design. They used a polycarbonate resin model of a novel reverse prosthesis (Affinis Inverse; Mathys Ltd, Bettlach, Switzerland). The glenoid component had a 39-mm diameter (compared with the 42 mm of this study), and it was placed with a slight inferior overhang. However, the biggest difference compared with this study is that they did not consider muscle wrapping, which is shown to influence the outcomes of muscle moment arms in biomechanical models.[25] Moreover, Herrmann et al[15] used anatomy-based computer models derived from computed tomography scans of 7 cadaveric specimens. In the Newcastle Shoulder Model,[6] the skeletal reconstruction and parameterization were extracted from only one cadaver, the Visible Human data set,[22] and especially the anatomic transverse cryosections.

Moment arms, muscle lengths, and impingement should be considered together to explain the deficient external rotation observed in patients who have undergone RTSA. Even if the TM external rotation moment arm is higher in RTSA than in the normal shoulder, the decreased length could impair its force generation. Moreover, the impingement between the inferior scapular border and the polyethylene humeral cup represents a major problem for ROM.

The HV of the prosthesis had a large impact on impingement and ROM. In a simple scapula plane abduction, a retroverted fixation increases the impingement-free ROM, but only this information does not cover the complexity of the HV in impingement. As expected, when the humerus is rotated, a retroverted fixation increased the external ROM, and vice versa (anteverted fixation increased internal rotation). This reflected on the impingement during ADLs; a large retroverted fixation (−40° HV) resulted in heavy contact of the cup with the anterior-superior part of the glenoid, especially in the tasks in which the arm reaches the contralateral side (tasks 1, 2, and 5). However, the inferior impingement that was occurring during the beginning and end of each task was minimum when humeral fixation was at maximum retroversion.

On the basis of the results of this study, 0° and −20° HV showed the best compromise between improved function of TM (moment arm and length) and ROM (simple tasks and ADLs). This range of humeral fixation provides a good moment arm, both in adduction and in abduction, combined with an adequate muscle length. Twenty degrees of anteversion (+20 HV) allows greater rotational moment arm; however, it is associated with very short TM muscle length (especially in tasks and ADLs with low humeral elevation), which may reduce its efficiency because of slackening. A +20° HV may also result in increased risk of inferior impingement and creation of scapular notches.[5] On the contrary, an extreme retroverted fixation (−40° HV), even if it stretches the TM length closer to its normal shoulder length values, also results in a small TM moment arm (smaller in 4 of 6 ADLs compared with the normal shoulder). The same fixation will also result in heavy contact of the humeral cup with the anterior-superior glenoid border, especially in activities that bring the arm to the contralateral side.

One of the main goals of this study was to analyze the biomechanics of RTSA during ADLs. Limited external rotation is functionally debilitating when the shoulder is abducted. We tested motions that require the combined ability to elevate and externally rotate the shoulder in common hygiene, feeding, and everyday object activities. Our findings match previous information about impingement-free ROM and stability of RTSA. Biomechanical studies demonstrated that greater retroversion increased the amount of external rotation before impingement.[11] It has been suggested to place the humeral component in 0° to 20° of retroversion to maximize internal rotation with the arm at the side.[11] Moreover, little or no retroversion improves implant stability.[7]

However, there are limitations to the current investigation. The model represents the anatomy of a single individual, whose subjective characteristics determine TM moment arm and length. Thus, the absolute values recorded specifically refer to this subject, and statistical analysis is not possible. The study has analyzed only one type and one size of a reverse prosthesis (Delta III, size 42), and it is shown that different prosthesis designs can alter the biomechanical properties of RTSA.[12,13,17] Thus, the results of this study should be considered as implant dependent. However, this is a biomechanical study, and similar models (with only one skeletal geometry) have been previously used to explain the mechanism of various aspects of RTSA.[18,24]

Conclusions

The change in TM moment arm and length as well as the impingement that is observed in RTSA can explain the deficient external rotation that patients experience after RTSA. Even if the TM external rotation moment arm is higher in RTSA than in the normal shoulder, the decreased length could impair its force generation when the arm is in low levels of abduction. Active external rotation can be increased by optimizing the TM function with the most appropriate HV. In general, retroverted fixation will increase external ROM and the length of TM but will decrease its moment arm and increase the risk of anterior impingement. According to the results of this study, a placement of 0 or −20° HV presents the best compromise that can improve the function of TM and the ROM of RTSA.

Disclaimer

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jse.2014.08.019.

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