■ SHOULDER & ELBOW

SECEC Grammont Award 2024: The critical role of posture adjustment for range of motion simulation in reverse total shoulder arthroplasty preoperative planning

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Aims
The objective of this study was to compare simulated range of motion (ROM) for reverse total shoulder arthroplasty (RTSA) with and without adjustment for scapulothoracic orientation in a global reference system. We hypothesized that values for simulated ROM in preoperative planning software with and without adjustment for scapulothoracic orientation would be significantly different.

Methods
A statistical shape model of the entire humerus and scapula was fitted into ten shoulder CT scans randomly selected from 162 patients who underwent RTSA. Six shoulder surgeons independently planned a RTSA in each model using prototype development software with the ability to adjust for scapulothoracic orientation, the starting position of the humerus, as well as kinematic planes in a global reference system simulating previously described posture types A, B, and C. ROM with and without posture adjustment was calculated and compared in all movement planes.

Results
All movement planes showed significant differences when comparing protocols with and without adjustment for posture. The largest mean difference was seen in external rotation, being 62° (SD 16°) without adjustment compared to 25° (SD 9°) with posture adjustment ($p < 0.001$), with the highest mean difference being 49° (SD 15°) in type C. Mean extension was 57° (SD 18°) without adjustment versus 24° (SD 11°) with adjustment ($p < 0.001$) and the highest mean difference of 47° (SD 18°) in type C. Mean abducted internal rotation was 69° (SD 11°) without adjustment versus 31° (SD 6°) with posture adjustment ($p < 0.001$), showing the highest mean difference of 51° (SD 11°) in type C.

Conclusion
The present study demonstrates that accounting for scapulothoracic orientation has a significant impact on simulated ROM for RTSA in all motion planes, specifically rendering vastly lower values for external rotation, extension, and high internal rotation. The substantial differences observed in this study warrant a critical re-evaluation of all previously published studies that examined component choice and placement for optimized ROM in RTSA using conventional preoperative planning software.

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Introduction
In past decades, reverse total shoulder arthroplasty (RTSA) has emerged as a valuable option for various shoulder pathologies, restoring function and alleviating pain.[1,2] Despite the positive outcomes associated with RTSA, some patients encounter

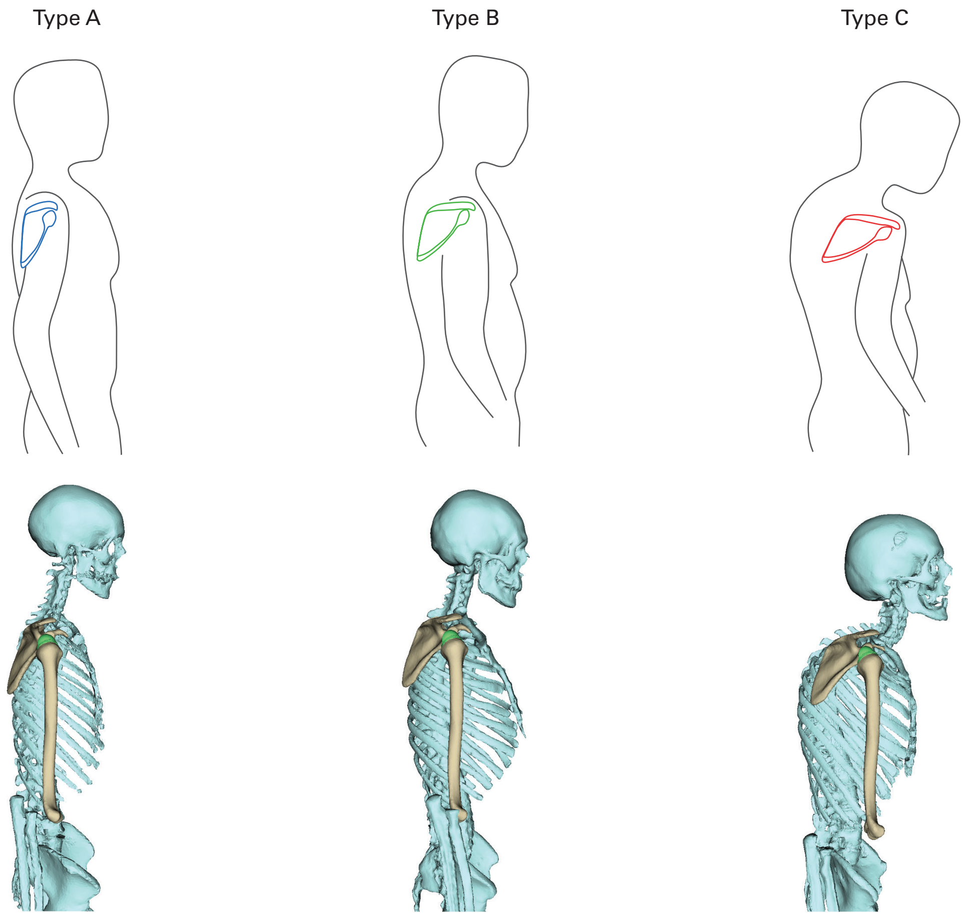

Fig. 1

Three posture types, based on previously established values for scapulothoracic orientation.[8] Type A shows an upright posture with retracted scapulae, while type C presents with advanced thoracic kyphosis and subsequent increase in scapula internal rotation, anterior tilt, downward, rotation, protraction, and drooping. Type B constitutes an average patient. The statistical shoulder shape model of humerus and scapula fitted into different posture types is shown below each type.

certain challenges such as restricted range of motion (ROM), instability, component loosening, or scapular notching.[3,4]

With modern technologies such as 3D preoperative planning software, surgeons can explore different component combinations and placements for RTSA, in an attempt to maximize theoretical impingement-free ROM. However, recent literature suggests that there is a marked disparity between the calculated ROM and the actual clinical outcome.[5-7] All current commercially available preoperative planning software for shoulder arthroplasty merely considers glenohumeral anatomy and does not account for scapular orientation with regard to the thorax. It has recently been shown that posture and scapulothoracic orientation, which vary between individuals, have an impact on theoretically achievable ROM in RTSA.[8,9] For clinical application, variations in scapulothoracic orientation between patients were grouped into three different posture types (type A with upright posture and retracted scapulae; type B with average posture; and type C with advanced thoracic kyphosis and subsequent internal scapular rotation, anterior tilt, protraction, and drooping) (Figure 1).[8]

The objective of this study was to compare simulated ROM for RTSA with prototype development software with and without adjustment for scapulothoracic orientation. We hypothesized that values for simulated ROM for RTSA with and without adjustment for scapulothoracic orientation would differ significantly.

Methods

Ethics. This study was based on CT data collected in a multicentre shoulder arthroplasty registry (Arthrex, USA) approved by its institutional review board (Salus IRB/AIRR-00608).

Shoulder statistical shape model. Based on a training set of 50 CT scans that included the entire humerus and scapula, a shoulder statistical shape model (SSM) was created. CT scans were collected from the Virtual Implant Positioning (VIP; Arthrex) database to represent the patient population. CT scans were obtained from 31 female and 19 male patients with a mean age of 71 years (34 to 93), including 33 right and 17 left shoulders. For the shoulder SSM, only right shoulders were considered and left shoulders were mirrored to simulate right shoulders.

All patients with previous shoulder surgery, osteoarthritis, cuff arthropathy, or other bony pathology were excluded. All CT scans were manually segmented, and 3D surfaces of humerus and scapula were reconstructed using Mimics (Materialise NV, Belgium). To compute the shoulder SSM reference between all points, the training set surfaces were determined according to previously described methods for humeral and scapular correspondences computation.[10,11] We then applied principal component analysis to compute the principal modes of variations – eigenvectors with eigenvalues – of the shoulder SSM. The calculated principal modes of variation allow for alterations of the shoulder SSM along the anatomical variations, so that a large number of shoulder models can be created.

Prototype development software. For the purpose of this study, preoperative planning software was created that allowed virtual implantation of a RTSA (Univers Revers; Arthrex). This prothesis is marked by a humeral semi-inlay design with a 135° neck-shaft angle and a modular glenoid system allowing for 4 mm baseplate lateralization and 4 mm glenosphere lateralization or eccentricity. The ROM is automatically calculated by rotating the humerus with the humeral implant around the centre of rotation (COR) in predefined reference systems, detecting collisions with an algorithm. Two sets of reference systems were defined in the software: scapular and global reference systems. The scapular reference system is defined as a best-fit plane between the trigonum scapulae, the glenoid centre, and the inferior angle, various superficial points (Y_s), a normal to this best-fit plane (X_s), and the cross product of those two planes (Z_s). The global reference system is defined as follows: X_g (sagittal plane), Y_g (coronal plane), and Z_g (axial plane) (Figure 2). For the conventional ROM calculation with the scapular reference system, the humerus is moved in relation to the scapula around the implant COR. Abduction and adduction movements are calculated around the X_s axis, flexion/extension movements are calculated around the Y_s axis, and internal and external rotations are calculated around the Z_s axis. To compute posture-adjusted ROM, the software rotates the scapula to the previously published mean values for the scapular internal rotation, upward/downward rotation, and anterior/posterior tilt of the scapula in respect of global reference axes for posture types A, B, and C (Table I; Figure 3).[9] The starting position of the humerus is aligned according to the global reference system (Figures 2 and 4). Abduction/adduction movements are calculated around the X_g axis, flexion/extension movements are calculated around the Y_g axis, and internal/external rotations are calculated around the Z_g axis.

Preoperative planning. A SSM was fitted into ten shoulder CT scans randomly selected from 162 patients who underwent RTSA and six fellowship-trained shoulder surgeons (PM, PR, PJD, BCW, BJE, PS) independently planned a RTSA with their own preferences using the prototype development software (Arthrex). Possible choices for glenoid and humeral component selection and placement included all the commercially available choices for the implant system used. Simulated

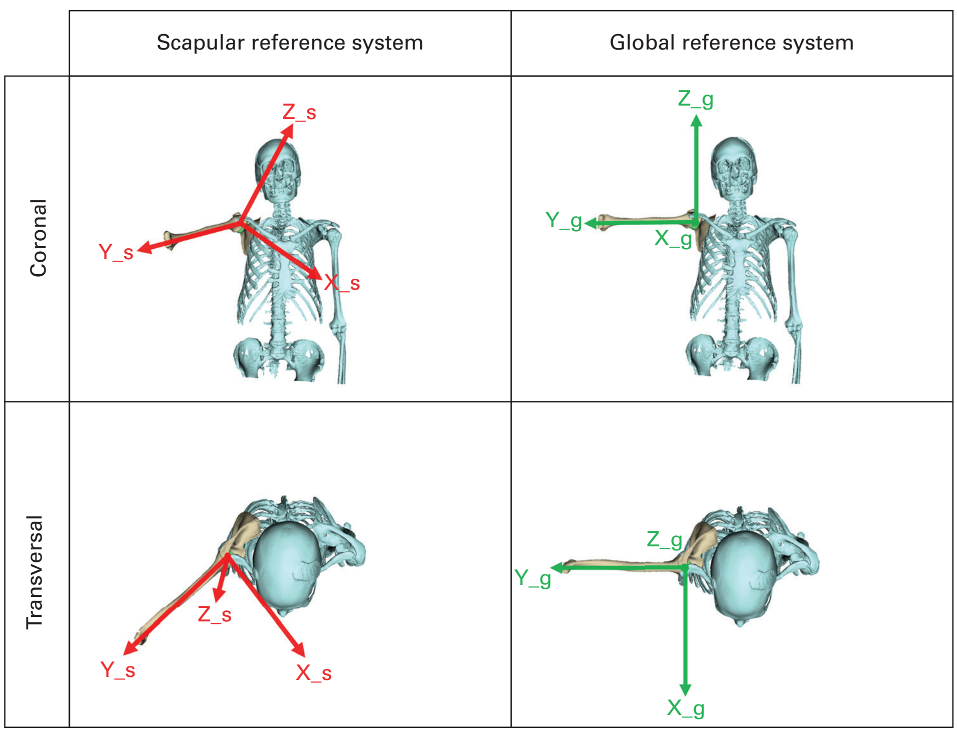

Fig. 2

Illustration of scapular and global reference systems for abduction kinematic plane of the humerus applied in a type C patient in a coronal and transverse view. In all commercially available software, movements are referenced to the scapula, which is considered to be in neutral orientation. This means that an abduction motion is aligned with the scapular axis and not orthogonal to the coronal body axis, as would be the case utilizing a global reference system.

Table I. Measurements for scapulothoracic orientation for individual posture types, based on previously published data.[9]

Parameter	Type A	Type B	Type C
Mean scapular internal rotation, ° (SD)	32 (6)	42 (3)	53 (5)
Mean scapular upward rotation, ° (SD)	-3 (6)	-12 (7)	-15 (13)
Mean scapular anterior tilt, ° (SD)	23 (11)	24 (8)	33 (7)

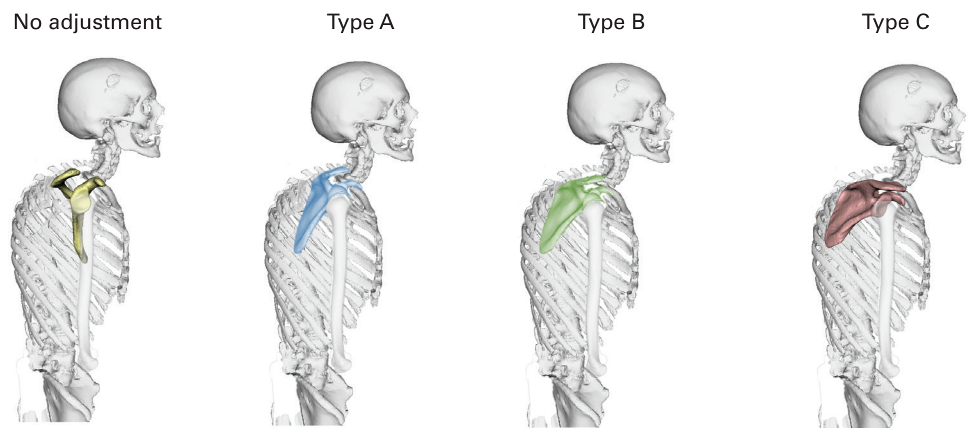

Fig. 3

Illustration of different scapulothoracic orientations in space in a type C patient. The scapula either non-adjusted or adjusted according to types A, B, or C.

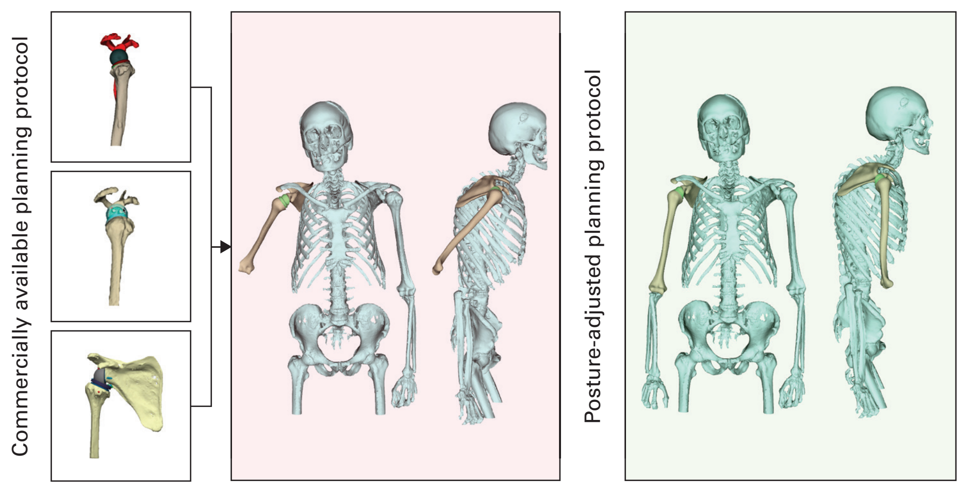

Fig. 4

Illustration of starting position of the humerus in a posture type C patient in three different types of commercially available planning software and a posture-adjusted software. In a standard software, the starting position is aligned with the scapula that is neutrally oriented in space. Therefore, considering the whole body and scapulothoracic orientation, the starting position of the humerus is incorrect. With a posture-adjusted software, a neutral starting position of the humerus can be achieved.

impingement-free ROM without and with posture adjustment for each type was obtained for the following movements: abduction, adduction, flexion, extension, external rotation (ER), external rotation in 30° abduction (hER), internal rotation (IR), and internal rotation in 30° abduction (hIR).

Statistical analysis. Statistical analysis including descriptive statistics were performed with SPSS Statistics software v. 29.0 (IBM, USA). The level of statistical significance was set to an α of 0.05, and all tests were two-sided. All outcome variables were analyzed using a Kolmogorov-Smirnov test and showed a normal distribution. For comparison of ROM outcomes between standard and adjusted software, a paired *t*-test was used.

Results

All movement planes showed significant differences in ROM when comparing results without adjustment and mean results

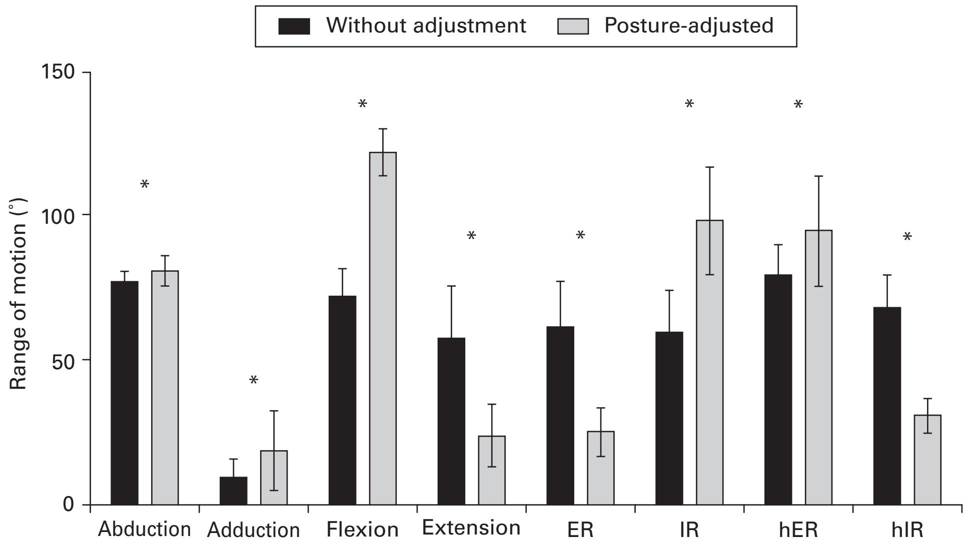

Fig. 5

Comparison of the mean simulated mean range of motion (ROM) and SD in different planes simulated without posture adjustment protocol (black) to mean ROM with a posture-adjusted protocol (blue). *p < 0.001, paired *t*-test. ER, external rotation; hER, high external rotation; hIR, high internal rotation; IR, internal rotation.

for posture adjustment (Figure 5). Mean abduction was 77° (SD 4°) without adjustment compared to 81° (SD 5°) with posture adjustment (Mean pairwise differences (Δ) = 4°; p < 0.001). Adduction was 10° (SD 6°) without versus 19° (SD 14°) with posture adjustment (Δ = 9°; p < 0.001). While flexion was lower without adjustment (72° (SD 10°)) compared to 122° (SD 8°) with posture adjustment (Δ = 50°; p < 0.001), extension was higher without (57° (SD 18°)) compared to with (24° (SD 11°)) posture adjustment (Δ = -33°; p < 0.001). ER was 62° (SD 16°) without versus 25° (SD 9°) with posture adjustment (Δ = -36°; p < 0.001), while IR was 60° (SD 15°) without versus 99° (SD 19°) with posture adjustment (Δ = 39°, p < 0.001). While hER was 79° (SD 11°) without adjustment compared to 95° (SD 19°) with posture adjustment (Δ = 16°; p < 0.001), hIR was 69° (SD 11°) without versus 31° (SD 6°) with posture adjustment (Δ = -38°; p < 0.001).

Individual results comparing ROM without adjustment to each posture type (A, B, and C) are seen in Figure 6. All movement planes showed significant differences (p < 0.001), except for hER in type B (p = 0.610), abduction (p = 0.003) and adduction (p = 0.032) in type C. Mean pairwise differences are summarized in Table II. Figure 7 shows diffent contact areas between the humeral component and the scapula for conventional and posture adjusted planning software.

Discussion

The present study demonstrates the importance of incorporating scapulothoracic orientation and global reference planes when simulating ROM for RTSA. We observed large differences in most planes of motion and particularly overestimated values for extension, external rotation, and internal rotation in 30° of abduction using a conventional simulation protocol compared to a posture-adjusted protocol. These results question the validity of currently commercially available planning solutions to simulate ROM in RTSA and their value in helping to guide the user in optimizing implant position for the best outcomes. These available systems do not currently consider the patient-specific orientation of the scapula, starting point of the humerus, and COR of the joint, and thus may render misleading results.

The value of preoperative planning in understanding and addressing glenoid deformities is widely recognized.[12-14] Studies have demonstrated that accurate component placement can be achieved by following a preoperative plan.[15] This facilitates the precise positioning of the central screw or post and increases bony containment.[16] Jacquot et al[17] showed that using preoperative planning enhances the accuracy of freehand positioning, and patient-specific guides may even improve the position of the central entry point. Optimized glenoid component position may improve postoperative movement and decrease risk of complication, such as scapular notching.[16] Furthermore, by using 3D planning techniques, surgeons can estimate the appropriate size of the glenoid baseplate and determine approximate screw lengths. Additionally, they can make reasonably accurate predictions regarding the required shaft sizes for the humeral component.[15,18] With various component options available, surgeons can even simulate lateralization or distalization to achieve the desired configuration. One promising feature of commercially available planning software has been simulated ROM. These systems allow for the rotation of the humeral component around the glenosphere in multiple planes, enabling surgeons to assess potential mechanical impingement and provide a prediction of ROM that can be expected postoperatively. However, CT scans of the affected shoulder only capture the glenohumeral joint and disregard the natural relationship between the scapula, the humerus, and the thorax. As shown in Figure 3, in standard software, the scapula is used as a reference that defines the starting position of the humerus and the movement planes based on the scapular axis, rather

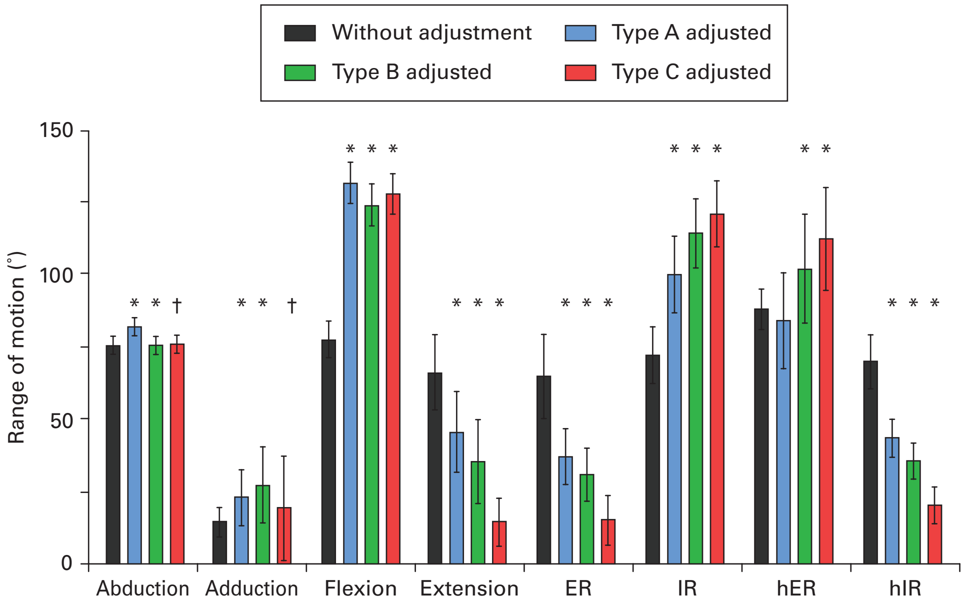

Fig. 6

Comparison of the mean range of motion and SD in different planes simulated without posture adjustment protocol to an adjusted protocol for all posture types. *p < 0.001, †p < 0.05, paired *t*-test; ER, external rotation; hER, high external rotation; hIR, high internal rotation; IR, internal rotation.

Table II. Pairwise differences (Δ) in simulated mean range of motion between non-adjusted and adjusted preoperative shoulder arthroplasty planning software.

Variable	Mean Δ, ° (SD; range)		
	Non-adjusted vs type A adjusted	**Non-adjusted vs type B adjusted**	**Non-adjusted vs type C adjusted**
Abduction	8 (3; 4 to 17)	3 (3; 0 to 11)	4 (3; 0 to 13)
Adduction	11 (7; 2 to 38)	15 (10; 0 to 49)	13 (10; 0 to 51)
Flexion	53 (11; 32 to 84)	46 (11; 26 to 83)	51 (11; 30 to 88)
Extension	24 (18; 2 to 68)	31 (19; 2 to 68)	47 (18; 13 to 80)
External rotation	27 (16; 0 to 60)	33 (16; 4 to 64)	49 (15; 23 to 80)
Internal rotation	28 (15, 0 to 54)	41 (15, 2 to 77)	48 (14, 15 to 84)
External rotation in 30° abduction	18 (11, 2 to 45)	22 (17, 0 to 51)	29 (19, 2 to 60)
Internal rotation in 30° abduction	27 (11, 6 to 47)	35 (11, 13 to 54)	51 (11, 30 to 71)

ER, external rotation; hER, high external rotation; hIR, high internal rotation; IR, internal rotation.

than the individual body axes. As scapular rotation increases, as seen in type C patients, the disparity between the scapular and body axes (global reference) becomes more pronounced. The adjusted software used in this study not only accounts for changes in scapulothoracic orientation (types A, B, and C) but is uniquely calibrated to a global reference for humeral starting position and kinematic planes.

The substantial simulated ROM differences observed between posture-adjusted and non-adjusted planning software can be explained by the fact that the repositioning of the humerus and scapula in the global reference system leads to different contact scenarios in the various kinematic planes (Figure 7). The study findings revealed a significant difference in measured flexion when posture adjustment was implemented compared to when it was not, across all scapulothoracic orientation types. During flexion, in a standard simulation with the scapula in a straight position, the humeral component encounters interference with the coracoid process below 90°. Conversely, when considering scapular internal rotation within the same movement, the coracoid process is relatively medialized, allowing the humeral component to extend until it reaches the anterior acromion, enabling increased movement. In the analysis of rotational movement, the non-adjusted software demonstrated a balanced ROM for internal and external rotation and internal and external rotation in 30° of abduction. However, with incorporated posture adjustments, imbalances in rotational movement were observed. These findings align with previous studies that used simulations accounting for the humeral starting position in relation to the body axes.[8,9] Specifically, it was observed that in 0° abduction, internal rotation was favoured when there was advanced scapular internal rotation (type C), while external rotation was diminished. This phenomenon has been previously described.[9] Interestingly, in the case of 30° abduction, our simulation yielded opposing results compared to adducted rotation. Upon closer examination of the model (Figure 7), it can be observed that in type C patients, the changed scapulothoracic

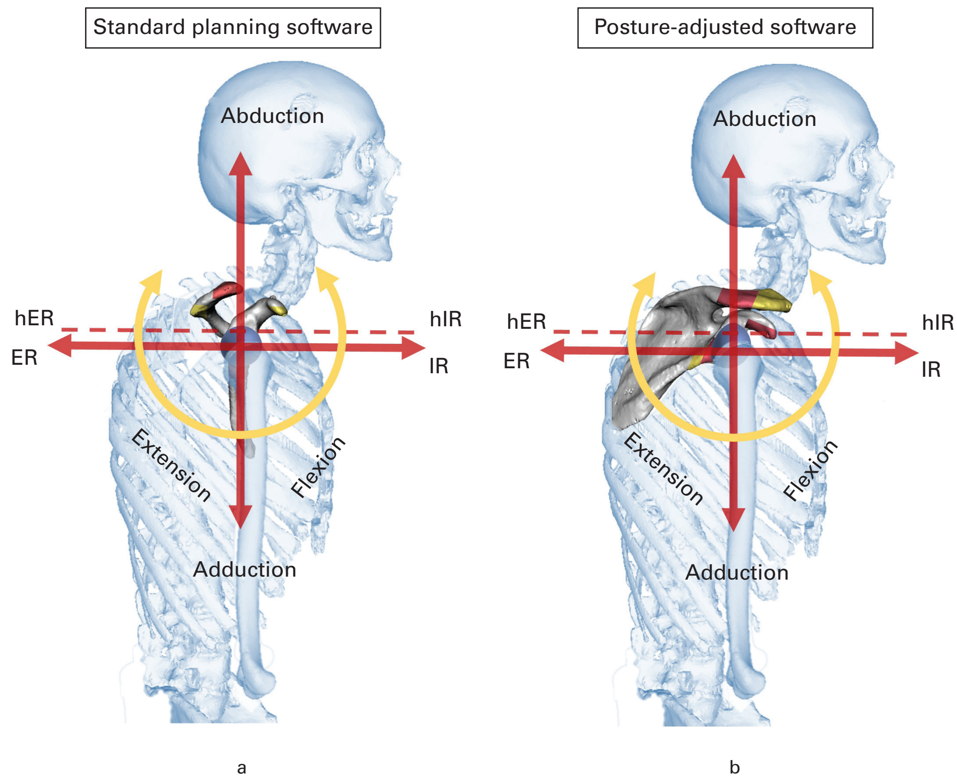

Fig. 7

Illustration of range of motion (ROM) simulation in a type C patient using a) a conventional preoperative planning protocol and b) a posture-adjusted protocol. Due to the altered scapulothoracic orientation, simulated mechanical impingement occurs in different areas of the scapula (red and yellow), explaining divergent ROM results between protocol with and without posture adjustment. ER, external rotation; hER, high external rotation; hIR, high internal rotation; IR, internal rotation.

orientation resulted in early impingement with the coracoid process. However, there is more space available for rotation towards the posterosuperior part of the glenoid before encountering notching, which can explain a better abducted external rotation. These observations align with clinical observations where external rotation in adduction after RTSA may lead to early posteroinferior notching, while external rotation in 30° abduction has a larger range before notching occurs. Similarly, it might explain the often-limited internal rotation after RTSA, such as reaching behind one's back, which requires a combination of internal rotation and abduction resulting in an impingement with the coracoid. Baumgarten[5] conducted a study to examine the disparities between ROM calculated using preoperative software and the actual active ROM observed at the one-year follow-up. Interestingly, they observed a similar pattern in external rotation compared to the results of our study. Their software tended to overestimate external rotation by an absolute difference of 28°, but underestimated it in abducted external rotation, with an absolute difference of 32°. Moreover, their software substantially overestimated abducted internal rotation, with an absolute difference of 62°. The biggest difference was found in abduction. However, it is crucial to note that their clinical measurements included scapulothoracic movement, while their simulation is based on glenohumeral motion only, which is also true for our study. Moreover, variances in humeral retrotorsion may impact both internal and external rotation, with each surgeon selecting their preferred rotation during planning. Increased retrotorsion is associated with greater external rotation, while decreased retrotorsion is associated with favoured internal rotation.[19] However, the substantial differences in simulated ROM observed in this study justify re-evaluation of all previously published studies that examined component choice and placement for optimized ROM in RTSA using conventional preoperative planning software.

Despite the arguable improvement in simulating ROM after RTSA when scapulothoracic orientation is adjusted, certain limitations remain, including the lack of simulation of scapula kinematics and soft-tissue impingement. It is important to acknowledge that the simulation solely accounts for glenohumeral movement and does not consider scapulothoracic motion. Consequently, cautious interpretation is advised, particularly when assessing values of abduction and flexion in clinical practice. Furthermore, component choice for the surgeons and placement were not further analyzed in this study. Humeral component torsion in particular could have an impact on rotational movement. While this does not allow for interpretation of individual implantation styles on ROM outcome in different posture types, the effect of scapulothoracic orientation seems to be present across a variety of different configurations, as the planning was performed by six independent shoulder surgeons according to their individual preferences. Additionally, the simulation employed shape models that were chosen at random, which underlines the generalizability of the obtained results. Furthermore, the values used for scapulothoracic orientation of each posture type were based on previously published data.[9] The obtained values were derived from whole-body CT scans in the supine position, which could affect scapulothoracic orientation. In a study comparing scapulothoracic orientation in supine and standing position, Matsumura et al[20] observed less upward rotation, anterior tilting, and internal rotation of the scapula in the standing position. Analyzing standing patients could therefore offer more realistic values for scapulothoracic orientation, potentially enhancing diagnostic accuracy in preoperative planning.

The present study demonstrates that taking scapulothoracic orientation and global reference planes into account has considerable impact on simulated ROM for RTSA, specifically rendering much lower values for extension, external rotation, and internal rotation in 30° of abduction. The substantial differences in posture-adjusted and non-adjusted simulated ROM observed in this study question the validity of all currently commercially available solutions to simulate ROM in RTSA, and their value in guiding the surgeon to optimize implant position for the best outcome.

Take home message

- Simulated range of motion in preoperative planning protocols is affected by adjustment for scapulothoracic orientation.
- Considering individual body posture renders different results in all movement planes, especially external rotation, extension, and high internal rotation.

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