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Scapulohumeral rhythm in shoulders with reverse shoulder arthroplasty

David Walker, PhD[a], Keisuke Matsuki, MD, PhD[b], Aimee Struk, MS[c], Thomas W. Wright, MD[c,*], Scott A. Banks, PhD[a]

[a]*Department of Mechanical Engineering, University of Florida, Gainesville, FL, USA*
[b]*Department of Orthopaedic Surgery, Teikyo University Chiba Medical Center, Ichihara, Chiba, Japan*
[c]*Department of Orthopaedics and Rehabilitation, University of Florida, Gainesville, FL, USA*

Background: Little is known about kinematic function of reverse total shoulder arthroplasty (RTSA). Scapulohumeral rhythm (SHR) is a common metric for assessing muscle function and shoulder joint motion. The purpose of this study was to compare SHR in shoulders with RTSA to normal shoulders.
Methods: Twenty-eight subjects, more than 12 months after unilateral RTSA, were recruited for an Institutional Review Board–approved study. Subjects performed arm abduction in the coronal plane with and without a 1.4-kg hand-held weight. Three-dimensional model-image registration techniques were used to measure orientation and position for the humerus and scapula from fluoroscopic images. Analysis of variance and Tukey tests were used to assess groupwise and pairwise differences.
Results: SHR in RTSA shoulders (1.3:1) was significantly lower than in normal shoulders (3:1). Below 30° abduction, RTSA and normal shoulders show a wide range of SHR (1.3:1 to 17:1). Above 30° abduction, SHR in RTSA shoulders was 1.3:1 for unweighted abduction and 1.3:1 for weighted abduction. Maximum RTSA shoulder abduction in weighted trials was lower than in unweighted trials. SHR variability in RTSA shoulders decreased with increasing arm elevation.
Conclusion: RTSA shoulders show kinematics that are significantly different from normal shoulders. SHR in RTSA shoulders was significantly lower than in normal shoulders, indicating that RTSA shoulders use more scapulothoracic motion and less glenohumeral motion to elevate the arm. With these observations, it may be possible to improve rehabilitation protocols, with particular attention to the periscapular muscles, and implant design or placement to optimize functional outcomes in shoulders with RTSA.
Level of evidence: Basic Science, Kinesiology.

Keywords: Reverse total shoulder arthroplasty; rehabilitation; implant design; surgical technique; shoulder motion; scapulohumeral rhythm

Reverse total shoulder arthroplasty (RTSA) has become a widespread treatment option for patients with rotator cuff arthropathy. RTSA studies have yielded promising results not only in the relief of chronic pain due to patients' previous osteoarthritis but in restoration of range of motion during functional activities. Despite good clinical

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*Reprint requests: Thomas W. Wright, MD, 3450 Hull Road, 3rd Floor, Gainesville, FL 32608, USA.

E-mail address: wrightw@ortho.ufl.edu (T.W. Wright).

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outcomes, potential issues still occur after RTSA that are associated with deltoid tensioning and joint range of motion. Potential instability, scapular notching, and polyethylene wear may lead to significantly decreased functional outcomes and increased risk of RTSA failure.[2-4,22] Better knowledge of shoulder joint motion is critical to understanding how shoulders with RTSA function. With a better understanding of reverse shoulder motion, optimal design and configuration of the implants can be achieved to increase functional outcomes and to lower RTSA failure rates. This study quantifies the kinematics of shoulders with RTSA and compares these results with kinematics of young healthy shoulders studied with identical methodology.

Altered scapular kinematics are often associated with shoulder disorders.[17] Scapulohumeral rhythm (SHR) has been used to quantify the relative motion of the scapula and humerus, and it is a sensitive measure of shoulder dysfunction.[1,5,17,20,21] Many methods have been developed to measure shoulder motion and SHR, most of which are noninvasive and require placement of markers on the skin.[1] As with any methods using markers that are not rigidly fixed to the bones, there can be significant soft tissue movement that affects the measurement.[14] Fluoroscopic imaging and model-image registration techniques have been used for more than 20 years to quantify the motions of implants and bones in vivo, including the shoulder.[1,9,11] These radiographic methods quantify implant or bone motion directly and are unaffected by motions of the surrounding skin or soft tissues.

Although studies have been performed to assess the maximum range of shoulder motion with RTSA, there is no information directly quantifying scapulothoracic and scapulohumeral motion in these shoulders. The goal of this study was to quantify SHR in shoulders with RTSA during abduction with and without a hand-held weight and to compare these measures with those previously obtained from healthy young shoulders by the same protocol and methods.

Materials and methods

Participants

Twenty-eight subjects with RTSA gave written informed consent to participate in this Institutional Review Board–approved study. They were an average of 37 months after unilateral RTSA (range, 12-63 months) and had an average age of 73 years (range, 63-85 years). There was no previous shoulder arthroplasty performed on any patient, although some had orthoscopic rotator cuff repair that failed. Patients were also required to have had no previous history of fractures or revisions to the joint. Patients were selected on the basis of their ability to perform weighted abduction. The RTSA group was composed of 23 women and 5 men. The sample size difference found between male and female patients was primarily due to the fact that severe rotator cuff tears are more prevalent in women than in men. Each RTSA subject had at least 2 rotator cuff tendon tears that were deemed not repairable by the surgeon as well as secondary arthritis. These RTSA patients were treated with 3 different implant designs. Seven RTSA subjects received implants with a glenosphere center of rotation within 2 mm of the glenoid face and a medialized humeral design having a line of action within the humerus (Aequalis; Tornier, Bloomington, MN, USA). Sixteen RTSA subjects received implants with a glenosphere center of rotation at least 6 mm lateral to the glenoid face and a medialized humeral design (Reverse Shoulder Replacement; DJO Surgical, Austin, TX, USA). Ten RTSA subjects received implants with a medial center of rotation glenosphere and a lateralized humeral design (Equinoxe; Exactech, Gainesville, FL, USA). Each variation of prosthetic shoulder geometry is intended to provide mechanical advantage to the deltoid.[2,3,7-9,11,13,18,22] Subjects with all 3 implant designs composed the RTSA study cohort.

Image acquisition and 3D modeling

Single-plane fluoroscopic images of the shoulder during coronal plane abduction were captured at 7.5 Hz. Motions were performed so that 1 cycle required approximately 15 seconds to complete, moving from the arm at the side to maximum abduction and returning to the arm at the side. Subjects were prompted to follow an investigator's example during elevation and lowering of the arm, with specific attention to keeping the torso upright in a standing posture. Subjects performed unweighted trials and weighted trials with a 1.4-kg hand-held weight. Subjects rested for 2 minutes between trials to minimize the potential for fatigue. Subjects were positioned so that the coronal plane was perpendicular to the x-ray beam.

Fluoroscopic images were undistorted with use of custom software (MathWorks, Natick, MA, USA), and 3-dimensional (3D) to 2-dimensional model-image registration techniques were used to determine the 3D motions of the implants from the undistorted images.[1,17] Subject-specific implant models for the humeral and glenoid components were created so that measured implant rotations corresponded to anatomic shoulder motions. These 3D implant models were projected onto the undistorted fluoroscopic images, and their 3D pose was adjusted to match the implant silhouette in the fluoroscopic image, providing humeral and scapular component kinematics (Fig. 1).[17] Elevation of the humeral and scapular components in the coronal plane was determined (Fig. 2), and a third-order polynomial was fitted to a plot of scapular elevation (ordinate) vs. humeral elevation (abscissa) to permit resampling at equal intervals of humeral elevation. SHR was then calculated as $(\Delta H - \Delta S)/\Delta S$, where ΔH is the incremental humeral elevation and ΔS is the incremental scapular elevation. The accuracy of our image registration technique was found to be 1 mm for translations and 0.5° for rotations.[1,17]

We use our previously reported results for healthy young shoulders as the basis for quantitative comparison of RTSA shoulder function.[17] These normal shoulders were studied with the same methods and calculations.

Statistical methods

Comparison of RTSA shoulders with healthy young shoulders was performed by 2-way repeated-measures analysis of variance with the level of significance of .05. The Tukey honestly significant difference was used to perform pairwise post hoc comparisons at specific humeral elevation angles.

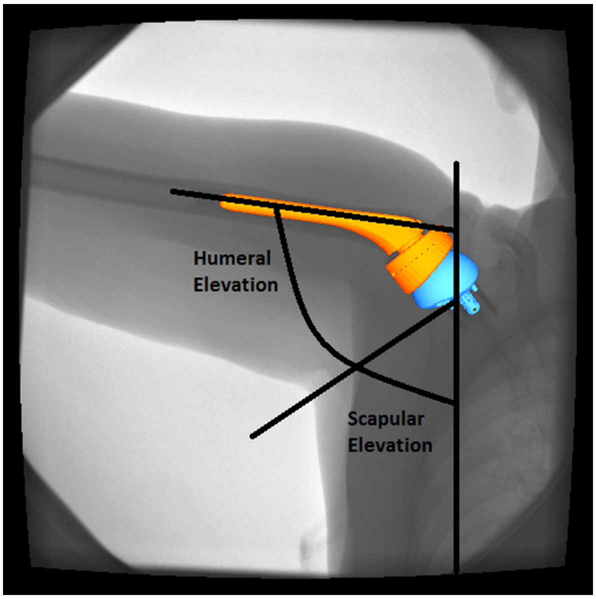

Figure 1 The 3-dimensional to 2-dimensional model registration for RTSA subject.

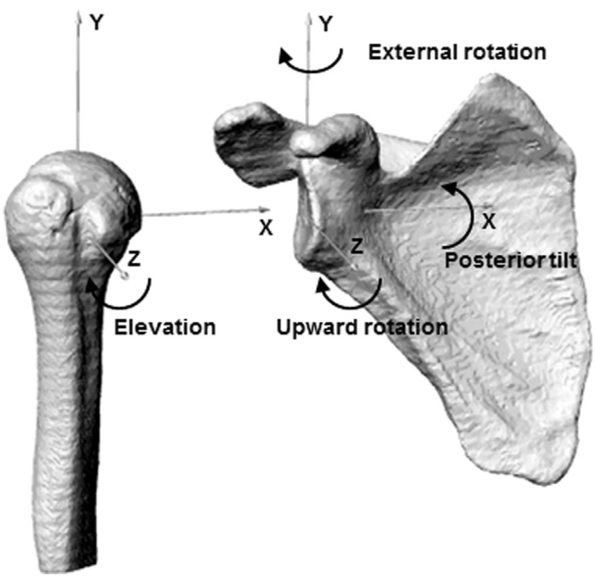

Figure 2 Humerus and scapula coordinate system definitions in accordance with the International Society of Biomechanics standards.

Results

For abduction above 30°, shoulders with RTSA exhibited an average SHR of 1.3:1 during unweighted abduction (Fig. 3). There was no significant SHR difference between abduction with and without 3-kg hand-held weights (1.3:1 weighted; Fig. 4), nor was there a significant difference between elevation and lowering. SHR was highly variable for abduction <30°, with SHR ranging from 2:1 to 17:1. The mean SHR for normal shoulders was 3:1 (Figs. 3 and 4). Maximum unweighted abduction averaged 150° for normal shoulders, 110° for unweighted abduction in RTSA shoulders, and 90° for weighted abduction in RTSA shoulders. A difference of range of motion was not observed between implant groups. We were unable to do a meaningful statistical analysis to look at implant group comparisons because of the varying cohort sizes for each implant group and patient follow-up times.

Discussion

RTSA is an increasingly important treatment option for severe trauma and degeneration of the shoulder. There is active debate on the best implant geometric configurations to restore shoulder function but few quantitative in vivo data to guide this debate. We performed this study to determine if shoulders with RTSA show close to normal SHR and found that shoulders with RTSA exhibit low SHR values, or less glenohumeral motion, as the arm moves through the abduction arc.

Two study limitations need to be considered, both related to the fact that the primary implant used for RTSA changed over time. First, we enrolled subjects with 3 different RTSA implant designs, presenting a range of geometric configurations. We did not detect significant differences in SHR between these 3 subgroups and present the data as a single inclusive RTSA group. It is possible that comparisons of larger groups of subjects would reveal significant differences in SHR between implant types. Second, the postoperative follow-up interval was different for subjects receiving each of 3 different RTSA designs. It is possible that differences in SHR will be manifested when subjects receiving the 3 designs are all studied at the same postoperative intervals. Differences in SHR between male and female sample groups were not measured because of the inability to do a statistically meaningful assessment with a small cohort (male, n = 5).

SHR is an important and widely documented parameter to describe coordinated motion in healthy and diseased shoulders. SHR in young normal shoulders has been reported to average 3:1,[25] whereas SHR in RTSA shoulders has been reported to average 1.3:1.[10,12,26] Matsuki et al[17] showed differences in scapular motions between dominant and nondominant shoulders in healthy young subjects, but the SHR values did not differ (2.6:1 and 2.7:1, respectively). Our study of 28 shoulders with RTSA showed SHR averaging 1.3:1 for unweighted abduction and 1.3:1 for weighted abduction. Consistent with previous reports, we found that SHR in shoulders with RTSA is consistently lower than in healthy shoulders.

At arm elevation angles <30°, SHR in shoulders with RTSA is highly variable. This is consistent with the scapular setting phase described in previous studies.[2,3,6,17-19,22] At higher elevation angles, SHR in shoulders with RTSA

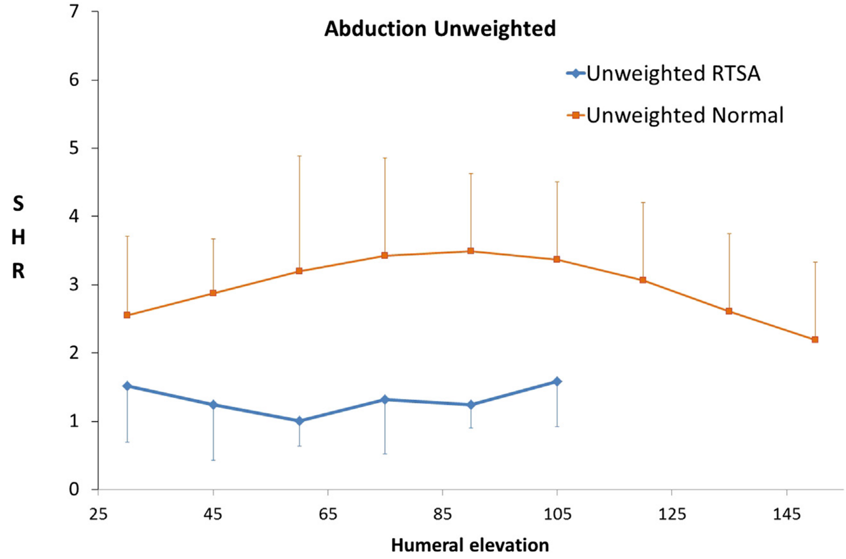

Figure 3 Scapulohumeral rhythm (*SHR*) during unweighted abduction. *Blue*, Normal data set; *Orange*, Reverse shoulder population.

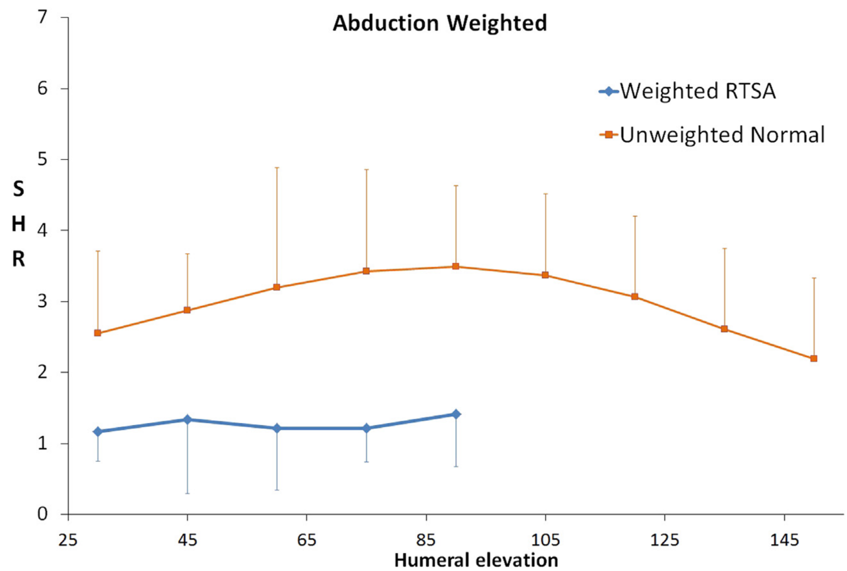

Figure 4 Scapulohumeral rhythm (*SHR*) during weighted abduction. *Blue*, Normal data set; *Orange*, Reverse shoulder population.

(1.3:1) is much more consistent and is lower than SHR in normal shoulders (roughly 3:1). Reduced glenohumeral motion with RTSA may result from a combination of muscular and articular mechanisms. Shoulders with RTSA lack a competent rotator cuff, and this may contribute to reduced glenohumeral motion. In particular, without the supraspinatus and infraspinatus, the shoulder lacks the intrinsic muscles that can assist the deltoid in raising and lowering the arm against gravity.[15,25] Cuff dysfunction may also elicit deltoid inhibitory signals,[4,15,25] further reducing the ability of the deltoid to provide glenohumeral motion. In addition, the RTSA articulation and implants may restrict glenohumeral motion. Imposing a fixed center of rotation on the glenohumeral joint, especially if it is different from the natural anatomy, may change the relationship between the torque elevating the humerus and the reaction forces acting on the glenoid,[23] and these altered mechanics may affect glenohumeral motion. Implant impingement, as has been observed in numerous studies,[23,24] is an obvious factor in restricting glenohumeral motion.[23,24] Efforts to improve postoperative function in shoulders with RTSA should focus attention on reduced glenohumeral motion and seek to understand how these muscular and articular factors contribute.

Greater scapular motion is observed in shoulders with RTSA. An SHR of 1.3 is consistent with previous reports[16] and implies greater activity in the trapezius. This same cohort of RTSA study subjects was also observed with electromyography and motion capture during arm abduction, and their upper trapezius electromyographic activity was found to be significantly higher than in normal age- and gender-matched subjects.[21,26] Increased scapulothoracic motion may have profound clinical implications, as periscapular muscle pain, subscapular bursitis, acromioclavicular joint pain, and scapular spine stress fractures have all been observed in shoulders with RTSA.[24] Shoulder rehabilitation after RTSA may benefit from focused strengthening of the periscapular muscles to facilitate these increased demands for scapular movement.

Conclusions

Improving function in shoulders with RTSA is an increasingly important pursuit with the growing utilization of this treatment. Shoulders with RTSA, by definition, have suffered from severe mechanical insult or disease, and they do not show normal scapulohumeral coordination after surgery. Our results suggest 2 important fronts for improving clinical and functional results with RTSA. First, the interplay of altered musculature and joint geometry must be further studied so that treatments can be objectively designed to achieve the best possible glenohumeral motion with RTSA. Second, there are greater demands for scapular motion after RTSA, and rehabilitation strategies should increasingly focus on strengthening the periscapular muscles to enhance function and to avoid common complications.

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