Biomechanical effects of humeral neck-shaft angle and subscapularis integrity in reverse total shoulder arthroplasty

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Background: The variability in functional outcomes and the occurrence of scapular notching and instability after reverse total shoulder arthroplasty remain problems. The objectives of this study were to measure the effect of reverse humeral component neck-shaft angle on impingement-free range of motion, abduction moment, and anterior dislocation force and to evaluate the effect of subscapularis loading on dislocation force.

Methods: Six cadaveric shoulders were tested with 155°, 145°, and 135° reverse shoulder humeral neck-shaft angles. The adduction angle at which bone contact occurred and the internal and external rotational impingement-free range of motion angles were measured. Glenohumeral abduction moment was measured at 0° and 30° of abduction, and anterior dislocation forces were measured at 30° of internal rotation, 0°, and 30° of external rotation with and without subscapularis loading.

Results: Adduction deficit angles for 155°, 145°, and 135° neck-shaft angle were 2° ± 5° of abduction, 7° ± 4° of adduction, and 12° ± 2° of adduction (P < .05). Impingement-free angles of humeral rotation and abduction moments were not statistically different between the neck-shaft angles. The anterior dislocation force was significantly higher for the 135° neck-shaft angle at 30° of external rotation and significantly higher for the 155° neck-shaft angle at 30° of internal rotation (P < .01). The anterior dislocation forces were significantly higher when the subscapularis was loaded (P < .01).

Conclusions: The 155° neck-shaft angle was more prone to scapular bone contact during adduction but was more stable at the internally rotated position, which was the least stable humeral rotation position. Subscapularis loading gave further anterior stability with all neck-shaft angles at all positions.

Level of evidence: Basic Science Study, Biomechanics.

Keywords: Arthroplasty; reverse shoulder; biomechanics; notching; anterior dislocation

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Reverse total shoulder arthroplasty is a treatment option for patients with irreparable massive rotator cuff tear or cuff tear arthropathy. The reverse total shoulder arthroplasty prosthesis has a unique design with a convex glenoid hemisphere and a concave humeral socket. This design mediates the center of rotation of the glenohumeral joint and lengthens the moment arm of the deltoid muscle. In addition, the congruent articulation between the two prosthetic components allows a semiconstrained motion that compensates for the dysfunctional rotator cuff.

Clinical studies have reported excellent functional improvement as well as pain relief after reverse total shoulder arthroplasty. However, despite its clinical success, reverse total shoulder arthroplasty has been associated with relatively high complication rates, with scapular notching rates ranging from 5% to 96% and dislocation rates as high as 30%, both of which may be the result of implant design or subscapularis integrity.

The influence of implant design on potential range of motion is due to impingement between the prostheses and scapula. In particular, scapular notching from impingement between the medial aspect of the humeral component and the inferior scapula is often observed and is known to decrease the impingement-free range of adduction motion. Moreover, scapular notching has been shown to correlate with poorer clinical outcomes and has been implicated as the cause of failure in several patients. Previous studies have shown that reducing the humeral neck-shaft angle decreases adduction deficit; however, there is a classic concern that the reduced neck-shaft angle may predispose to prosthetic instability.

Another concern of reverse total shoulder arthroplasty is to overcome pseudoparalysis. One of the clinical indications of reverse total shoulder arthroplasty is chronic pseudoparalysis, which means incapability of scapular abduction, and one of the dramatic benefits from reverse total shoulder arthroplasty is the restoration of scapular abduction by lengthening of the deltoid lever arm. Several biomechanical studies of the abduction moment arm using computer analysis or cadaveric specimens have been published; however, there have been no studies measuring the abduction moment according to various neck-shaft angles of the humeral component and thereby revealing the best neck-shaft angle to overcome the pseudoparalysis, if any.

The subscapularis remains intact in a portion of patients with severe cuff tear arthropathy, and it is therefore important to understand the potential function of the remaining subscapularis in patients after reverse total shoulder arthroplasty. However, controversy remains about the clinical effect of the subscapularis tendon in reverse total shoulder arthroplasty, especially in terms of postoperative instability. Some authors claim that repair of the subscapularis has no effect on functional outcomes, whereas others suggest that an irreparable subscapularis at the time of reverse total shoulder arthroplasty results in an increased risk for postoperative dislocation.

Therefore, the purpose of this cadaveric study was to examine the effects of humeral component neck-shaft angle, specifically 155°, 145°, and 135°, in reverse total shoulder arthroplasty by measuring impingement-free range of motion (scapular plane adduction and internal and external humeral rotation), abduction moment, and anterior dislocation force at various humeral rotational angles. The effect of subscapularis integrity was evaluated by measuring the anterior dislocation force with and without subscapularis muscle loading. We hypothesized that the 155° neck-shaft angle will have less impingement-free range of motion, lower abduction moments, and greater dislocation forces compared with the other neck-shaft angles. We also hypothesized that loading of the subscapularis will increase the force required for anterior dislocation.

Materials and methods

Specimen preparation

Six fresh-frozen human cadaveric shoulders (4 left and 2 right from 3 men and 3 women) with a mean age of 68.3 years (range, 51–96 years) were used. The specimens were stored at −20°C, and each specimen was thawed overnight at room temperature in preparation for dissection and testing. The specimens were kept moistened with physiologic saline solution to prevent desiccation of the remaining soft tissues. All soft tissues were removed except the insertions of the teres minor, the subscapularis, and the anterior, middle, and posterior deltoid muscles on the humerus. Suture loops of 2-0 FiberWire (Arthrex Inc, Naples, FL, USA) were made with a modified Kessler stitch at the insertion of each muscle and the 3 insertion points of the deltoid.

Surgical procedures of the reverse total shoulder arthroplasty

Each specimen was implanted with the Aequalis reversed shoulder prosthesis (Tornier, Edina, MN, USA). Three humeral neck-shaft angles were evaluated: 155°, the standard neck-shaft angle for the Aequalis reversed shoulder prosthesis, and 145° and 135° neck-shaft angles (Fig. 1). The metaphyseal components of 145° and 135° neck-shaft angles were provided by the manufacturer and could be attached directly to the standard stem. To prepare the glenoid component, a hole near the center of the inferior glenoid circle was drilled with a guide to allow the use of the glenoid reamer. The preset guided reamer was used to ream the glenoid to achieve 10° of inferior tilt of the glenosphere to ensure minimal impingement and optimal force distribution. The baseplate was then fixed to the glenoid with superior and inferior baseplate screws. The superior screw was directed toward the base of the coracoid process in an anterosuperior direction; the inferior screw was drilled parallel to the lateral border of the scapula in a posteroinferior direction for optimal screw purchase and baseplate stability. The 36-mm glenosphere was then fastened to the baseplate.

The humerus was prepared by first making an oblique cut through the humeral head, using the cutting guide and an entry point at the most superior point of the humerus to ensure an osteotomy parallel to
the articular margin of the humeral head in each specimen to more closely preserve normal range of motion. The humeral shaft was then reamed, and the $155^\circ$ implant with a 9-mm stem was then placed in the humeral shaft to ensure proper version and fit. Once adequate placement and version were noted with the $155^\circ$ neck-shaft angle, the $145^\circ$ and $135^\circ$ neck-shaft angles were placed in the humerus and the osteotomized humeral neck was trimmed to ensure that all 3 neck-shaft angles could fit unobstructed within the humeral head. The standard 9-mm stem was customized for this study by drilling 2 holes perpendicular to the shaft of the stem for two transcortical screws in order to avoid cement fixation of the humeral implant so that the different neck-shaft angle implants could be interchanged for the same specimen. Two screws (2.7 mm) were placed transcortically through the stem of the implant, perpendicular to the axis of the humeral shaft, at 6.8 cm and 10.0 cm inferior to the most superior tip of the implant. Because changing the neck-shaft angle would also change the humeral height, the humeral heights were standardized to the $155^\circ$ neck-shaft angle. Before testing, the difference of humeral height between each neck-shaft angle was measured by a vernier height gauge, and custom spacers were developed to be placed between the stem and humeral head to adjust for the height difference while testing. Lateralized polyethylene inserts with a height of 9 mm were used for all 3 neck-shaft angles.

For each shoulder specimen, the neck-shaft angle was changed after all parameters were measured for a given neck-shaft angle. The neck-shaft angle was changed by unscrewing the humeral screws and removing the entire humeral component. The head of the humeral component was then unscrewed from the stem, and the humeral head of the new neck-shaft angle with its corresponding spacer was screwed on to the stem. The humeral stem with the new neck-shaft angle was then placed back in the humerus and secured by the same 2 humeral screws with use of the preexisting cortical holes from the prior neck-shaft angle. The custom spacers were also manufactured to ensure the appropriate humeral head version when each head was tightened to the stem.

**Biomechanical testing**

After implantation of the reverse total prosthesis, biomechanical testing was performed with a custom shoulder testing system used in previous shoulder biomechanical studies (Fig. 2). An aluminum rod was inserted into the medullary canal of the humeral shaft and secured with several screws to center the humerus with the aluminum rod. The scapula was fixed with 3 screws to an aluminum plate so that the medial border was oriented vertically with $20^\circ$ of anterior tilt in the sagittal plane. The aluminum rod was inserted in a custom device that incorporated a hollow shaft rotational potentiometer (Novotechnik US, Inc, Southborough, MA, USA) for measurement of humeral rotation. The custom
device allowed humeral axial rotation and also had the capability to lock the humeral rotation at a desired angle. The humeral rod attachment was then secured to the arc of the testing system, which allowed shoulder abduction in the scapular plane. Humeral axial rotation was defined on the basis of the anatomic relationship between the bicipital groove and the anterolateral corner of the acromion, as determined from a previous study. When the bicipital groove was aligned with the anterolateral corner of the acromion at 90° of shoulder abduction, the humeral rotation was defined as 20° of external rotation. Humeral abduction was determined by a digital level (M-D Building Products, Oklahoma City, OK, USA) that was manually aligned with the humeral aluminum rod. Zero degrees of abduction was defined when the humerus was perpendicular with the horizon. Muscles were loaded in an anatomic orientation with use of the previously placed tendon sutures with 5 N for the subscapularis, 5 N for the teres minor, and 15 N for the deltoid (5 N for each insertion point).

The abduction impingement angle, internal and external rotation impingement angle, abduction moments at the glenohumeral joint, and anterior dislocation forces were measured for each neck-shaft angle. The angle of impingement was determined by direct visualization of the polyethylene insert abutting the scapular neck and measured with a digital level aligned with the distal end of the humeral rod. Five impingement angles were measured: impingement with abduction at 0° of humeral rotation, and impingement with internal and external humeral rotation at 0° and 30° of shoulder abduction. For neck-shaft angles that did not reach 0° of adduction, internal and external rotations were measured at the lowest possible unimpinged angle of abduction. For each impingement angle, 2 observers took 2 separate measurements, allowing a 2° intraobserver and a 5° interobserver difference to ensure repeatability. If the repeatability between the measurements was greater, the measurements were repeated by both observers. If these conditions were satisfied, all 4 measurements were averaged to give a final impingement angle. The 2 observers were kept constant throughout the experiment.

The abduction moment of the glenohumeral joint was directly measured at both 0° and 30° of glenohumeral abduction with 0° of humeral rotation by a multiaxis load cell (ATI Industrial Automation, Garner, NC, USA) that was attached to the scapula-fixing aluminum plate (Fig. 2). These measurements were recorded while the load on the middle deltoid was increased from 5 N to 30 N, in increments of 5 N with constant loads of 5 N applied to the subscapularis, teres minor, anterior deltoid, and posterior deltoid. The final loading force (30 N) was determined as a safe force to maintain the suture loop used for force loading through several pilot trials. Repeated incremental loading of the middle deltoid was done for every condition to ensure reproducibility, and the 2 values were averaged if the moments were within 0.5 Nm of each other.

The anterior dislocation forces were measured at 30° of glenohumeral abduction with the humerus locked in 3 positions: 30° of internal rotation, 0° of rotation, and 30° of external rotation. The anterior dislocation forces were measured with 5-N loads applied to the subscapularis, teres minor, and anterior, middle, and posterior deltoid and then repeated without the subscapularis loading. The proximal humerus was pulled anteriorly with a specially designed traction system (Fig. 2) that measured the dislocation force with an S-type force transducer (Interface Advanced Force Measurement, Scottsdale, AZ, USA). A fishing line was tied to the proximal humerus at the most superior insertion of the pectoralis major. This position was chosen to provide an anatomic reference to reproducibly apply the anteriorly directed load. The fishing line was then attached to a ratchet and force transducer that was suspended from the testing system and aligned directly anterior to the humerus and parallel to the horizon. The string was then tightened incrementally with the ratchet device and the force in the string monitored until the humerus began to sublux. The highest force before subluxation measured with the force transducer was then recorded. Two trials were performed for each neck-shaft angle, allowing a 5-N difference in repeatability between the 2 measurements. The values from the 2 trials were then averaged to give a final measurement. To evaluate the effect of subscapularis loading, the anterior dislocation forces were measured for each neck-shaft angle with and without subscapularis loading.

A repeated-measures analysis of variance with a Tukey post hoc test was performed to compare the adduction, internal and external rotation impingement angles, glenohumeral abduction moments, and anterior dislocation forces for all 3 neck-shaft angles. In addition, a paired t test was performed to compare the anterior dislocation forces between the loaded and unloaded subscapularis measurements. Statistical significance was set at $P < .05$.

**Results**

At 0° of humeral rotation, the 155° neck-shaft angle was the only angle that impinged before reaching adduction (2° ± 5° of abduction). The adduction impingement angles for the 145° and 135° neck-shaft angles at 0° of humeral rotation were found to be 7° ± 4° and 12° ± 2° of adduction, respectively.

The impingement angle for the 155° neck-shaft angle was significantly less than the impingement angles for both the 145° neck-shaft angle ($P = .004$) and the 135° neck-shaft angle ($P = .0003$). However, there was no statistical difference in the adduction impingement angle between the 145° and 135° neck-shaft angles ($P = .053$). At 0° of
abduction with the 155° neck-shaft angle, 4 of the 6 specimens did not have bone impingement in either internal or external rotation, and 1 of the 6 specimens for the 145° neck-shaft angle also did not have bone impingement. There were no significant differences in comparing those specimens that had bone impingement in internal and external rotation at 0° of abduction (Fig. 3, A). There were also no significant differences in internal and external rotation impingement angles between the different neck-shaft angles at 30° of shoulder abduction (Fig. 3, B).

There was a trend toward decreased abduction moment for the 135° neck-shaft angle at 0° of abduction; however, this was not statistically significant. The differences in abduction moments were not statistically significant between the 3 different neck-shaft angles for all applied forces to the middle deltoid for either 0° or 30° of abduction (P > .05; Fig. 4).

With the subscapularis loaded, the anterior dislocation force was significantly higher for the 135° neck-shaft angle than for the 155° neck-shaft angle at 30° of humeral internal rotation (P = .006). However, there was no significant difference in anterior dislocation force at the 0° rotation position between the 3 neck-shaft angles (Fig. 5). With the subscapularis unloaded, there was no statistically significant difference in the dislocation forces between the different neck-shaft angles at all 3 humeral rotational angles (P > .05; Fig. 5). The anterior dislocation forces were significantly higher when the subscapularis was loaded for all 3 neck-shaft angles (i.e., 135°, 145°, and 155°) at all 3 humeral rotational angles (i.e., 30° internal rotation, 0°, and 30° external rotation; P < .01).

**Figure 3**  The impingement angles during internal and external rotation were shown at 0° shoulder abduction (A) and 30° shoulder abduction (B).

**Figure 4**  The abduction moment for all applied forces to the middle deltoid at 0° (A) and 30° (B) abduction angles.

**Discussion**

Reverse total shoulder arthroplasty has become the treatment of choice for patients with pseudoparalysis due to massive irreparable rotator cuff tear with glenohumeral arthritis as well as severe proximal humerus fracture sequelae and
prosthesis revision in rotator cuff–deficient shoulders and has resulted in excellent functional improvement as well as pain relief.\textsuperscript{5,14,29} Even though several authors have reported good clinical outcomes, there are still a host of problems and complications reported in the literature, including scapular notching, instability, baseplate failures, and infections.\textsuperscript{4} Therefore, we investigated the biomechanical effect of the humeral neck-shaft angle in reverse total shoulder arthroplasty on scapular notching and instability and demonstrated that the 155° neck-shaft angle implant had a larger adduction deficit than the other neck-shaft angles. The 155° neck-shaft angle was also found to have the lowest dislocation force in the externally rotated position and the highest dislocation force at the internally rotated position. The differences in neck-shaft angle did not affect the abduction moment, and subscapularis loading improved stability regardless of neck-shaft angle.

Various efforts have been made to reduce the complication rate of reverse total shoulder arthroplasty, such as increasing the center of rotation offset, inferior glenosphere placement, and inferior glenosphere tilt.\textsuperscript{14,20,25} Despite these modifications, scapular notching of 24.5% to 96% has been reported.\textsuperscript{4,27} Contrary to the glenoid component, few previous studies have investigated the neck-shaft angle of the humeral component in reverse total shoulder arthroplasty. Our results support those previously reported by Gutierrez et al.\textsuperscript{14} who found that decreasing the neck-shaft angle allowed increased adduction of the humerus before scapular impingement for varying amounts of lateral offset. Whereas increasing lateral offset also decreased the adduction deficit, the humeral neck-shaft angle was found to have a greater influence on adduction deficit. The impingement-free range of motion during internal and external rotation was not different between the various neck-shaft angles. This suggests that rotational scapular notching is not related to the neck-shaft angle of the humeral component but a matter of implant version. A previous cadaveric study that examined the effect of humeral component version on scapular notching in reverse total shoulder arthroplasty demonstrated that proper retroversion of the humeral component might reduce scapular notching by achieving rotational balance.\textsuperscript{27}

Abduction moment is dependent on the moment arm of the deltoid muscle. The reverse total shoulder prosthesis moves the joint center of rotation medially and inferiorly, thereby increasing the moment arm of the deltoid.\textsuperscript{3} Grammont and Baulot\textsuperscript{11} found that if the center of the glenoid hemisphere was medialized by 10 mm, the abduction moment arm of the deltoid increased by 20% when the arm was abducted to 60°. We postulated that decreasing the neck-shaft angle should lateralize the humeral contact point on the glenosphere, increasing the deltoid moment arm and potentially increasing the abduction moment. This hypothesis was disproven in this study as we did not show any statistical difference in abduction moment, perhaps because of the small changes in moment arm with change in neck-shaft angle.

A variety of factors are related to the instability of a reverse total shoulder arthroplasty: prior surgery, poor deltoid function, surgical approach, soft tissue tension after implanting, subscapularis reattachment, and implant design factors, such as a medial center of rotation, insert depth, sphere diameter, and offset.\textsuperscript{1} The clinical significances and implications of these factors are not completely understood. The anterior dislocation forces increased as the humerus rotated from internal rotation to external rotation because of the contact configuration of reverse total shoulder arthroplasty. Therefore, external rotation should be considered a more stable position for anterior stability. At the unstable internal rotation position, the 155° neck-shaft angle might result in more anterior stability through the articular contact at the inferior aspect of the glenosphere compared with the 135° neck-shaft angle. However, at the more stable external rotation position, the 135° neck-shaft angle might provide more anterior stability than the 155° neck-shaft angle because of the articular contact being located at a more superior part of the glenosphere. However, there were no differences between the 3 neck-shaft angles at 0° of humeral rotation, suggesting that the articular contact location at a certain rotational position might be the determinant factor for stability.

In relation to instability, subscapularis integrity after reverse total shoulder arthroplasty has recently received considerable attention in the literature. Boulahia et al.\textsuperscript{5} stated that repair of the subscapularis did not affect the functional outcome after reverse total shoulder arthroplasty. Wall et al.\textsuperscript{28} also reported no effect of subscapularis repair on postoperative complications in their series. However, Edwards et al.\textsuperscript{10} demonstrated that an insufficient subscapularis at the time of reverse total shoulder arthroplasty significantly increased the risk of postoperative dislocation. Our study supports the notion that subscapularis repair plays a role in stability after reverse total arthroplasty. Therefore,
subscapularis integrity should be considered an important outcome parameter after reverse total shoulder arthroplasty. There are several limitations to the present study. First, this was a cadaver study, and limited positions were tested in the scapular plane. We chose several clinically relevant positions for activities of daily living but acknowledge that not all clinically relevant positions were tested. Second, we evaluated anterior instability only, not inferior or posterior instability, and we acknowledge that it is more difficult to define the direction of instability after reverse total shoulder arthroplasty. Therefore, we tested only anterior stability according to common clinical situations. Third, the muscle forces acting on the in vivo glenohumeral joint are more complex than in our model. Fourth, we used only one implant design in our study, and it is possible that other implant designs may behave differently. Finally, for the measurement of abduction moment, the load cell might not be sensitive enough to detect differences in abduction moment because of the small changes in moment arm that occurred with the changes in neck-shaft angles.

Conclusion

The 155° neck-shaft angle implant was more prone to scapular bone contact during adduction but had the advantage of being more stable at the internally rotated position, which was the least stable humeral rotation. The differences in neck-shaft angle did not affect the abduction moment, and subscapularis loading increased anterior stability regardless of the neck-shaft angle. Therefore, neck-shaft angle of the humeral implant is another important variable for successful reverse total shoulder arthroplasty.

Disclaimer

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