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Stresses in the Scapular Fossa Do Not Exceed the Yield Stress When Elevated up to 135 Degrees of Abduction after Reverse Shoulder Arthroplasty

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ABSTRACT

Reverse shoulder arthroplasty (RSA) is an effective treatment for rotator cuff tears. Despite its advantages, complications occur at a high rate. Complications requiring revision include a high rate of base plate failure, 38% of which are due to instability. The primary stability the base plate ensures is a crucial factor and, thus, is the subject of much debate in clinical studies and biomechanical research. This study is aimed to provide data that will contribute to the base plate's primary stability and glenoid longevity by clarifying the stresses at the scapular fossa and base plate interface associated with elevation after RSA. A 3D finite element model was created from the DICOM data for the scapulohumeral joint and SMR shoulder system. For loading conditions, 30 N was applied for each position with abduction angles of 0, 45, 90, and 135 degrees. A three-dimensional finite element analysis was performed using the static implicit method with LS-DYNA. The von Mises stresses in the scapular fossa were found not to exceed the yield stress on the bone even after elevation to an abduction angle of 135 degrees after RSA. It is rough to uniformly compare the yield stress and the von Mises stress, but it was inferred that the possibility of fracture is low unless a large external force is applied. A maximum von Mises stress showed 0 degrees of abduction, suggesting that the lowered position is in a more severe condition than the elevated position. If better improvement is desired, it may be necessary to devise ways to reduce the stress on the upper screw.

1. INTRODUCTION

The two main causes of rotator cuff tears are injury and wear. Because most wears are largely caused by the normal wear and tear that goes along with aging, people over 40 are at greater risk. Surgery may be indicated if the pain does not improve by non-surgical means. Surgery to repair a torn rotator cuff most often involves re-attaching the tendon to the head of the humerus. A traditional open surgical incision is often required if the tear is large or complex. Nevertheless, this type of procedure is not as beneficial for patients with large rotator cuff tears who have developed a complex type of shoulder arthritis called cuff tear arthropathy. For these patients, conventional total shoulder replacement may result in pain and limited motion, and reverse shoulder replacement (RSA) is a better option [1-3].

Reverse shoulder arthroplasty is an effective treatment for rotator cuff tears. Despite its advantages and ever-expanding indications, the complication rate is higher than in Total Shoulder Arthroplasty (TSA) [4, 5]. Base plate failure accounts for the highest percentage of complications requiring postoperative revision, with 38% of the causes being instability [4, 6]. This indicates the base plate primary stability of the base plate is crucial. The assessment of primary stability should be compared to scientific evidence, such as the yield stress on the scapula, which we believe will lead to a longer life of the glenoid.

Compared to TSA, Grammont-style RSA has an advantage in elevation because the upper arm is lowered and the deltoid is extended, resulting in a more extended moment arm [4, 7]. Although RSA theoretically extends the shoulder's range of motion, few reports compare stresses and strains on the scapular fossa and other biomechanical data in the abductions, respectively. Patients spend most of their time in the lowered abduction position daily. The biomechanical knowledge gained about the degree of stress produced by the abduction is clinically informative. Not only surgeons but also engineers engaged in implant development will lead RSA to success, provided that they understand the relationship between these indicators and clinical outcomes to improve the function of the shoulder joint after surgery [7].

This study aims to determine the stress at the scapular fossa and base plate interface after RSA. Comparison of stresses at the scapular fossa with literature values will allow discussion of fracture likelihood and implant failure. The distribution of stresses exerted on the scapular fossa by the peg and screw will provide insight into improvements in prosthesis design and lead to longer life of the glenoid [8]. Knowledge of these mechanical parameters after the device is implanted will lead to improved surgical procedures, which in turn will produce superior clinical outcomes.

2. MATERIALS AND METHODS

The finite element model was constructed from DICOM data obtained by CT imaging of the scapula model (A Pacific Research Company, WA, USA). Consent was obtained from Lima for the acquisition of the three-dimensional geometry of the SMR shoulder system (Lima, Italy). Permission was obtained from Lima for the acquisition of geometry data for the SMR shoulder system. The analytical model was constructed in five parts: Scapula, 36 mm Glenosphere, Base plate, Upper screw, and Lower screw. Elements were subdivided into a total of 58,450 to improve accuracy (**Figure 1**). The physical properties of the analytical model were assumed to be CoCrMo for the glenosphere, base plate, and pegs, Ti-6Al-4V for the upper and lower screws, and the scapula was assumed to be the cancellous bone of an aged person with severe conditions [9, 10]. These materials were homogeneous, and material constants were defined based on the literature (**Table 1**) [11, 12].

The medial border of the scapula was fixed entirely as a boundary condition [13]. The glenosphere was placed 4 mm inferior to the scapular fossa to avoid scapular notching [14, 15]. For the contact conditions between the scapula and the artificial shoulder joint, the two were not fixed but only made contact. The loading condition was 30 N applied as the weight of the upper arm. The rationale was based on the assumption that an aged Asian weighs 50 kg and that the load on the glenosphere was calculated to be the weight of the upper arm, equivalent to 6% of the body weight or 3 kg. The loading directions were 0, 45, 90, and 135 degrees of abduction with respect to the base plate installation surface to simulate elevation (**Figure 2**) [16].

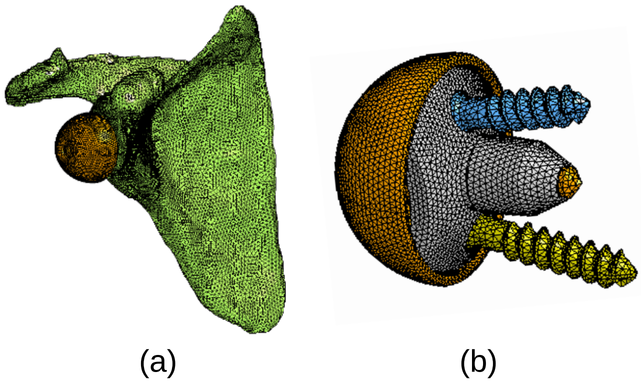

Figure 1. Three dimentional finite elements models. (a) Scapula and glenosphere; (b) Base plate and central peg. Blue is upper cancellous screw. Yellow is lower cancellous screw.

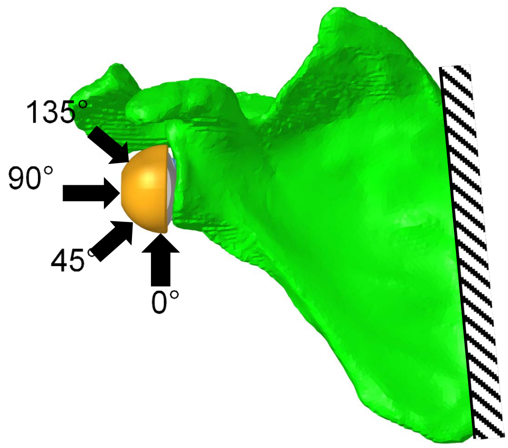

Figure 2. Boundary and load conditions. Fixed the shaded area. 30 N was applied in the direction of the arrow.

Table 1. Material properties for each component.

	CoCrMo	Ti6Al4V	Scapula
Density [kg/m³]	8.30×10^3	4.40×10^3	1.80×10^3
Elastic modulus [GPa]	215	100	17
Poisson's ratio [−]	0.30	0.34	0.30

A Precision 3650 (DELL, TX, USA) workstation was used for the analysis. The software LS-DYNA ver. R11.1 (LSTC, CA, USA) was used for the static implicit analysis. A comparison was made with simulation results published in the literature [17, 18] to validate the model. The load applied in the literature was 100 N. The loading direction was perpendicular to the contact surface between the bone and the base plate. The same loading conditions were used for the comparison of results. The maximum principal stress results agreed with the literature results (**Table 2**).

Table 2. Model validation using maximum principal stress and micromotion.

Maximum principal stress [MPa]	
Our results	2.9
Results from literature [Friedman 2021]	2.5
Results from literature [Farron 2006]	2.9

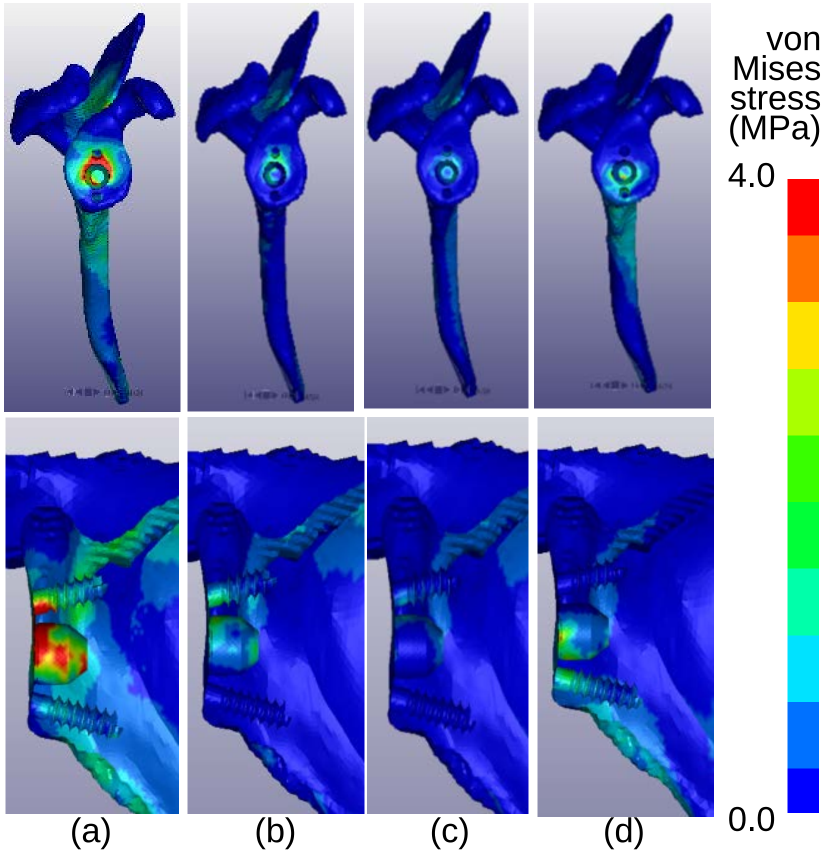

Figure 3. Von Mises stress distribution. The top images show the stress distribution in the sagittal plane of the scapular fossa. Left is anterior. Right is posterior. The lower images show the stress distribution in the frontal plane at the center of the peg. (a) Abduction 0˚; (b) Abduction 45˚; (c) Abduction 90˚; (d) Abduction 135˚.

3. RESULTS

The von Mises stress of the scapular fossa was found not up to 135 degrees of abduction after RSA. The von Mises stress in the scapular fossa was 4.39 MPa at an abduction angle of 0 degrees, which was higher than at other abduction angles. The stress distribution showed that as the abduction angle increased, the stress of about 1 MPa shifted from the upper screw to the lower screw (Figure 3).

4. DISCUSSION

Interest in RSA has been high, with a series of reports in biomechanical studies as well as clinical studies [6, 7, 19, 20]. Attempts have been made to improve implant designs to solve the revision problem, and new designs of Reverse Shoulder Prostheses have been launched one after another by various manufacturers. As designs evolve, continued discussion and scrutiny of the relationship between each implant and clinical outcomes should lead to successful RSA. Presumably, the conditions are more severe for the scapular fossa in the lowered position than in the elevated position. If better designs are desired, it may be necessary to devise ways to reduce the stress on the upper screw. Regarding scapular spine fractures after RSA, Kennon *et al.* reported significantly more scapular and scapular spine fractures in the group where an upper screw was inserted [21]. The idea that higher stresses around the upper screw will likely lead to more fractures is consistent with the stress distribution results.

Osteoporosis has been reported to be a significantly higher risk factor in scapula fractures after RSA [22]. Peri-implant fractures are a complication to be aware of after RSA. For the bone quality of aged patients for whom RSA is indicated, comparisons with yield stress allow a scientifically based determination of postoperative fracture risk. Therefore, we performed an analysis assuming cancellous bones aged persons. The von Mises stress was lower than 135 MPa, which is the yield stress on the cancellous bone, and we inferred that fracture was unlikely [23]. We inferred from this that the RSA for the aged persons would avoid bone quality-dependent failures. However, there is a lack of evidence to accurately determine the risk of postoperative fractures.

In this study, we preferred to draw a simple conclusion by reducing the number of divided cases. We did not dare to increase the parameters and set up the base plate with a glenoid inclination of 0 degrees and a glenoid version of 0 degrees. First, our report should be interpreted simply in light of this process, and we are prepared to continue the report with more parameters. A limitation of this study is that the scapula was treated as a homogeneous material. Because of this, values for stress, strain, and micromotion are expected to vary. Given the anisotropic nature of bone, however, our conclusion will not be overturned that prostheses gain stability leading to bone growth.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

REFERENCES

1. Cuff, D., Clark, R., Pupello, D., *et al.* (2012) Reverse Shoulder Arthroplasty for the Treatment of Rotator Cuff Deficiency: A Concise Follow-Up, at a Minimum of Five Years, of a Previous Report. *The Journal of Bone and Joint Surgery*, **94**, 1996-2000. https://doi.org/10.2106/JBJS.K.01206

2. Frankle, M., Siegal, S., Pupello, D., *et al.* (2005) The Reverse Shoulder Prosthesis for Glenohumeral Arthritis Associated with Severe Rotator Cuff Deficiency. A Minimum Two-Year Follow-Up Study of Sixty Patients. *The Journal of Bone and Joint Surgery*, **87**, 1697-1705. https://doi.org/10.2106/00004623-200508000-00005

3. Smith, C.D., Guyver, P. and Bunker, T.D. (2012) Indications for Reverse Shoulder Replacement: A Systematic Review. *The Bone and Joint Journal*, **94**, 577-583. https://doi.org/10.1302/0301-620X.94B5.27596

4. Boileau, P., Watkinson, D.J., Hatzidakis, A.M., *et al.* (2005) Grammont Reverse Prosthesis: Design, Rationale, and Biomechanics. *Journal of Shoulder and Elbow Surgery*, **14**, 148S-161S. https://doi.org/10.1016/j.jse.2004.10.006

5. Stephens, B.C., Simon, P., Clark, R.E., *et al.* (2016) Revision for a Failed Reverse: A 12-Year Review of a Lateralized Implant. *Journal of Shoulder and Elbow Surgery*, **25**, 115-124. https://doi.org/10.1016/j.jse.2015.09.027

6. Boileau, P., Moineau, G., Roussanne, Y., *et al.* (2011) Bony Increased-Offset Reversed Shoulder Arthroplasty: Minimizing Scapular Impingement While Maximizing Glenoid Fixation. *Clinical Orthopaedics and Related Research*, **469**, 2258-2567. https://doi.org/10.1007/s11999-011-1775-4

7. Henninger, H.B., Barg, A., Anderson, A.E., *et al.* (2012) Effect of Lateral Offset Center of Rotation in Reverse

Total Shoulder Arthroplasty: A Biomechanical Study. *Journal of Shoulder and Elbow Surgery*, **21**, 1125-1135. https://doi.org/10.1016/j.jse.2011.07.034

8. Sanjay, G. and Prosenjit, D. (2004) Bone Geometry and Mechanical Properties of the Human Scapula Using Computed Tomography Data. *Trends in Biomaterials and Artificial Organs*, **17**, 61-69.
9. Huang, Y., Ernstbrunner, L., Robinson, D.L., *et al.* (2016) Complications of Reverse Total Shoulder Arthroplasty: A Computational Modelling Perspective. *Journal of Clinical Medicine*, **10**, 5336. https://doi.org/10.3390/jcm10225336
10. Anglin, C., Tolhurst, P., Wyss, U.P., *et al.* (1999) Glenoid Cancellous Bone Strength and Modulus. *Journal of Biomechanics*, **32**, 1091-1097. https://doi.org/10.1016/S0021-9290(99)00087-1
11. Denard, P., Lederman, E., Persons, B.O., *et al.* (2016) Finite Element Analysis of Glenoid-Sided Lateralization in Reverse Shoulder Arthroplasty. *Journal of Orthopaedic Research*, **35**, 1548-1555. https://doi.org/10.1002/jor.23394
12. Yang, C.C., Lu, C.L., Wu, C.H., *et al.* (2013) Stress Analysis of Glenoid Component in Design of Reverse Shoulder Prosthesis Using Finite Element Method. *Journal of Shoulder and Elbow Surgery*, **22**, 932-939. https://doi.org/10.1016/j.jse.2012.09.001
13. Bonnevialle, N., Geais, L., Muller, J.H., *et al.* (2020) Effect of RSA Glenoid Baseplate Central Fixation on Micromotion and Bone Stress. *JSES International*, **4**, 979-986. https://doi.org/10.1016/j.jseint.2020.07.004
14. Nyffleler, R.W., Werner, C.M.L. and Gerber, C. (2005) Biomechanical Relevance of Glenoid Component Positioning in the Reverse Delta III Total Shoulder Prosthesis. *Journal of Shoulder and Elbow Surgery*, **14**, 524-528. https://doi.org/10.1016/j.jse.2004.09.010
15. Mollon, B., Mahure, A.S., Roche, P.C. and Zuckerman, D.J. (2017) Impact of Scapular Notching on Clinical Outcomes after Reverse Total Shoulder Arthroplasty: An Analysis of 476 Shoulders. *Journal of Shoulder and Elbow Surgery*, **26**, 1253-1261. https://doi.org/10.1016/j.jse.2016.11.043
16. Berliner, J.L., Regalado-Magdos, A., Ma, B.C. and Feeley, T.B. (2015) Biomechanics of Reverse Total Shoulder Arthroplasty. *Journal of Shoulder and Elbow Surgery*, **24**, 521-526. https://doi.org/10.1016/j.jse.2014.08.003
17. Farron, A., Terrier, A. and Büchler, P. (2006) Risks of Loosening of a Prosthetic Glenoid Implanted in Retroversion. *Journal of Shoulder and Elbow Surgery*, **15**, 521-526. https://doi.org/10.1016/j.jse.2005.10.003
18. Friedman, R.J., Sun, S., She, X., *et al.* (2021) Effects of Increased Retroversion Angle on Glenoid Baseplate Fixation in Reverse Total Shoulder Arthroplasty: A Finite Element Analysis. *Seminars in Arthroplasty*, **31**, 209-216. https://doi.org/10.1053/j.sart.2020.11.014
19. Matsuki, K., King, J.J., Wright, T.W. and Schoch, B.S. (2018) Outcomes of Reverse Shoulder Arthroplasty in Small- and Large-Stature Patients. *Journal of Shoulder and Elbow Surgery*, **27**, 808-815. https://doi.org/10.1016/j.jse.2017.11.011
20. Routman, H.D., Flurin, P.H. and Wright, T.W. (2015) Reverse Shoulder Arthroplasty Prosthesis Design Classification System. *Bulletin of the Hospital for Joint Diseases*, **73**, S5-S14.
21. Kennon, J.C. and Crosby, L.A. (2014) Reverse Shoulder Arthroplasty for Massive Cuff Tears in Patients <65 Years: An Age-Old Dilemma. *Seminars in Arthroplasty*, **25**, 262-267. https://doi.org/10.1053/j.sart.2015.02.006
22. Nabergoj, M., Denard, P.J., Collin, P., *et al.* (2021) Mechanical Complications and Fractures after Reverse Shoulder Arthroplasty Related to Different Design Types and Their Rates: Part I. *EFORT Open Reviews*, **6**, 1097-1108. https://doi.org/10.1302/2058-5241.6.210039
23. Bayraktar, H.H., Morgan, F.E., Niebur, L.G., Morris, E.G., Wong, K.E. and Keaveny, M.T. (2004) Comparison of the Elastic and Yield Properties of Human Femoral Trabecular and Cortical Bone Tissue. *Journal of Biomechanics*, **37**, 27-35. https://doi.org/10.1016/S0021-9290(03)00257-4