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ORIGINAL ARTICLE

Three-Dimensional Finite Element Analysis of a Notched Insert Design for Reverse Total Shoulder Arthroplasty to Prevent Scapular Notching

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Abstract

Purpose Reverse total shoulder arthroplasty (RSA) is an effective treatment option for rotator cuff arthropathy. Scapular notching following RSA remains a major complication and has a high incidence. This finite element analysis (FEA) study provides a future reference for the optimal design of the insert component of RSA. This study aims to clarify the effect of a new design RSA with a notched insert on the range of adduction, scapular notching, and stress variation of its insert component using three-dimensional (3D) FEA.

Methods 3D nominal Grammont-type monobloc RSA implant components are modeled on the sawbones glenohumeral joint. The polyethylene insert is redesigned with notching of the inferior part. The comparison of standard and notched designs was performed by FEA for stress pressure of scapular notching and the degree of adduction. 3D mesh models are created for stress analysis to compare the results between standard and notched inserts for the adduction.

Results The redesigned notched inserts had an additional ~ 11.2° on adduction and prevented scapular notching. The stress analysis results for the notched insert design were lower than the standard ones (4.7 vs 22.4 Kpa).

Conclusions Notched insert design of Grammont-type RSA could provide additional adduction with lower stress on the glenoid, leading to less scapular notching. Further experimental and clinical studies on different RSA types are needed to verify this effect.

Study Design Basic Science Study; Biomechanics and Computer Modeling.

Keywords Reverse total shoulder arthroplasty · Scapular notching · Insert · Finite element analysis · Notched insert · Cuff tear arthropathy

Introduction

Rotator cuff arthropathy is the primary and classical indication for reverse total shoulder arthroplasty (RSA). However, the expanding indications are pseudoparalysis due to massive cuff tears, tumor resection, revision shoulder arthroplasty, fracture sequelae, and unreconstructable proximal humerus fractures [1]. RSA is designed on the principle of reversing the natural biomechanics of the glenohumeral joint, where the humerus transforms into a socket and the glenoid into a ball. This non-anatomical design medializes and lowers the center of rotation so that both shear forces are reduced and the lever arm of the deltoid is improving [2]. Despite successful clinical results reported in short- and

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medium-term studies, RSA has significant revision rates in long-term follow-up [3]. Depending on the reverse design of RSA and the anatomical and physical characteristics of the patients, many complications similar to traditional total shoulder arthroplasty (TSA) and specific to reverse prosthesis are observed. These complications include neurological injury, hematoma, infection, dislocation or loosening, scapular fractures, and scapular notching [4]. Due to the expanding RSA indications, the frequency of application has increased and the frequency of complications has increased accordingly.

The altered center of rotation due to the original design of the RSA tends to cause mechanical impingement between the inferomedial aspect of the humeral polyethylene insert and the lower part of the scapular neck. This repetitive mechanical contact results in scapular notching, one of the most commonly reported complications associated with RSA. Although the incidence of scapular notching has been reported between 50 and 96% in various studies, according to many authors, glenoid component implantation applied with older techniques inevitably causes scapular notching [2, 5, 6]. Scapular notching has been shown clinically to harm the long-term outcomes of reverse shoulder arthroplasty, and impingement might induce prosthetic wear and osteolysis [7]. Many changes have been made in RSA designs to reduce notching, including enlarging or lateralizing the glenosphere, altering the polyethylene insert, glenosphere eccentricity, and neck-shaft angle [8–10]. Although there are many studies in the literature on prosthetic components to reduce and prevent scapular notching, the notched insert design will be the first to our knowledge.

The hypothesis of this study is to prevent scapular notching, which is a major problem especially for Grammont-type prostheses, by proposing a new notched insert design. A notched insert design can provide additional adduction while reducing scapular notching by reducing pressure on the glenoid.

Materials and Methods

Three-dimensional (3D) nominal Grammont-type monoblock RSA implant components were modeled on the sawbones glenohumeral joint which is called finite element analysis (FEA) that is increasingly used in orthopedics and biomedical fields and allows for planning the ideal implants and prostheses [3, 11, 12]. The polyethylene insert was redesigned with a notching of the inferior part. To compare the standard and notched designs, 3D FEA is used for stress pressure of scapular notching and the degree of adduction. 3D mesh models were created for stress analysis to compare the results between standard and notched inserts for the adduction.

The nominal prosthesis stem and nominal polyethylene pieces were modeled in three dimensions with the actual measurements via Unigraphics *(software version NX™, July 2002, Plano / Texas)*. The monoblock Grammont-type design prosthesis model we referenced offers 38 or 42 mm outer diameter and + 3, + 6, + 9 options as standard for the humeral cup polyethylene insert (*Delta Xtend.Pdf*, n.d.). Since we designed a notched insert, we preferred the longest 9 mm insert option with a 38 mm outer diameter, which is appropriate for the humerus and scapula we have modeled. The insert thickness was calculated as 10 mm when 1 mm of space left for possible revisions in the original design was added to this.

The new design prosthesis stem was modeled with a length dimension of 140 mm and a 155° neck-shaft angle similar to the nominal model. However, given the design change in the polyethylene part, the thickness of the region where scapular notching was most commonly seen, was reduced from 10 to 6 mm. A notched design was created by performing a breaking process with a diameter of 2 mm in the inferior of the polyethylene, where the notching occurred. On the one hand, it was determined as 4 mm in diameter to create sufficient breaking to prevent scapular notching; on the other hand, it was aimed to avoid possible instability by leaving 6 mm in the thinnest part of the insert (Fig. 1).

Scapula and the Prosthesis Head: As scapular notching mainly affects the inferior portion of the glenoid and

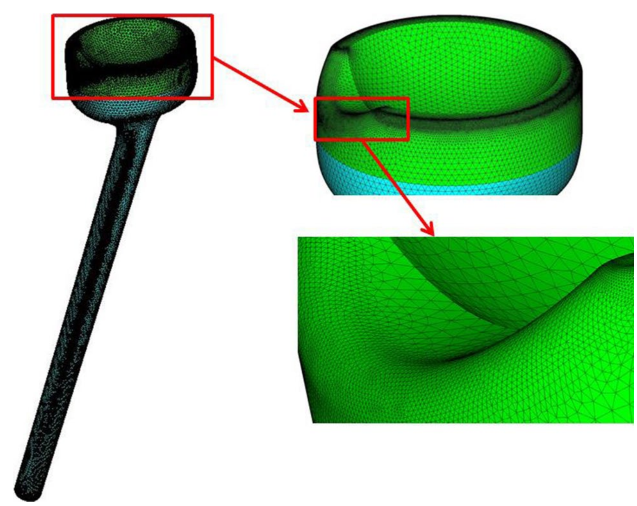

Fig. 1 The notched insert design. The humeral stem is modeled in the new design model, as in the nominal model, with a 140 mm length and a 155° shank inclination. However, with the design altered in the polyethylene part, the thickness of the area where scapular notching is seen most was reduced from 10 to 6 mm. Afterward, a softer surface was created in case of possible contact by breaking the corner with a radius of 2 mm to the area where this material was removed

prosthetic head, the remaining parts were not modeled. The prosthesis head was designed with a diameter of 38 mm.

Humerus: As scapular notching occurs between the polyethylene and the scapula, the humerus model was not utilized in the analysis.

Material Selection: The materials of the parts used in the models were selected by investigating the modulus of elasticity and Poisson's ratio, following human anatomy and current designs. The prosthesis stems and prosthetic headpiece was selected as titanium. The insert was chosen to be polyethylene.

Assembly: The nominal and new design models created were assembled in the Unigraphics program and their designs were checked.

Finite Element Model: Applying the required load and limit conditions, stress analysis was performed for the nominal and new design prosthesis with the models defined geometric and material structure.

Von Mises and Tresca's hypotheses are used for ductile materials, as it takes advantage of the yield strength of the material. Although normal stresses and shear stresses can be looked at separately when evaluating FEA results, a combined stress value is needed to compare these results with yield strength. For this case, Von Mises's stress theory is used in the FEA model [13]. In this study, the stress results of the nominal and new design models are Pa and compared over Von Mises values, and following the hypothesis, scapular notching and scapular stresses are focused.

The loading and limitation conditions were assumed to be frictionless. There was a firm contact between the polyethylene and the prosthetic head. The back surface of the scapula was held in the X, Y, and Z planes so that it was fixed. Besides, the motion of the humeral prosthesis was restricted perpendicular to the page plane (Y-axis). The purpose was to observe the effect which may have only risen from the horizontal adduction motion. The force was given the same in both models. Considering the heaviest loads we can handle in daily life, the effect of the moment that 20 kg of weight will create on our arm on the implant arm has been calculated. When our arm is in 90-degree abduction and a 20 kg load is lifted, we calculated the resulting force as approximately 1000N.

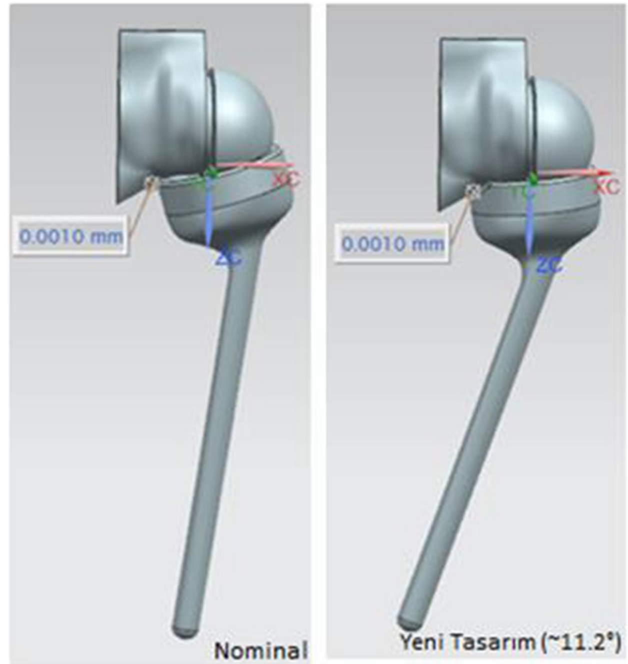

Fig. 2 Modeling of extra adduction motion provided by notched insert design against nominal design. It is calculated that the new design model gives ~ 11.2° extra adduction range of motion after the newly designed models are created with the nominal prosthetic parts whose three-dimensional models are created with their real dimensions. Scapular notching, which is seen even when the arm is at rest, is predicted to occur only during extreme adduction movements of the arm due to this additional range of motion

Results

The redesigned notched inserts gained an additional 11.2° of adduction (Fig. 2). After contact of the polyethylene with the scapula, tension occurred at the contact points as notching occurred. The resultant stress was 22.4 Kpa for the nominal prosthesis. This was 4.7 Kpa for the new design prosthesis (Fig. 3). In the case of contact of the polyethylene insert with the scapula, the stress was 36.5 kPa in the nominal design; while, it was 5.5 kPa in the new design prosthesis (Fig. 4). With the 3D stress analysis performed under the same loading and limit conditions, surface enhancements made in the new design model resulted in lower stress values.

Discussion

The notched insert design modeled in this finite element analysis promises to reduce scapular notching, one of the most common complications of RSA, and to increase the amount of adduction by more than 10°.

The popularity of total reverse shoulder arthroplasty is constantly increasing today. Although its indications have expanded over time, it has become a standard procedure, especially for cuff tear arthropathy. In light of Grammont's core principles, the search for the ideal RSA design continues.

Grammont-type RSA has significantly improved its ability to treat patients with rotator cuff disorders and shoulder arthritis. Although there are many complications associated with RSA such as scapular notching, dislocation, glenoid loosening, unscrewing, infection, scapular spine and

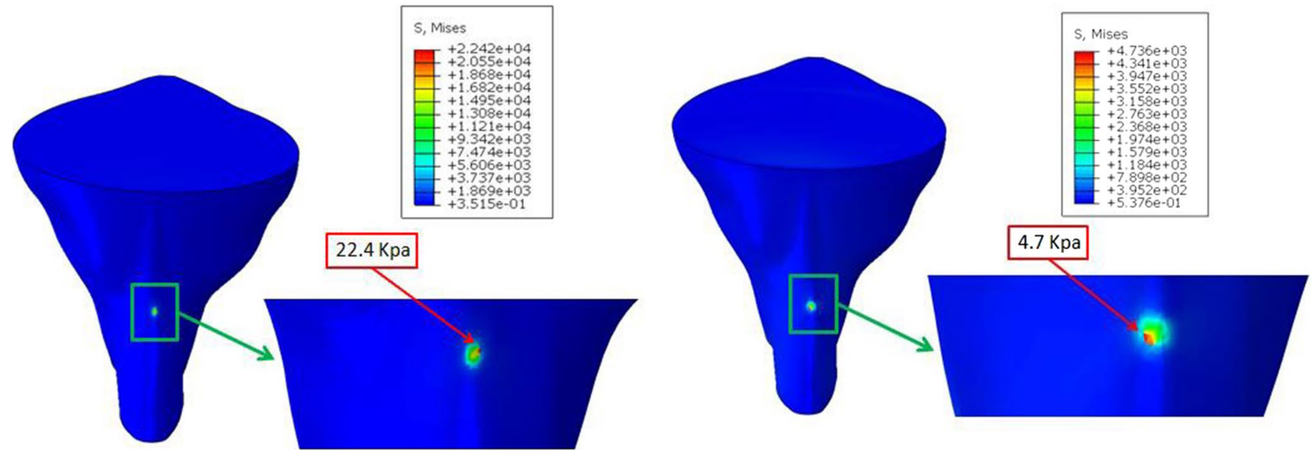

Fig. 3 Comparison of the stress distribution results on the glenoid of nominal and notched designed prostheses. After contact of the polyethylene with the scapula, tension occurred at the contact points as notching occurred. The resultant stress was 22.4 Kpa for the nominal prosthesis. This was 4.7 Kpa for the new design prosthesis

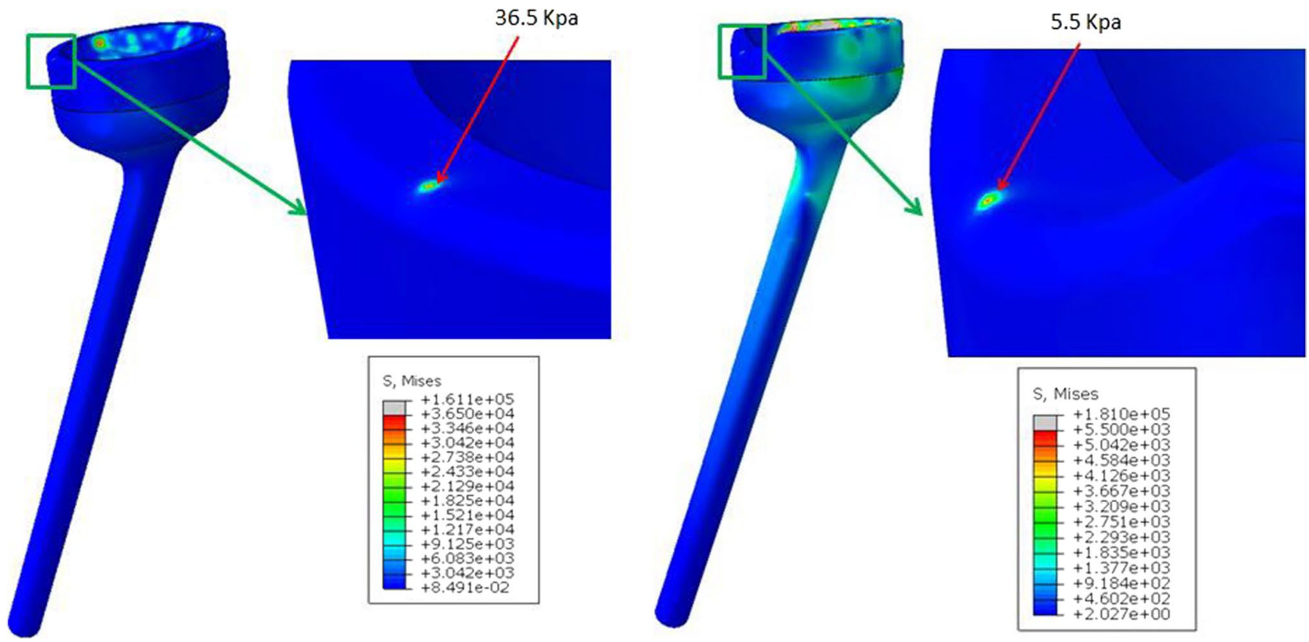

Fig. 4 Comparison of stress distribution results of nominal and notched designed prostheses. In the case of contact of the polyethylene insert with the scapula, the stress was 36.5 kPa in the nominal design; while, it was 5.5 kPa in the new design prosthesis

acromion fractures, and neuropraxia; In particular, scapular notching stands out with a higher incidence reaching 96% in some series [2, 14]. Nevertheless, scapular notching continues to be the most common problem waiting to be solved, with increasing frequency and severity as the follow-up period increases [15].

Scapular notching, which is a specific complication of RSA, is a condition that is frequently studied. Although there are different opinions on its effect on clinical outcomes, it has been reported that scapular notching is associated with decreased strength and anterior elevation, and it has been suggested that everything possible should be done to prevent this entity [16].

Although many clinical, biomechanical, and FEA studies in the literature suggest alteration of the parts that make up the monoblock modular Grammont-type prosthesis, the notched insert design is an original idea that is based on a well-known phenomenon in an idealized and simplified model to demonstrate our hypothesis. First, the contact stress of conforming surfaces is reduced compared to non-conforming surfaces (from 36.5 Kpa to 5.6 Kpa), and second, the range of motion is increased by reducing the sector coverage angle provided by the insert (11.2° additional adduction). This study aims to clarify the effect of a new design reverse shoulder arthroplasty (RSA) with a notched insert on the range of adduction, scapular notching, and stress variation of its insert component using 3D FEA. The study provides a future reference for the optimal design of the insert component of RSA.

As in the literature and sample parts, the 155° neck-shaft angle was modeled in the nominal prosthesis. Compared to the anatomical normal humeral neck-shaft angle, which is between 135° and 140°, the Grammont-type humeral component has a 155° non-anatomical design. The increased neck-shaft angle of the polyethylene cup provides a more horizontal orientation resulting in an inferior scapular impingement and abduction [9]. The redesigned notched inserts gained an additional 11.2° of adduction. This range of motion is expected to reduce the scapular notch problem that can occur even in the resting position of the arm.

Abdulla et al. reported that neither the stability of the prosthesis nor the range of motion increased in their study in which they changed the polyethylene cup constraint. They also emphasized that this is not surprising since the center of rotation is still the same despite the increase in insert depth [8]. Our study showed that changing the insert's design may provide extra adduction and reduce notching.

Different implant designs are utilized in reverse shoulder arthroplasty. Grammont's humeral component is designed with a nonanatomic humeral neck inclination of 155° but the normal humerus mean neck-shaft angle is 135°–140° [1]. Changes in the neck-shaft angle of the humeral component affect the clinical range of motion. At the same time, with the increased neck-shaft angle, the polyethylene cup becomes more horizontal and, thus, scapular notch occurs [1].

We know that the lateralized design prosthesis has significantly reduced scapular notching. In future studies, using this new notched design prosthesis together with the lateralized design could reduce scapular notching while providing the patient with a greater range of motion. However, it should be kept in mind that there may be a higher rate of glenoid baseplate loosening with this lateralized prosthesis [17].

As another method, placing the glenosphere in an eccentric (inferior) position provides a space to reduce notch formation between the glenosphere and the scapular neck [18]. Torrens et al. demonstrated that using a larger glenosphere reduces the possibility of notching without significant influence on functional outcomes compared with smaller ones. The difference in our study is that we focus on insert design independently of the glenosphere size and provide extra adduction while reducing scapular notching [18]. These studies, which focus on the separate parts of the reverse shoulder prosthesis with a modular design, may be used together to reach the ideal prosthesis design in the future and should be evaluated clinically and biomechanically.

Although biomechanical studies show promise, clinical trials have not confirmed the advantage of glenosphere component inferior inclination [19]. In their biomechanical study, Chae et al. showed that inferior tilt fixation of the glenoid component has poor outcomes in terms of stability contrary to popular opinion [20].

The novel design, which focuses on the solution of scapular notching, one of the most common and important complications of conventional Grammont-type medialized designs, was planned based on a 9 mm insert in order not to cause a possible instability. Thus, the insert thickness was 6 mm in the inferomedial, and 10 mm in the superolateral, when the 1 mm margin in the original design of RSA was added after the 2 mm radius fracture. In this way, we aimed to avoid instability by avoiding notching and increasing adduction medially, while providing deltoid tension laterally. Since we experimented in the coronal/frontal plane, it is not possible to make a definitive interpretation, although there is a risk of possible sagittal and horizontal plane instability. Countless possibilities can be studied with FEA by changing the amount of radius to break and the insert thickness to be selected.

Impingement and range of motion limitation, which are common problems with conventional designs, are caused by the chock-like contact between the insert and the glenoid. The notched insert design offers a more harmonious contact surface by proposing a notched concave area against the convex glenoid edge instead of the existing point contact area.

Our study should be interpreted under certain limitations. The most important of these is the absence of soft tissue detail and muscle contractions in the models. Another important limitation was the inability to evaluate sagittal and horizontal plane movements and possible instabilities in our study, which was based on frontal plane movement to evaluate scapular notching. Although we state that the model increases straight adduction, it is not possible to comment on forward elevation, adduction, and extension. In addition, it is not possible to make an inference about the possible negative consequences of thinning the polyethylene insert. In the modeling basically, the results of two measurements were aimed at, the stress analysis of the contacting surfaces and the adduction degrees of the models.

Finally, the notched insert design of Grammont-type reverse shoulder arthroplasty could provide additional adduction with lower stress on the glenoid which might lead to less scapular notching. Further experimental and clinical studies on different RSA types are needed to verify this effect. Considering all these studies, we can see that scapular notching is a challenging complication. It appears that there is a need for more study and new ideas to overcome this problem.

Although various solutions and new designs have been proposed to prevent scapular notching, the ideal implant design has not been reached yet. The notched insert design is promising to improve Grammont-type medialized RSA in the future.

Conclusion

The notched insert design of Grammont-type RSA could provide additional adduction with lower stress on the glenoid which might lead to less scapular notching.

Author Contributions NZ: concept, manuscript writing, critical revision. HB, performing the biomechanical experiments, creating the models, and doing finite element analysis. VU, concept and data collection. EB, performing the biomechanical experiments, creating the models, and doing finite element analysis. MK, concept, manuscript writing, critical revision. KB, concept, manuscript writing, critical revision.

"Three-Dimensional Finite Element Analysis of a Notched Insert Design for Reverse Shoulder Arthroplasty to Prevent Scapular Notching" to the International Orthopaedics in the event the work is published. The mentioned authors warrant that the article is original, is not under consideration by another journal, and has not been published previously. We confirm and accept responsibility for releasing this material.

I would like to point out that our research is a basic science/computer modeling study without experimental animals, cadavers, or human subjects. Notched insert design was studied using the finite element analysis (FEA) method in three-dimensional (3D) saw bone glenohumeral joint models created by computer modeling. For these reasons, local ethics committee approval and informed consent were not obtained.

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Availability of Data and Materials Not applicable.

Declarations

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Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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