Journal of Mechanical Science and Technology 35 (1) 2021

Original Article
DOI 10.1007/s12206-020-1241-x

Keywords:
· Reverse total shoulder arthroplasty
· Stemless humeral component
· Fin length
· Fin shape

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Citation:
Bae, T. S., Ritzer, E. E., Cho, W., Joo, W. (2021). Effect of fin length and shape of stemless humeral components in a reverse shoulder implant system: a FEA study. Journal of Mechanical Science and Technology 35 (1) (2021) 417~422. http://doi.org/10.1007/s12206-020-1241-x

Received May 21st, 2020
Revised September 29th, 2020
Accepted October 9th, 2020

† Recommended by Editor Sehyun Shin

Effect of fin length and shape of stemless humeral components in a reverse shoulder implant system: a FEA study

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Abstract The recent reverse total shoulder arthroplasty (TSA) implant designs employ shorter humeral component stems; some designs even eliminate the stem completely. The short stem provides several advantages: preserved bone, less stress shielding, ease of revision surgery, and freedom of humeral component location due to the minimal stem length and non-complex shape. However, due to the reduction in contact surface and frictional fixation, this stemless design may cause failure of the implant, especially during early stages following surgery. In this study, the effect of fin shape and fin length of stemless humeral components were investigated, and hypothesis was that stress and micromotion would decrease as the ratio of fin length to baseplate radius increases and the overall size of the humerus component increased. 15 different 3D models of stemless humeral components, 5 different lengths and 3 different shapes, within reverse TSA systems were developed. Each humerus component was analyzed using finite element analysis (FEA) to investigate the effects of stem length and fin shape on the initial stability of the component. The highest stress and micromotion were observed at the shortest fin length; lowest stress and micromotion were found at the longest fin length. Results suggest that the length of the fin affects the stress at the bone as well as the amount of micromotion; 20-30 % longer fin length than baseplate radius would be ideal for the stemless humeral component design. However, the various fin shapes showed mixed effects on the results and further investigation is required.

1. Introduction

For rotator cuff deficient shoulders, reverse total shoulder arthroplasty (TSA) has proven to be a reasonable solution in regaining a sufficient range of motion post-surgery. Though many different versions of the prosthesis for this procedure were developed in the 1970s, a system created by Grammont et al. differed from previous designs and became the most popular model [1]. Created in 1985, this model included a glenoid component with a press-fit central peg as well as a humeral component. This model aimed to improve stability and to reduce the risks of mechanical failure associated with the reverse system [2]. Grammont et al. has since updated this model with modifications to the humeral component, creating Delta III in 1991. Due to the varying rates of reverse TSA failure with Delta III, other models have been developed and are being used though complication rates do not show much improvement.

Many studies of reverse TSA patients have shown varying dislocation rates, some as low as 2.4 % and some as high as 31 % [3]. A study performed at the Department of Orthopaedic Surgery in Lyon, France followed up with 199 shoulders for two years post-surgery. Of these shoulders, 15 were displaced. This 7.5 % rate of dislocation was the most common complication with the surgery [4]. In a systematic review of the reverse TSA studies, instability was again the most common problem, occurring in 37 of 782 cases, resulting in a 4.7 % complication rate. Glenoid and humeral stem disassembly was reported [5]. Many other factors may affect the relative stability of the reverse total shoulder arthroplasty (TSA) system including the indication for surgery, humeral version, glenoid tilt, stem length, and post-surgical activity level/range of motion. Therefore, the investigation of the optimization of these factors and design parameters is necessary to provide a guideline of the best ways to prevent instability and other complications in short and long-term follow-ups [6].

Recently many orthopedic implant companies provide various humeral component designs for the reverse TSA system with different stem lengths, ranging from a stemless humeral component to a full humeral stem [7]. Stemless components have been the result of the goal of bone preservation and ease of potential revision surgeries, as well as reducing the risk of additional stem-related complications like loosening or stress shielding effects on the surrounding bone [8]. However, because of the minimization of implant-to-bone contact and decreased frictional fixation of stemless humeral components, this stemless design may cause failure of the implant, especially during early stages following surgery. The application of stemless humeral components is also limited by humeral bone stock [9]. Many clinical results show that improvements can be made to reduce complications [10, 11].

In a shoulder, the humeral head is held up against the glenoid cup by a compressive force generated by the muscles surrounding the joint. As a group these are known as the rotator cuff. The resultant compressive force is made up of the action from the subscapularis, latissimus dorsi, infraspinatus and teres minor [12]. When one or more of the muscles in the rotator cuff are damaged, the compressive force holding the humerus within the glenoid cup is reduced, leading to a loss of range of motion as well as an increase in instability of the joint [13]. Therefore, one mode of failure in the stemless reverse TSA implant has been a dislocation of the humeral component as it slips out of its socket in the humerus due to this reduced force from injury to the rotator cuff.

The effects of stemless or short system humeral component shapes have not been investigated fully due to the relative newness of the concept. One way to conduct a preliminary investigation on the aspects of the stemless components design is to use finite element analysis (FEA). FEA is a computational method that can determine the stress and displacement of a system virtually. It provides an opportunity to examine the effects of complex geometry, material interface, and environmental conditions in a short time, and the results can be used to make reasonable inferences towards the mechanism of the failure of the modeled system.

Therefore, in this study various reverse shoulder implant systems were designed and analyzed using FEA. The aim of this study is to, using FEA, 1) to identify the effect of fin shape and fin length of stemless humeral components in terms of initial stability (bone stress and displacement) especially before osseointegration happens, and 2) to have adequate results to make conjectures about the best length to radius ratio for a stemless humeral component, as well as conjectures toward the effectiveness of different fin shapes and their impact on the clinical outcomes. The hypothesis was that stress and micromotion would be decreased as the ratio of fin length to baseplate radius increases and the overall size of the humerus component would be increased because of increased bone-to-implant contact area.

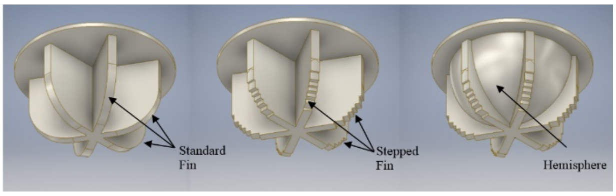

Fig. 1. Three shapes of fin design. From left to right: standard fin, stepped fin, and stepped fin with hemisphere. Note that these shapes are 1:1 ratio of baseplate radius-to-fin length.

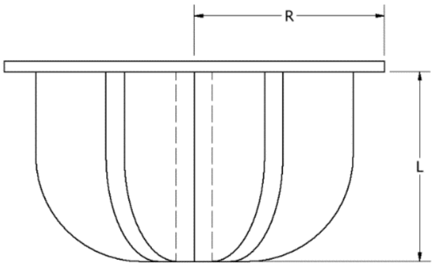

Fig. 2. Model with standard fin. Radius of base plate (R) and fin length (L) are shown. R = 18 mm constant and L = 10.8 mm, 14.4 mm, 18 mm, 21.6 mm, and 25.2 mm.

2. Materials and methods

To investigate the effect of fin shape and length, multiple reverse TSA stemless humeral components were developed using 3D modeling software (Inventor, Autodesk, San Rafael, CA, USA; Solidworks, Dassault Systemes, Waltham, MA, USA).

The shapes of the fin were modeled as three different geometries, and are referenced as "standard fin," "stepped fin," and "stepped fin with hemisphere" as shown in Fig. 1. The standard fin design has six fins of 2 mm thickness with each having a fillet radius of 10 mm. The stepped fin has the same fin geometry as the standard fin but has step-like geometry on the filleted region.

The stepped fin with hemisphere has the same geometry as stepped fin but a hemisphere was added at the center of the structure. Radii of the based plate (R) were determined as 18 mm for comparability to existing products on the market (Fig. 2). To investigate the effect of fin length, fin lengths (L) were determined as a ratio of fin length-to-base plate radius. The following ratios were used; 0.6:1, 0.8:1, 1:1, 1.2:1, and 1.4:1. These resulted in fin lengths of 10.8 mm, 14.4 mm, 18 mm, 21.6 mm, and 25.2 mm, respectively, for the 18 mm baseplate radius model. For the stepped fin with hemisphere model, the 1:1 ratio model has 14 mm radius half sphere, and the shape of the sphere became elliptical for the other ratio models based on a ratio of fin length-to-base plate radius. All other dimen-

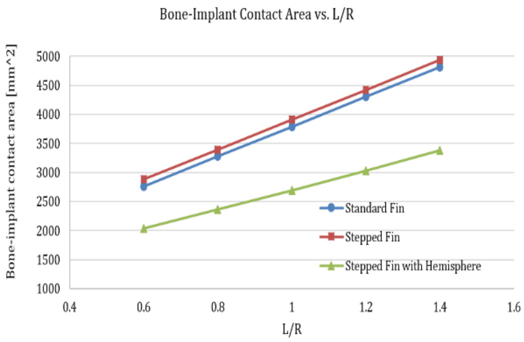

Fig. 3. Bone-implant contact area vs. fin shapes & length.

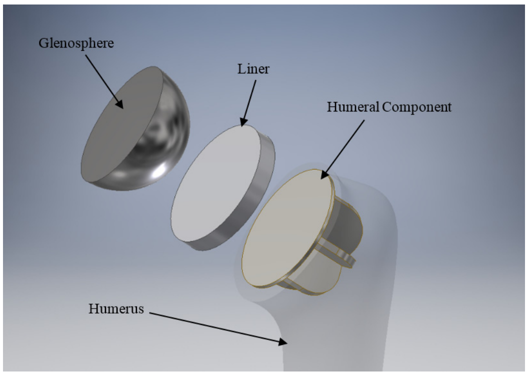

Fig. 4. Explode view of reverse TSA assembled model. 1:1 ratio standard fin model is shown.

sions remain the same between all models. A total of 15 different stemless humeral components of reverse TSA were modeled for this study. As a result, standard fin and stepped fin design had very similar bone-implant contact area, while the stepped fin with hemisphere had lowest contact area. For all fin shapes, the contact area was increased linearly as the fin length increased (Fig. 3).

Using CAD software, 3D models of other reverse TSA components, such as a liner and a glenosphere, were developed. All reverse TSA components were assembled into a standard humerus 3D skeletal model to form assemblies of each case of the system as shown in Fig. 4. Material properties, physiological constraints and loading conditions were applied using FEA software. The material properties were assigned to each component as follows: titanium alloy (Ti6AL4V) for the humeral component, ultra-high molecular weight poly ethylene (UHMWPE) for the liner, cobalt chrome alloy (CoCr) for the glenosphere.

A common material used in lab testing to simulate bone is polyurethane rigid foam block [14]. This rigid foam complies with American Society of Testing and Materials Standard F1839-97 (Sawbones Solid Rigid Foam 1522-04; Pacific Research Laboratories, Vashon, WA). Therefore, the properties of this rigid foam were taken as the properties of the humerus. The material property values are provided in Table 1, and all materials were treated as homogeneous, isotropic, and linear-elastic.

Table 1. Material properties for the FEA [15].

	Poisson's ratio	Yield strength [MPa]	Elastic modulus [GPa]	Density [kg/m^3]
Ti6AL4V	0.34	880	110	4400
CoCr	0.3	980	230	7900
UHMWPE	0.42	25	0.93	940
Bone	0.3	200	0.55	480

Table 2. Muscle forces for the FEA [16].

Muscle	Force [N]
Medial deltoid	434 N
Anterior deltoid	323 N
Subscapularis	283 N
Infraspinatus	205 N
Supraspinatus	117 N

It is clear that there is a wide variation in reported loading values during shoulder motion [17]. In this study, physiological loading conditions during the abduction of the arm were used as forces from the medial deltoid, anterior deltoid, subscapularis, infraspinatus, and supraspinatus as shown in Table 2 [16].

Abaqus (Dassault Systemes, Waltham, MA) was used for analysis and assembled models were meshed using tetrahedral elements. The humeral component and surrounding bone interface were modeled as a 0.5 mm interference fit (humeral components as a master surface and bone as slave surface) and contact to mimic the lack of bone growth onto the fin within the first few weeks after surgery. This study evaluated only the proximal portion of a humerus for maximum stress (von Mises) and displacement (micromotion) at various locations for each model.

3. Results

Throughout the models, max stress and micromotion were observed at the proximal-lateral area of the implant-humerus interface, which is where all max stress and micromotion values were measured for the study.

Results showed that the shape of fin has an effect on stress and micromotion. The stepped fin design showed the highest stress and micromotion, followed by the standard fin design and stepped fin with hemisphere design regardless of fin length. Maximum von-Mises stress for standard fin of all fin lengths was 3.61±1.55 % lower than stepped fin and maximum von-Mises stress of stepped fin with hemisphere were 12.66± 3.10 % lower than stepped fin (Fig. 5). Results for the micromotion showed that the standard fin was 3.99±1.67 % lower than the stepped fin and the micromotion of stepped fin with hemisphere were 13.21±2.59 % lower than the stepped fin (Fig. 6).

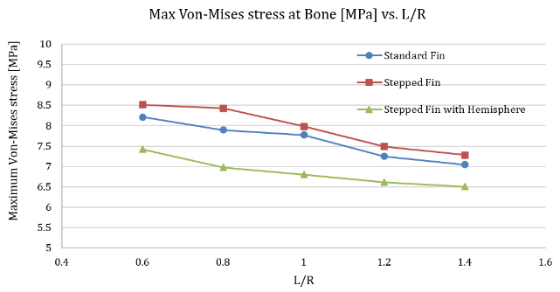

Fig. 5. Max von-Mises stress at bone vs. L/R.

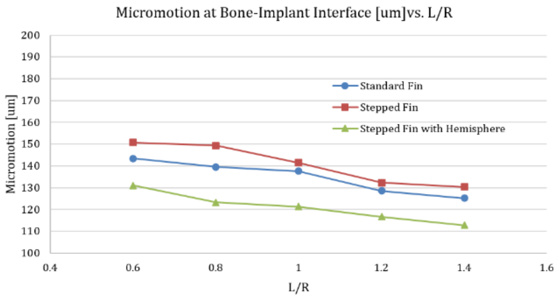

Fig. 6. Micromotion at bone-implant interface vs. L/R.

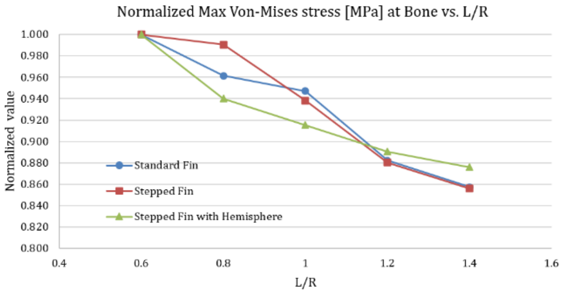

Fig. 7. Normalized max stress at bone vs. L/R. Values of each model were normalized by own peak stress which happened at 0.6 ratio model.

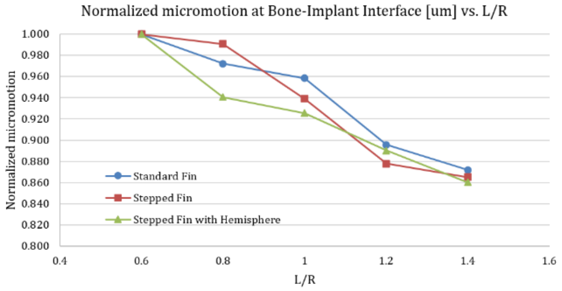

Fig. 8. Normalized micromotion at bone-implant interface vs. L/R. Values of each were normalized by own peak micromotion which happened at 0.6 ratio model.

Increasing fin length lowered the maximum von-Mises stress and the amount of micromotion at the interface of implant-bone for all three designs. Values for the stress and micromotion were normalized by the corresponding peak values which happened at 0.6 ratio model (Figs. 7 and 8). For all fin shapes, the 0.6 ratio model showed the highest stress and micromotion, which both decreased as fin length increased. The standard fin showed stress decreased 3.8 %, 5.3 %, 11.8 %, and 14.3 %, respectively, and micromotion decreased 2.8 %, 4.2 %, 10.5 %, and 12.8 %, respectively, as fin length increased. The stepped fin showed stress decreased 0.8 %, 6.2 %, 12.0 %, and 14.4 % and micromotion decreased 0.9 %, 6.1 %, 12.2 %, and 13.5 %, respectively, while the stepped fin with hemisphere showed stress decreased 6.0 %, 8.5 %, 11.0 %, and 12.4 % and the micromotion decreased 6.0 %, 7.5 %, 11.0 %, and 14 %, respectively.

4. Discussion

The reverse total shoulder implant is a good option for patients with rotator cuff deficient shoulders who want to regain a normal range of motion. Though there are several options for the prosthesis, stemless components are becoming more popular for several reasons, including the preservation of bone, ease of revision surgery, and less stress shielding around the implant. It is well established that osseointegration of medical implants takes weeks to occur, which is a major reason for motion and subsequent failure of some implant systems. In the case of the reverse total shoulder arthroplasty, this problem exists when stemless components are used. In this study, humeral components with three fin shapes, five fin lengths, and two baseplate sizes were compared using FEA to determine which, if any, seem to reduce the amount of micromotion and stress within the system. When analyzing the difference that fin shape and length had on the displacement and stress within the system, it was hypothesized that more surface contact between bone and implant would yield better results. Hypothetically, more surface contact would introduce more frictional forces to keep the implant in place and would supply more area for eventual osseointegration.

Results from this study provided information about the effect of fin shape and length of stemless humeral components in the reverse TSA system. Results supported the hypothesis that a longer fin length and larger overall size of the humeral component decreases the stress and micromotion as it increases contact area with surrounding bone. However, results showed mixed data for sensitivity of micromotion and stress to fin length and effect of fin shapes.

Results showed that fin shapes have an effect on stress and micromotion. The stepped fin shape showed the highest stress and micromotion. Because standard fin and stepped fin have very similar surface areas (stepped fin design has 2.3 % more surface area than standard fin), the stepped fin shape was expected to have similar differences or no differences in stress and micromotion; however, it showed higher stress and micromotion by 3.61 % and 3.99 %, respectively. This might be caused by stress concentrations on the sharp edges of steps on the components. The stepped fin with hemisphere has the smallest surface area (24.1 % less than standard fin) but showed the lowest stress and micromotion. Therefore, the hypothesis that more area would be better for stress and micromotion was not well supported with respect to fin shapes.

It was hypothesized that a longer fin length would reduce the amount of motion and stress due to the increased surface area of the fins as well as the longer length making it more difficult for the implant to slip out of place. Results supported this hypothesis well, as the longer fin length decreased stress and micromotion, and stepped fin with hemisphere showed lowest among them. Because the initial stability of stemless humeral component is a clinical concern, a longer fin length with added hemisphere would be ideal based on the results, such as 1.4 ratio fin with sphere; however, the 1.4 ratio stepped fin with hemisphere model requires the largest cut into the humerus, resulting in the loss of the most bone during the procedure. One of the benefits of the stemless humeral component design is the preservation of bone and ease of revision surgery, and the 1.4 ratio design could potentially eliminate these benefits. The 1.4 ratio stepped fin with hemisphere design can also be considered as a short stem humeral component due to its shape and length, although it is not curved in shape like that of a traditional short stem humeral component.

This study allowed us to investigate the effects of 15 different implant designs, which were virtually simulated, that would be very challenging in the vitro experimental method. This FEA technique permitted the direct design-to-design comparison for the stress and micromotion of the humerus component for the early stage of reverse shoulder implant surgery. Based on this study, it was determined that a longer fin length results in the least displacement and stress on the implant prior to osseointegration. Further studies would be necessary to verify these findings.

This study also has some limitations. FEA modeling required many assumptions to be made such as material properties and boundary conditions. It does not account for the impaction of the humeral component into the bone that takes place during the surgery although interference fit was applied in attempts to mimic in vivo conditions. The model does not account for biological variability such as different elastic modulus distribution throughout the humerus, and 3D models of the stemless reverse TSA humeral components have generic shapes without details. However, any associated error is present in all FEA models equally, and the comparison of the results of each design should not be significantly affected by such errors. In addition, the biomechanical experiments for the design validation using the biological tissues, such as animal bone or human cadaver, were not conducted in this study. Therefore, there are limitations to validate the effect of the design due to human subject validation for the results of this computational analysis. In the future, more detailed and lifelike FEA simulations including more accurate implant-to-bone interface, non-linear material properties, physiological loading conditions of rotator-cuff deficient shoulders, and biomechanical testing could be run to further explore the mechanisms of the failure and stress patterns within the reverse shoulder implant system.

5. Conclusions

Results of this study showed that the highest stress and micromotion were observed at the shortest fin length, the lowest stress and micromotion were found at the longest fin length, and the various fin shapes showed mixed effects on the results. A longer fin would provide better results, but may not fit well anatomically in the humerus and eventually fall into a "short stem" category, thus losing the benefit of stemless design. Therefore, researchers and clinicians should be aware of the various advantages and disadvantages of the different stem design and length. Further investigation is required to find the optimal design that maximizes the benefit of stemless humeral components of reverse TSA, while meeting the critical clinical outcomes.

Acknowledgments

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), which is funded by the Ministry of Education (NRF-2017R1D1A3B04033410).

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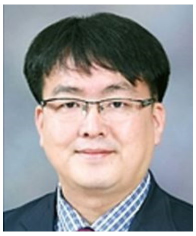

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