Biomechanical Assessment of Shoulder Implants: a Comparative Study Using FE Analysis

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Abstract Shoulder arthroplasty is one of the leading joint replacement procedures performed worldwide and is a treatment option for various traumatic pathologies of the glenohumeral (GH) joint, such as proximal humerus fractures. Implants that conform to the patient's anatomy offer various advantages compared to conventional one-fit-for-all designs. A number of studies have found variations of critical parameters of the humeral morphometry between different races and have pointed out the need for implants that conform to the particular anatomy. Most of the available commercial implants are developed based on the data of the Caucasian population. The present study describes Mukherji's Shoulder Prosthesis (MSP), a shoulder arthroplasty implant that conforms to the anatomy of patients of South Asia, especially those of Indian origin, and compares it to the commercially available implants of stemmed and stemless nature – Global Unite Shoulder (GUS) and Sidus Stemfree Shoulder (SSS), respectively – using finite element (FE) analysis. The present study found stress shielding was substantially high for the GUS implanted humerus as compared to the MSP implanted one. The computational results found the new device to be a viable alternative to conventional arthroplasty implants, especially for the population of India, and predicted comparable biomechanical characteristics.

Keywords Finite element analysis, proximal humerus fracture, shoulder arthroplasty, stress shielding, customized implant.

I. INTRODUCTION

Proximal humerus fractures (PHFs) are among the most frequent bone fractures in adults, representing about 5.7% of all cases, and are the third most common non-vertebral fracture in the elderly (>64 years old), after femoral neck and distal radius fractures. Owing to the high prevalence and expected increase in incidence, they are associated with a significant healthcare burden [1]. First performed by Péan in 1893 and pioneered by Neer in 1955, shoulder replacement surgery (arthroplasty) has now become a successful treatment option for a variety of pathologies, such as severe comminuted PHFs, avascular necrosis (AVN), and cuff-tear arthropathy. It involves the replacement of the glenohumeral (GH) joint by a prosthesis. Many studies have reported the increase in the incidence of shoulder arthroplasties worldwide and project that it could be one of the leading surgeries performed worldwide [2-5].

The success of shoulder arthroplasty depends on a significant number of factors, with the patient's race being one of them [6-8], and so better implants can be designed if racial variation of bone anatomy is taken into account as well. The sexual dimorphism of the humerus is debatable and can be site-dependent, but racial variation of humeral anatomy has been established through extensive morphometric studies worldwide [9-15]. These racial variations arise due to differences in hereditary, environmental and social factors [16]. The use of prostheses that do not match the GH anatomy is shown to diminish all motions, including flexion, external and internal rotation, and maximum elevation [17]. Compared to the Caucasian population, the humeri of Indian patients are characterised by a smaller humeral radius of curvature, smaller articular surface diameter, smaller inclination angle and a larger retroversion angle of the humeral head. Most shoulder implants are designed and optimised based on the Caucasian population, and hence might not be an apt fit for the Asian population, leading to the requirement of optimisation of implant geometries based on their GH morphometrics.

The primary objective of this study is to compare a novel implant design of Indian origin with commercially available implants. This implant features a non-cylindrical shaft and matches the neck shaft angle of the South Asian humeri. We hypothesise that the customised implant based on shoulder morphometry of the Indian population would be a viable alternative to the prevailing commercial implants and an anatomy-specific option for Indian patients.

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II. METHODS

The 3D model of the left humerus was generated from a CT scan dataset (512 × 512 pixels with a slice thickness of 1 mm) of the shoulder of an Indian female patient using the Materialise Mimics Research 21.0 software (Materialise, Antwerp, Belgium). The cortical and cancellous bone geometries were separated and a two-part Neer fracture with displacement of the humeral head was generated where less than 8 mm calcar region remains attached to the humeral head. This condition was considered because it is regarded that less than 8 mm calcar attachment would lead to significant vascular compromise [18], which can be an indication for considering arthroplasty with humeral head replacement to prevent avascular necrosis of the bone [19].

Two 3D implant models replicating the existing commercial implant (the Sidus® Stem Free Shoulder (SSS) System from Zimmer Biomet (Warsaw, Indiana) and the Global Unite™ Shoulder (GUS) from DePuy Synthes (Raynham, Massachusetts)) and one customised implant (based on the inputs of Dr. Mukherjee and Orthotech India Pvt. Ltd. (Gujarat, India)) were developed in the NURBS modeling environment of Rhinoceros 7 (Rhinoceros, Robert McNeel & Associates, Seattle, USA) (Fig. 1). The customised implant will henceforth be referred to as the Mukherjee's shoulder implant (MSP). The selected implant specifications were based on the best fit from the commercially available size ranges. Full specifications of the SSS, GUS, and MSP implants are given in Table I.

The intact and implanted humeri models were meshed into quadratic tetrahedral elements and the FE analysis was performed on Ansys Mechanical 2022 R2. The material model for bone and implant was considered as per Table II. Linear elastic, isotropic, and homogeneous material properties were applied to all materials. The implant materials were considered titanium (Ti) alloy (Young's Modulus, E = 110 GPa). Poisson's ratio was set as 0.3 for all materials. All contacts between implant and bone were assigned based on the surface condition and were assumed to be grit blasted (μ=0.6). *In vivo* forces and moments of the GH joint were obtained from the publicly available Orthoload Database [20]. The patient data of S3L were chosen for 90° abduction condition. Appropriate conversions were made to adapt the data to the left humerus and normalise to the weight of the patient. The data were presented according to the frame of reference as shown in Fig. 2. The pattern of force change with time can be observed on the website (https://orthoload.com/database/), and the instance of maximum force and moment of abduction was chosen as the loading conditions for this study. The detailed values are shown in Table III.

All nodes of the base of the humerus were constrained to avoid rigid body motion. A mesh sensitivity study assessed the numerical convergence of all the models using three different meshes of edge lengths 0.5 mm, 1 mm, and 1.5 mm and a comparison between their predicted maximum displacements (Fig. 3). The difference of maximum displacements was predicted. The medium mesh of 1 mm edge length was considered an acceptable trade-off between solution accuracy and computational efficiency.

III. RESULTS

Fig. 3 illustrates the von Mises stress distribution in the humeral cortex for both intact and implanted cases. The average von Mises stress of the entire cortical region for the intact bone was found to be 9 MPa, while it was found to be 1.4 MPa, 1.3 MPa, and 1.6 MPa for the humeri implanted with SSS, GUS and the MSP, respectively. Fig. 4 predicts the stress distribution in the implants. The implant-induced stress shielding was calculated for all nodes of the cortical bone for the stemmed implants as the percentage of stress decrease in the implanted bone compared to the intact bone. The stress shielding was found to be 76% GUS implant, while the stress shielding for the MSP implant was found to be 59% for the given load case.

The maximum displacement of the MSP implanted humerus was compared to that of the SSS and GUS implanted humerus. Displacement for the MSP implanted humerus was predicted to be 0.02 mm compared to 1.5 mm for the intact humerus. For the GUS and SSS fixed humerus, the predicted maximum displacement values were 0.26 mm and 0.23 mm, respectively.

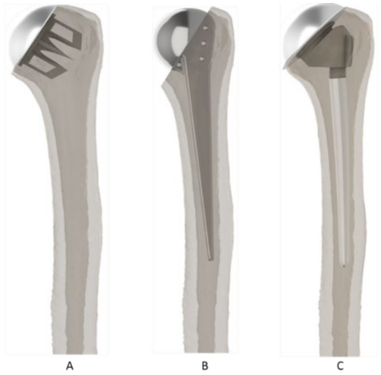

Fig. 1. Humerus virtually implanted with the three implants designed: A) SSS, B) MSP, C) GUS.

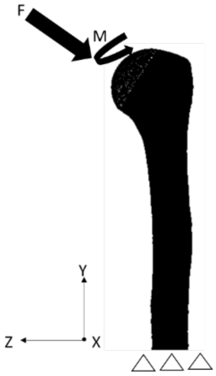

Fig. 2. Coordinate system and Loading Conditions.

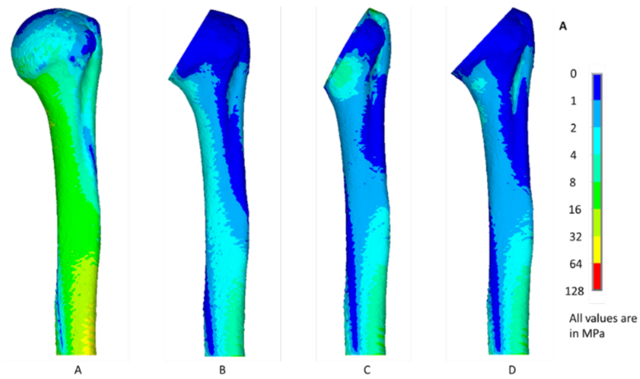

Fig. 3. The von Mises stress plot of intact and implanted bone: A) Intact bone, B) SSS, C) MSP, D) GUS.

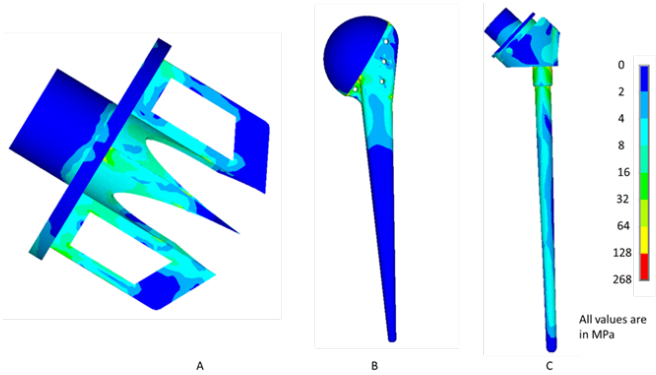

Fig. 4. The von Mises stress of implants: A) SSS, B) MSP, C) GUS.

TABLE I
DESIGN SPECIFICATIONS OF THE IMPLANTS USED

Parameter	SSS	GUS	MSP
Head width	42.5 mm	45 mm	35 mm
Head thickness	14 mm	17 mm	17.5 mm
Articular Surface Radius	22.9 mm	23 mm	17.5 mm[@]
Stem width	32 mm	6 mm	5 mm
Stem Thickness	-	6 mm[*]	3 mm
Stem length	22 mm[#]	100 mm	129 mm

Note: [#] The value specified is the anchor length of the stemless implant; [*] The stem is cylindrical; [@] The head is perfectly hemispherical.

TABLE II
MATERIAL PROPERTY DATA

Material	Young's Modulus (MPa)	Poisson's ratio
Cortical bone	17000	0.3
Cancellous Bone	1000	0.3
Implant	110000	0.3

TABLE III
GLENOHUMERAL JOINT FORCES AND MOMENTS

Activity	Force	Moment
90° abduction	128% BW	1.21% BWm

IV. DISCUSSION

Anatomical variation of a prosthesis can alter joint kinematics, delay bone union, or may cause refracture. A mismatch of even 5 mm can cause diminished motion during activities like rotation and elevation [17]. Previous studies have established, that there is an apparent variation in the humeral morphometry between the Caucasian and the South Asian populations [21]. This means there is a need for novel designs based on the anatomical variations of the Indian populations. The present study presents a prosthesis device suitable for the anatomy of the Indian population that can be used as a treatment option for various degenerative shoulder pathologies.

The proposed device consists of a head component, a stem component, a medial off-set component, and a lateral off-set component, which operate interconnectedly. The head component has a hemispherical shape with an outer diameter of 35 mm. The stem component has a substantially hexagonal cross-section (i.e., flat-corner equilateral triangular) with a height of 7.5 mm from the base to the tip of the apex, which minimises the rotation of the stem inside the medullary canal. The device has medial and lateral offset components instead of neck components. The advantage of not having a neck component is the reduced amount of bone resected during surgery. However, the regions of stress concentrations in the offset components present a noteworthy concern. The medial offset component has a flat base for better sitting over the calcar region between the head and stem. While there are no significant differences in the pattern of stress concentration in identical sites of GUS and SSS implanted humeri, there is a region of stress concentration in the lesser tubercle of the MSP implanted humerus. In the case of MSP, maximum stress was found between the intersection of the medial offset component and the humeral head. Stress concentration was also predicted at the neck region in both stemmed implants, while there was a significant decrease in stress in the stem of the MSP (Fig. 4).

The medial and lateral offset components are provided with holes for myosseous anchorage, medicalisation of the head component, and to provide proper retroversion of the prosthesis. Stress shielding was measured as a percentage decrease in stress compared to the intact bone. The Caucasian GUS implant had a higher percentage reduction than the MSP. The lower range of values of von Mises stress on the stem of the MSP compared to the GUS implant suggests its stability on the Indian humerus. A limitation of the study is that a single density value was considered to calculate the material property of the cortical and cancellous bone i.e., the heterogeneity of bone was not considered. Even though the contact interface between bone and implants can vary due to parameters like bone quality and surface finish of the implant, the present study assumed constant friction coefficients based on existing literature. Accordingly, the findings of this study should be regarded as assuming that the conditions affecting friction are similar for all implants. The value of force considered is the instance of maximum force, which is expected to be less during the immediate post-operative conditions. Also, instead of a single static instance, the dynamic nature of standard movements like abduction, flexion, and rotation can be simulated to provide an accurate representation of the activity. Finally, since the manufacturers do not provide all of the 3D CAD models of the implants studied, the models cannot be considered replicas of the implants available on the market. Nevertheless, the main objective of the study was to do a comparative analysis of the different implants (designs) w.r.t. anatomy of Indian patients. Hence, the biomechanical impact of the implant design is of primary focus, keeping the other parameters constant across all the simulations. To conclude, MSP is a viable fit for Indian patients factoring in other parameters, such as availability and cost, along with the comparable biomechanical characteristics of the MSP. Supporting *in silico*, *in vitro*, and, if possible, *in vivo* studies could render further insights into the efficiency of implants on patient anatomy.

V. CONCLUSION

The present study compares the biomechanical influence of commercially available stemmed and stemless shoulder prostheses to that of a novel design based on the morphometric variation of the Indian population. Although it has a few improvable features, MSP is a viable and cost-effective option that conforms to the glenohumeral anatomy of people of South Asian origin. MSP was found to have better stability than conventional implants with cylindrical stems. Further studies may be conducted by introducing patient-specific characteristics and simulating various loading conditions.

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VII. REFERENCES

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