J Shoulder Elbow Surg (2016) 25, 1076–1083

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Comparison of proximal humeral bone stresses between stemless, short stem, and standard stem length: a finite element analysis

Najmeh Razfar, MESc[a,b,c], Jacob M. Reeves, MESc[b,c], Daniel G. Langohr, MASc[a,b,c], Ryan Willing, PhD[d], George S. Athwal, MD, FRCSC[a,b,c,*], James A. Johnson, PEng, PhD[a,b,c]

[a]*Department of Biomedical Engineering, Western University, London, ON, Canada*
[b]*Roth|McFarlane Hand and Upper Limb Centre, St. Joseph's Health Centre, London, ON, Canada*
[c]*Department of Mechanical Engineering, Western University, London, ON, Canada*
[d]*Department of Mechanical Engineering, State University of New York at Binghamton, Binghamton, NY, USA*

Background: The stem lengths of humeral components used in shoulder arthroplasty vary; however, the literature on these devices is limited. This finite element study investigates the effect of humeral component length on stresses in the proximal humerus.

Methods: Intact and 3 reconstructed (standard length, short, and stemless implants) finite element models were created from shoulder computed tomography scan data (N = 5). Loading was simulated at varying abduction angles (15°, 45°, and 75°). The average bone stress (represented as a percentage of intact values) was reported at 8 transverse slices. In addition, the overall average change in cortical and trabecular bone stresses was quantified.

Results: Cortical bone stresses in the most proximal slice for the standard (58% ± 12%) and short (78% ± 10%) stem models were significantly reduced compared with the intact (100%) and stemless (101% ± 6%) models ($P = .005$). These reductions persisted in the second cortical slice for the standard stem compared with the intact, stemless, and short models ($P = .025$). Interestingly, stresses in the trabecular bone within these proximal slices were significantly elevated when stemless implants were used compared with all other implants ($P < .001$), regardless of abduction angle.

Conclusion: Reducing stem length produced humeral stresses that more closely matched the intact stress distribution in proximal cortical bone. Opposing trends presented in the proximal trabecular bone, probably because of differences in load transfer when shorter stems are used. Accordingly, the results suggest that implant stem length is 1 variable that can be modified in an attempt to better mimic intact bone stresses during humeral component insertion, provided stem fixation is adequate.

Level of evidence: Basic Science Study; Computer Modeling

Keywords: Total shoulder arthroplasty; stemless; proximal humerus; uncemented implant; finite element modeling; trabecular and cortical bone; osteoarthritis; stem length

Institutional Review Board approval was granted by Lawson Health Research Institute (Health Sciences REB No. 105912, Approval No. R-15-057).

*Reprint requests: George S. Athwal, MD, FRCSC, Roth|McFarlane Hand and Upper Limb Centre, St. Joseph's Health Care, 268 Grosvenor St, London, ON N6A 4L6, Canada.

E-mail address: gathwal@uwo.ca (G.S. Athwal).

1058-2746/$ - see front matter
http://dx.doi.org/10.1016/j.jse.2015.11.011

Total shoulder arthroplasty (TSA) for end-stage osteoarthritis relieves pain and restores nearly normal shoulder kinematics and biomechanics.[21] The stem of the humeral implant is responsible for load transfer to bone; therefore, stem design may have an influence on implant success.[12] Recently, implant manufacturers have begun offering shorter stems with the aim to reduce stress shielding and to facilitate revision surgery.[32] In addition, stemless implants have been introduced that employ a metaphyseal keel or anchor to fix the implant within the proximal humerus.[16] Between 2004 and 2013, approximately 10,000 stemless shoulder prostheses were implanted worldwide.[1] Ballas and Béguin reported that stemless implants can have some advantages over traditional stemmed implants, including significantly reducing blood loss and operative time.[5]

Stress shielding can result in bone atrophy.[18,35,39] Nagels et al measured bone cortex thickness for signs of stress shielding and reported a significant reduction in cortical thickness surrounding the humeral stem in 9% of the study population.[26] The effect of reducing stem length has been investigated for implants at other joints, including the distal ulna and hip.[3,17,27,29] Reduced stem lengths have been shown to closely mimic the intact state.[2,3,11,25,27,31,38] However, the literature contains no comprehensive assessments of stemless humeral implants. Factors such as stress shielding should be investigated to confirm that stemless implants perform at least equivalently to standard stemmed implants.

The purpose of this study was to investigate the effects of implant stem length on proximal humeral bone stresses by using finite element methods. It is hypothesized that reductions in implant stem length will produce cortical bone stresses that better mimic the intact state.

Methods

Preoperative computed tomography (CT) scans were acquired from 5 subjects (3 women and 2 men, 70 ± 6 years) who later underwent TSA. CT images, in DICOM format, were processed using Mimics (Materialise, Leuven, Belgium) to form a 3-dimensional solid model of the proximal humerus. Separate 3-dimensional models of the cortical and trabecular bones were created using a combination of automatic threshold-based segmentation and manual identification of trabecular/cortical bone boundaries. Under the supervision of an orthopedic surgeon (G.S.A.), a cut-plane was created in SolidWorks (Dassault Systèmes, Waltham, MA, USA) to resect the humeral head, as would be done during surgery.

After review of the humeral implants currently available in North America, computer-aided design models of 3 generic implants were created (Fig. 1). All implants shared an identical humeral head shape and differed only in terms of stem design. The 3 stems developed were classified as standard length (~100 mm), short (~50 mm), and stemless (~25 mm) designs and spanned the lengths of stems used clinically. Two regions were defined along the length of the standard stem: a cylindrical polished diaphyseal region (coefficient of friction = 0.4) and an expanded grit-blasted metaphyseal region

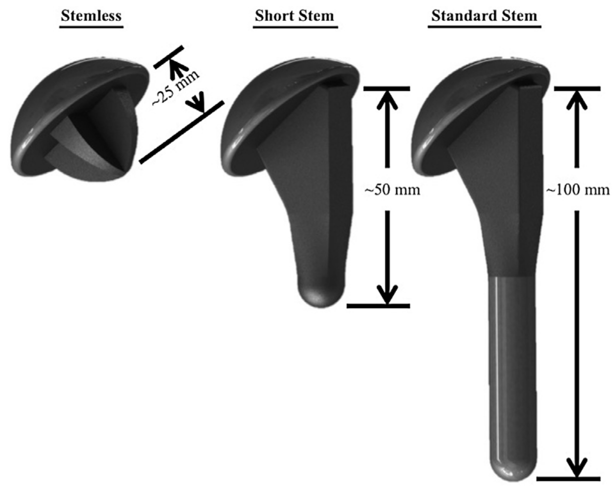

Figure 1 Generic stemless, short stem, and standard stem humeral components used for computational models.

(coefficient of friction = 0.63).[15,19] The short stem design removes the majority of the polished diaphyseal section but maintains an identical metaphyseal design to allow the direct comparison of these implants. The stemless implant was designed with a short cross-shaped metaphyseal keel that transfers load to the surrounding trabecular bone.

To account for geometric variations between patients (eg, humeral head diameter, canal diameter), a range of sizes of standard, short, and stemless implants were developed. These varied in terms of head diameter and stem diameter. Appropriate head geometry was maintained using an aspect ratio of 1.00:0.76 between the head radius and depth, respectively. To re-create surgical placement in a repeatable manner across all models, anatomic landmarks were used as reference points for implant positioning. After implant positioning, the appropriate implant stem and head diameters were selected for standard, short, and stemless implants by increasing the diameters in 1-mm increments until diaphyseal contact was detected, indicating a moderate cementless fixation that is consistent with current surgical techniques. After implant positioning and sizing, all model components were transferred from SolidWorks to ABAQUS v6.12 (Dassault Systèmes Simulia Corp, Providence, RI, USA). Bone was meshed using 2-mm quadratic tetrahedral elements based on a mesh convergence analysis. Careful mesh planning ensured that identical meshes could be used for different implant geometries, allowing element-by-element comparisons of stresses.

In agreement with previous studies, cortical bone was modeled as a homogeneous isotropic material with a Young modulus and Poisson ratio of 20 GPa and 0.3, respectively.[7,28] For trabecular bone, Young moduli were applied on an element-by-element basis and calculated on the basis of corresponding CT densities, as described previously.[4,13,20,23,33,36] The density-modulus relationship chosen for this study, which was reported by Morgan et al, is specific to trabecular bone.[23] Equation 1:

$$E = 8920\rho_{app}^{1.83}$$

where E is Young modulus and ρ_{app} is the apparent density of bone, calculated from Hounsfield unit data. All implant