The Effect of Shoulder Humeral Component Length on Bone Stresses: A Finite Element (FE) Analysis

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Introduction: Total shoulder arthroplasty (TSA) can restore function and provide effective pain relief for patients with osteoarthritis. Implant survivability, however, is limited; usually between 10 and 15 years [1]. Conventional shoulder implants replicate the anatomy of the glenohumeral joint and typically include a stemmed hemispherical humeral head component that is implanted into the humerus. Proper stem design is critical for implant success, as this component is responsible for load transfer to bone. Overly-stiff stems offer an alternative path for joint contact loads to be transmitted distally through the humerus, effectively bypassing the remaining proximal bone. This alters the stress distribution within the bone, which plays a critical role in bone remodeling. Stress shielding of the remaining proximal bone can lead to resorption and subsequent implant loosening, which is one cause of implant failure [2]. Recently, newer implant designs have been introduced for the shoulder that have shorter humeral stem lengths, or are “stemless”. The literature on these newer stemless or short stem implant designs, however, is limited. Accordingly, this study’s aim was to compare humeral implants of various stem lengths (i.e., standard length, short and stemless) using finite element (FE) models to determine how stem length affects the stress distribution in the surrounding bone following TSA.

Methods: Using preoperative CT scans of five subjects (3 females and 2 males, age = 69.8±5.7 yrs), proximal humerus FE models were developed using Abaqus (Dassault Systèmes, USA). An intact and three reconstructed models were created for each subject, for three different abduction angles (15°, 45° and 75°). The stem lengths tested included: standard length (~10 cm), short (~5 cm) and stemless. Implant models were each assigned material properties representative of Cobalt Chrome (E = 210 GPa, ν = 0.3) [3]. SolidWorks (Dassault Systèmes, USA) was used to design the implants and to prepare the 3D humeral bone model for the implants by simulating standard shoulder arthroplasty techniques. A second order tetrahedral mesh with typical element edge lengths of ~2 mm was generated (based on mesh convergence results). MIMICS (Materialise, Belgium) was used to assign each element of the trabecular bone a Young’s modulus (E) value based on local Hounsfield Unit data from the CT scans [4]. The maximum value of E assigned for any bone element in the model was 20 GPa (representing cortical bone). The humerus was constrained in the distal region, and joint reaction forces of 190 N, 440 N and 740 N for 15°, 45° and 75° of abduction respectively were applied to simulate glenohumeral contact. Force magnitudes and orientations were derived from previously published in-vivo instrumented shoulder implant data [5, 6]. A muscle force of 80 N was applied to the greater tuberosity by wrapping a block between the humeral and scapular deltoid insertion points for the configuration corresponding to 15° of abduction. Frictional contact was simulated between bone and implant: μ = 0.40 in the diaphysis.
where the stem is smooth, $\mu = 0.63$ in the metaphysis where the stem is textured [7, 8]. Creation of an identical mesh allowed for direct comparison between each element of the implant and the intact models. The average stress changes in 9 predefined regional bone slices were collected for trabecular and cortical bone for comparison. Stress changes were calculated by subtracting intact bone stresses from with-implant bone stresses. A two-way repeated measures ANOVA was used to assess statistical significance.

**Results:** For cortical bone, only slices 1, 2 and 9 presented with significant differences in stress (Figure 1). Within the first slice, the standard and short prostheses caused significant reductions in cortical bone stresses compared to the intact and stemless models ($p = 0.005$). Additionally, significant reductions in cortical bone stresses persisted in the second slice for the standard length implant compared to the intact (~26±36% less), stemless (~31±37% less) and short (~23±42% less) models ($p = 0.025$). Moreover, in the 9th (most distal) slice, cortical bone stresses of the intact models were significantly different than all reconstructions regardless of the abduction angle ($p = 0.019$). Additionally, at 15º of abduction, significant differences were again found between standard and short, and standard and stemless implants.

For trabecular bone, statistically significant differences between stem types only presented in slice 1. Within this slice, the average stress was significantly less for the standard length stem compared to both the short (~17±53% less) and stemless (~148±100% less) implants ($p < 0.038$), as well as the intact state (~14±40% change) ($p \leq 0.001$). Furthermore, regardless of abduction angle, the stemless implant significantly elevated trabecular stresses compared to intact, short and standard models ($p \leq 0.001$). Moreover, bone stresses of the short stem were significantly higher than those of the standard implant.

**Discussion:** The use of multiple specimens ($n = 5$) in this FE study allowed statistical significance to be assessed. Based on Wolff’s law, any change from the intact stress distribution of bone could cause structural changes as the result of bone remodeling. Accordingly, the change in bone stresses noted in the proximal humerus with the lengthening of humeral TSA stems is problematic, yielding an increased potential for bone remodeling. As expected, the reduction in stem length from the standard, to the shorter stem and the stemless implant yielded humeral stresses that better matched the intact stress distribution in cortical bone. Accordingly, it is suggested that, if adequate implant fixation can be achieved, stemless implants would offer superior performance by maintaining more of the intact stress distribution in the proximal humerus. One reason for the far greater change in cortical stress noted with the standard stem model is that diaphyseal contact occurred with the cortical bone, while the cortical stresses of the short and stemless models were diffused through the trabecular bone due to no direct cortical contact. Hence, the results suggest that the shorter implants better mimic the intact humeral stress state following total shoulder arthroplasty.

**Significance:** Bone resorption and stress shielding are problems that may arise from changes in the loading of the bone that surrounds implant stems following joint arthroplasty. Using a finite element model of the proximal humerus subjected to three implants with variation in stem length (from stemless to standard length), it was found that shorter implant stems provide the most natural stress distribution in the surrounding bone; hence, less invasive stemless devices may reduce the incidence of stress shielding by providing a more normal stress profile following shoulder arthroplasty.
Figure 1: Implant Geometries
Generic stemless, short and standard stem shoulder implant designs used for computational models.
Figure 2: Average Stress in Cortical Bone Slices
Mean±SD average stress in cortical bone slices are given for all stem length variations, where the resulting stress is presented as a percentage of the intact bone stress in each slice. Slices 2, 5 and 8 were chosen to correspond to the tips of the stemless, short and long implants, respectively.