Statistical Shape Modeling of the Humerus for Rapid Endoprosthetic Stem Design Iteration

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Disclosures:

Introduction: Variations in human anatomy present a significant challenge for the development of orthopaedic implants. In the case of percutaneous implants for osseointegrated prosthetic limb attachments, these variations are exacerbated by the level of amputation. A European group experimenting with percutaneous osseointegrated prosthesis (POP) has dealt with this issue through the production of custom implants [1]. However, to bring this technology into broader use, a cost effective way of sizing a discrete number of implant variations to fit a wide cross-section of the population must be developed. In this study, we have developed a statistical shape model of the human humerus. This model allows for isolation of morphological characteristics in three dimensions; an improvement over the two dimensional image processing techniques used previously for POP development [2].

Methods: Volumetric CT scans of 10, right, Caucasian male humeri were obtained using a Siemens SOMATOM Definition Flash scanner (120 kVp, 100 mAs, 512 x 512 acquisition matrix, 0.6mm slice thickness, B50s kernel, 192 mm field-of-view). Humeri were screened for gross morphologic abnormalities prior to being segmented and reconstructed in Amira (v5.4.1 Visage Imaging, San Diego, CA) using semi-automatic thresholding techniques to isolate the cortical bone boundary on both the endosteal and periosteal surfaces. 3D surface reconstructions were generated from segmentations, and consistently smoothed to reduce aliasing artifacts. Reconstructed surfaces were aligned in Amira using the included iterative closest point algorithm to minimize root mean square distance between the surfaces. A uniform bounding box was then assigned to all 10 reconstructed surfaces, and each was resampled to 0.17mm isotropic voxel spacing and exported as binary images for processing in the statistical shape modeling package, Shapeworks (Scientific Computing Institute, University of Utah, http://www.sci.utah.edu/software/shapeworks.html) [3].

Using the Shapeworks software, we computed a population model of the mean shape and variability of the humerus endosteal and periosteal surfaces. The Shapeworks algorithm models shape by automatically computing a dense set of surface landmark points, or correspondences, directly on the binary segmentations. The correspondences are computed to be statistically optimal, in the sense that they minimize the overall information content of the model while maintaining a good sampling of shape surface geometry. Principal component analysis (PCA) was used to reduce the dimensionality of the correspondence point data (4096 points) into a set of 9 orthogonal linear components (PCA modes) that represent variability in the space of shapes described by the model. Each PCA mode thus describes a primary type of variation in the population, and progression from the mean shape along an individual mode can be viewed independently. Surfaces representing the mean humerus shape and +/-3 standard deviations from the mean along each PCA modes were generated, aligned at a 50% amputation level, and binary outlines were produced to qualitatively examine which modes influenced the medullary canal where a POP device would be placed.

Results: The first 5 PCA modes accounted for >95% of the total population variation (Figure 1). When aligned and viewed at the 50% amputation length, it can be seen that modes 2, 3, and 4 dominant the variation seen in the medullary canal diameter and angle of divergence from resection plane to humeral head. Mode 1 (Length), accounted for nearly 56% of the total whole bone variation yet it had little influence on medullary canal geometry at midshaft. Likewise, Mode 5 (Greater Tubercle Offset) accounted for 3% of the total whole bone variation, but had little influence on canal geometry.

Discussion: The use of statistical shape modeling in the humerus represents the next progression in making data driven design decisions during implant development. It is a substantial departure from the creation of custom POP devices. Furthermore it is a progression of the 2D image processing techniques first utilized at the University of Utah for development of a POP implant in an ovine load bearing animal model. Continuing work will expand the sample population of humeri from 10 to 120, and expand the number of correspondence points used in the Shapeworks optimization for more robust results. At that point, using the identified Modes 2, 3 and 4 as axes defining a shape space, rapid assessment of implant fit against a population may be carried out [4]. Future studies will seek to apply this methodology to other bones.

Significance: To the author’s knowledge, this is the first statistical shape model of a human humerus. Based on these results, anatomic variables of bone length and greater tubercle offset can be ignored from the design criteria, since they didn’t contribute significantly to the medullary canal variations. Statistical Shape Modeling will be an invaluable tool for rapid design iteration of future POP devices for the above elbow amputee population as well as for other amputee populations. Additionally,
such a model could be used to examine remodeling patterns in long term amputees, cortical thickness variations with age or disease state, or even to interrogate current total arthroplasty stems on the market.

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