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Adaptive scapula bone remodeling computational simulation: Relevance to regenerative medicine

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ABSTRACT

Shoulder arthroplasty success has been attributed to many factors including, bone quality, soft tissue balancing, surgeon experience, and implant design. Improved long-term success is primarily limited by glenoid implant loosening. Prosthesis design examines materials and shape and determines whether the design should withstand a lifetime of use. Finite element (FE) analyses have been extensively used to study stresses and strains produced in implants and bone. However, these static analyses only measure a moment in time and not the adaptive response to the altered environment produced by the therapeutic intervention. Computational analyses that integrate remodeling rules predict how bone will respond over time. Recent work has shown that subject-specific two- and three dimensional adaptive bone remodeling models are feasible and valid.

Feasibility and validation were achieved computationally, simulating bone remodeling using an intact human scapula, initially resetting the scapular bone material properties to be uniform, numerically simulating sequential loading, and comparing the bone remodeling simulation results to the actual scapula's material properties. Three-dimensional scapula FE bone model was created using volumetric computed tomography images. Muscle and joint load and boundary conditions were applied based on values reported in the literature. Internal bone remodeling was based on element strain-energy density. Initially, all bone elements were assigned a homogeneous density. All loads were applied for 10 iterations. After every iteration, each bone element's remodeling stimulus was compared to its corresponding reference stimulus and its material properties modified. The simulation achieved convergence. At the end of the simulation the predicted and actual specimen bone apparent density were plotted and compared. Location of high and low predicted bone density was comparable to the actual specimen. High predicted bone density was greater than actual specimen. Low predicted bone density was lower than actual specimen. Differences were probably due to applied muscle and joint reaction loads, boundary conditions, and values of constants used. Work is underway to study this. Nonetheless, the results demonstrate three dimensional bone remodeling simulation validity and potential.

Such adaptive predictions take physiological bone remodeling simulations one step closer to reality. Computational analyses are needed that integrate biological remodeling rules and predict how bone will respond over time. We expect the combination of computational static stress analyses together with adaptive bone remodeling simulations to become effective tools for regenerative medicine research.

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1. Introduction

End-stage glenohumeral arthritis is a most debilitating disease affecting an individual's quality of life [1,2]. A common treatment option is total shoulder arthroplasty (TSA) which provides pain relief and partially restores the shoulder's function [3,4]. However, long-term success is limited with revisions required in 2–10% of the cases [5,6]. Furthermore, the success of TSA has been attributed to several factors such as, quality of bone, soft tissue balance, surgeon experience, and implant design, to name a few [7–9].

The use of computational modeling in research and development has continuously risen over the past several decades. As orthopaedic regenerative medicine research questions become more complex and alternative solutions more numerous integrative computational modeling presents a solution. Finite element (FE) analysis has played a key role in joint replacement research and has been extensively used to compute the stresses and strains in the prosthesis and bone [10–16]. Glenoid prosthesis design examines the material and shape to determine long term feasibility. It has been shown that the stresses and strains in the glenoid change in the presence of prosthesis and the amount of change is dependent on the material and geometry of the prosthesis [10,12,16,17]. Lower stresses compared to intact have been found in the proximal glenoid following implantation of glenoid prostheses with metal-backed designs showing greater reduction compared to the cemented or uncemented all-polyethylene designs [12,17,18]. This effect is also known as the stress shielding effect which means that the applied load passes through the glenoid prosthesis into the distal bone regions causing the proximal glenoid to experience lower stresses thereby leading to bone resorption [12], which can lead to glenoid prosthesis loosening, a major cause of TSA failure requiring revision [19–21]. Moreover, other drawbacks of glenoid prosthesis design such as fixation breakage, high cement stresses, metal debris, and polyethylene deformations can result in further clinical complications [22,23].

Existing FE models are three-dimensional and highly advanced with location specific bone material properties and physiologic load and boundary conditions [15–17,24]. However, most analyses are static, as multi-scale adaptive predictive simulations require melding of physiologic with structural engineering rules. Bone is known to modify its internal structure and shape depending on the mechanical environment it experiences as per Wolff's law of adaptive bone remodeling [25–29]. Recent work on subject-specific glenoid bone remodeling has been demonstrated and computationally validated using FE based numerical simulations [30]. In addition, long term effects of several glenoid prostheses designs have been predicted [31]. However, these methods were developed in two-dimensions and therefore were not able to fully incorporate the effects of out-of-plane bone structures or muscle forces. Therefore, there is a need to first develop a validated three-dimensional intact scapula bone remodeling simulation.

Adaptive predictive remodeling simulations would be a boon to the surge of orthopaedic regenerative medicine research, and joint replacement in particular. Physiologic rule-based computational remodeling simulations are needed for unveiling insights, culling experimental options, and developing new and improved orthopaedic therapeutic interventions. Therefore the purpose of this study was to (1) demonstrate the ability to perform three-dimensional adaptive scapula bone remodeling, and (2) develop and computationally validate a three-dimensional scapula bone remodeling FE based simulation.

2. Materials and methods

2.1. Scapula imaging and 3D scapula computer modeling

A normal intact right scapula cadaver specimen was obtained from a 55-year-old male donor in Midwestern United States. The scapula was of average size with superior-inferior glenoid length equaling 37 mm and inferior glenoid anterior-posterior width of 27 mm [32]. High-resolution volumetric computed tomography (CT) imaging (slice thickness: 1 mm; slice separation: 1 mm; voxel size: $0.4336 \times 0.4336 \times 1\ \text{mm}^3$) was performed using a GE Medical Systems HiSpeed CT/i scanner. The scapula specimen was placed in a custom designed stand such that CT axial cross-section was approximately perpendicular to the glenoid surface (Fig. 1(a)).

The scapula CT images were segmented for bone in a 3D visualization and modeling software (Amira®, Visage Imaging Inc., San Diego, CA). The bone contours were used to generate a 3D scapula tessellated computer model. This model was then converted to a 3D surface model in a reverse engineering software package (Rapidform®, Inus Technology Inc., Seoul, Korea). Fig. 1(a)–(e) shows the steps from imaging set up, CT images, bone segmentation, 3D tessellated model generation and conversion to 3D surface model.

2.2. Finite element modeling

The 3D scapula surface model was meshed using the solid 10-node tetrahedron element in a FE analysis software (Ansys Workbench®, Canonsburg, PA). The 3D scapula FE model consisted of 17,299 elements and 29,116 nodes (Fig. 2).

Scapula was modeled as a linearly elastic, isotropic, and non-homogeneous material. Location-specific bone element properties were based on the CT value at that element [33]. As the CT scans were not calibrated we assumed that the maximum CT hounsfield unit (HU) in the scapula volume (CT^{max}) had a bone density of 1.8 g/cc. It is known that water has a CT HU of 0 and a density of 1 g/cc. Assuming a linear relation between CT HU and density (ρ) resulted in the expression