The Effect of Muscle and Ligament Forces on Glenoid Micromotion: A Patient-Specific Finite Element Analysis of Reverse Shoulder Arthroplasty Driven by Musculoskeletal Simulations

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INTRODUCTION: Reverse shoulder arthroplasty (RSA) alleviates pain and restores shoulder function to patients with rotator cuff arthropathies [1]. 17% of RSA revisions are related to implant component loosening [2]. Studies have investigated micromotion of the glenoid fixation, which may be a biomechanical factor of component loosening in RSA, using finite element (FE) modeling; however, these investigations often omit the forces applied by the shoulder muscles and ligaments ('soft tissues') and utilize simplistic loading profiles that do not consider the effect of the complex, multiaxial forces typically observed during an activity of daily living (ADL) [3-5]. The objective of our study was to quantify the effect of modeling soft tissue forces on glenoid fixation. To this end, we used a patient-specific musculoskeletal models to predict joint and soft tissue forces and then transferred these forces to custom, matching FE models to evaluate micromotion of the glenoid fixation. We hypothesized that i.) simulating soft tissue forces would increase bone-implant micromotion compared to FE simulations with only joint loading and ii.) peak bone-implant micromotion would not occur during peak joint loading.

METHODS: Our computational approach (Fig. 1) used the soft tissue and joint contact force outputs of a multibody musculoskeletal model (the Newcastle Shoulder Model – NSM [6]) as inputs to a corresponding FE model to evaluate bone-implant micromotion. The NSM, which consists of 6 segments (thorax, clavicle, scapula, humerus, ulnar, and radius), 31 muscles, and 3 ligaments (soft tissues), was used to predict soft tissue forces and the glenohumeral (GH) joint forces of the RSA joint for the activity of daily living of reaching for an object at head height. The FE model then used all the soft tissue and GH joint forces as inputs to determine the micromotion at the interface of the implant and resected glenoid on the scapula. Both the musculoskeletal and FE models were adapted with the glenohumeral anatomy of five patients with rotator cuff arthropathies. The scapula and humerus were reconstructed from pre-operative CT scans and soft tissue attachments were customized to the patient-specific attachment sites. A commercially available RSA system (Comprehensive Reverse Shoulder System. Zimmer Biomet, Inc., Warsaw, IN) was then virtually implanted into each model. The component placement was verified by a board-certified shoulder orthopaedic surgeon (LG). In the FE models, the GH joint forces were applied to the center of the glenoid sphere and the soft tissue forces on the scapula were applied at the same locations as in the musculoskeletal models (i.e., their attachment sites). The bone was modeled as a non-homogenous material, with an elastic modulus (E) determined from the pre-operative CT scans using an empirical density-modulus relationship [7]. The glenosphere was modeled as a rigid body and the superior, inferior, and central locking screws and metaglene were modeled as a solid titanium alloy (E=113.8 GPa, Poisson's ratio, υ=0.3). The bone-implant interface was modeled as frictional, with a coefficient of 0.6. The bone was fixed at the medial border of the scapula and at the acromioclavicular joint [4]. For each FE model, we simulated two loading configurations: 1) application of only the GH joint force (Fig. 1a) and 2) application of both the GH joint force and the soft tissue forces (Fig. 1b). For each configuration, our primary outcome measure was the bone-implant micromotion (in micrometers, µm), which was computed as the difference in displacement between each pair of closest nodes at the bone-implant interface.

RESULTS: The GH joint force (reported in bodyweight, BW) exhibited a first, larger, peak of 0.52 BW ± 0.03 BW at 31% of the cycle and a second, smaller, peak of 0.47 BW ± 0.05 BW at 65% of the cycle (Fig. 2; top). At the first loading peak, the compression force was 0.49 BW ± 0.04 BW, and the shear force was 0.17 BW ± 0.06 BW. Additionally, compression represented 50% - 92% of the total GH joint force throughout the activity. When only the GH joint force was considered, the average peak micromotion varied from 3 µm ± 1 µm (at 33% of the cycle) to 6 µm ± 2 µm (at 73% of the cycle). Conversely, when both the soft tissue and GH joint forces were considered, the peak micromotion ranged from 13 µm ± 9 µm (53% of the cycle) to 18 µm ± 11 µm (79% of the cycle, Fig. 2; bottom). The peak GH joint force at 31% of the cycle corresponded to a micromotion of 14 µm ± 9 µm. This was smaller than the overall peak micromotion at 79% of the cycle, when the compression force was 0.20 BW ± 0.03 BW, and the shear force was 0.12 BW ± 0.02 BW.

DISCUSSION: By including the soft tissue forces in the FE models, we observed an average increase in micromotion by 370% across the activity cycle. While, for both loading conditions the micromotion throughout the cycle was small and within the acceptable limits compatible of bone ingrowth [8], our results suggest that the omission of soft tissue forces can lead to an underestimation of the burden placed on the bone-implant interface. Furthermore, by simulating an activity of daily living, we found that the instant of the largest peak micromotion for both loading configurations did not correspond with the instant of peak GH joint force, which has been a commonly used loading scenario for prior FE models of shoulder replacements [3-5]. At the instant of peak GH loading, we observed that joint compression accounted for 88% of the total force, whereas, at the instant of peak micromotion, joint compression accounted for 72% of the total force.

SIGNIFICANCE/CLINICAL RELEVANCE: To avoid potentially underestimating implant fixation mechanics, future computational studies of glenoid fixation should consider include soft tissue loading and simulate entire activity cycles. We aim to use our workflow to holistically evaluate the impact of the design and placement of the implant components of shoulder arthroplasty biomechanics.

REFERENCES: [1] Boileau, *JSES* (2006). [2] AOA National Joint Registry Annual Report (2022). [3] Sabesan, *JSES* (2019). [4] Bonnevialle, *JEO* (2022). [5] Elwell, *J Biomech* (2017). [6] Kontaxis and Johnson, *Clin Biomech* (2009). [7] Morgan, *J Biomech* (2003). [8] Jasty, *JBJS* (1997).

Fig. 1:

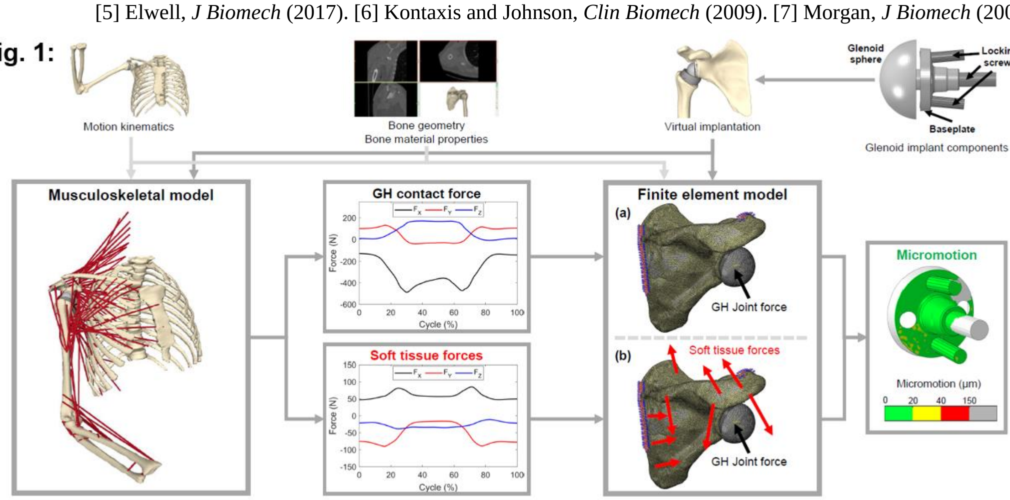

Fig. 2:

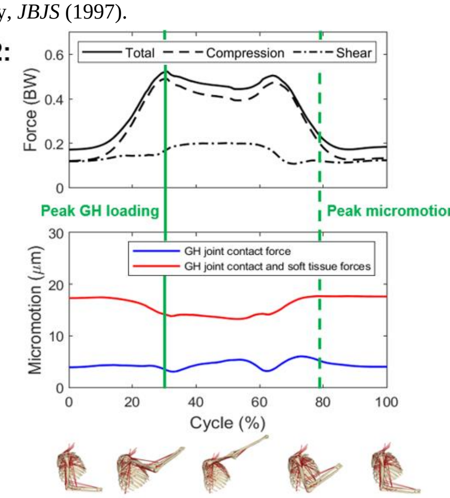

Figure 1: Overview of our computational approach to determine the bone-implant micromotion when **(a)** only the GH joint force was applied and **(b)** both GH joint force and soft tissue forces were applied. **Figure 2:** Top: Average GH joint forces (in BW) during the activity cycle. Solid line: total GH joint force; dashed line: compression force; and dot-dashed line: shear force. Bottom: Peak bone-implant micromotion (in µm) during the activity cycle. Blue line: configuration where only GH joint forces were considered; red line: configuration where both soft tissue and GH joint forces were considered. The dashed green vertical line represents the instant of peak net GH loading, and the green dot-dashed line represents the instant of overall peak micromotion.