Effect Of Reverse Total Shoulder Arthroplasty Lateralization On The Torque Generated By The Deltoid And Rotator Cuff Muscles

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INTRODUCTION: Modern reverse total shoulder arthroplasty (rTSA) designs can lateralize the glenoid and/or the humeral component and this affects the biomechanics of the deltoid and rotator cuff muscles. These implant design modifications affect both muscle moment arms and muscle lengths, and it is debated whether maximizing moment arms or restoring muscle lengths (which affects force production) optimizes post-operative function. As joint function depends on the torque that the muscles can generate (which is the product of the force produced by a muscle and its moment arm) the aim of this study was to use a biomechanical shoulder model to evaluate the impact of different rTSA lateralization strategies on the length-force relationship, moment arms, and torques generated by the deltoid and rotator cuff muscles.

METHODS: Computed tomography scans of 16 non-osteoarthritic subjects (10M/6F) were used to build customized computational models based upon the Newcastle Shoulder Model (NSM; Fig 1A) [1]. Here, the thorax, clavicle, scapula, and humerus of each subject was 3D reconstructed using Mimics (Materialize, Leuven Belgium) and anatomical landmarks were identified to define International Society Biomechanics joint and segment coordinate systems [2]. Next, a custom MATLAB (MathWorks, MA, USA) automation pipeline scaled the baseline NSM to the subject; replaced the generic bone geometries with the subject-specific 3D reconstructed geometries; and morphed the generic muscle attachment sites to the corresponding locations on the subject-specific geometries using a coherent point drift algorithm [3]. Subsequently, Hill-type muscle parameters including optimal fiber length, tendon slack length, and pennation angle were sourced from literature [4] and scaled to each of the 16 models using an optimization technique [5]. Physiological cross-sectional areas for all muscles were standardized to healthy values for all subjects. Four rTSA implant configurations were virtually implanted into each subject: 1) medialized glenoid – medialized humerus (MG/MH); 2) medialized glenoid – lateralized humerus (MG/LH); 3) lateralized glenoid – medialized humerus (LG/MH); and 4) lateralized glenoid – lateralized humerus (LG/LH) (Fig. 1). All configurations were implanted with a 135° neck-shaft angle humeral stem and 36 mm diameter glenoid sphere. Muscle operating length, force-production capacity (i.e., with the Hill-type muscle fully activated), moment arm, and maximum torque (product of the force-production capacity multiplied by the moment arm) were calculated for the middle deltoid during scapular plane elevation, and for the infraspinatus and subscapularis during external and internal rotation at 90° of abduction, respectively.

RESULTS: All rTSA configurations altered the distal and lateral position of the humeral head relative to the native shoulder (Fig. 1B) and modified post-operative muscle mechanics by shifting the range of active muscle force-length operation compared to native, although by varying degrees (Fig. 2A and 2B). Moment arms were consistent with prior literature: glenoid lateralization reduced deltoid moment arms up to 100° of elevation, whereas humeral lateralization increased moment arms for both the subscapularis and infraspinatus during internal and external rotation compared to glenoid lateralization, respectively (Fig. 2C). Regarding torque generation, the MG/LH configuration generated the largest deltoid torque during early elevation (at ~50°). Conversely, LG/LH was the only configuration to exceed the deltoid torque generated by the native shoulder throughout elevation (Fig. 2D). Peak deltoid torque was weakly correlated with changes in humeral distalization and lateralization (R^2<0.25, p<0.05). For both the infraspinatus and subscapularis muscles throughout rotation, the MG/MH and LG/LH configurations generated the smallest and largest rotational torque, respectively. Peak infraspinatus and subscapularis torque was correlated with distalization (R^2=0.84 and R^2=0.73 p<0.001) and lateralization (R^2=0.73 and R^2=0.81; p<0.001).

DISCUSSION: For the middle deltoid, the largest peak torque was generated by the MG/LH configuration at 50° of elevation due to a combination of a large force and moment arm. However, the torque generated by this configuration declined towards late elevation due to a decline in both force production and moment arm. Conversely, even if it did not have the highest moment arm, the force production of the LG/LH configuration helped generate the largest torque after 90° of elevation. For both the infraspinatus and subscapularis muscles, LG/LH (the most lateral configuration) generated the greatest torque due to the highest force production and the largest moment arm, whereas MG/MH (the most medial configuration) generated the least torque due to the lowest force production and the smallest moment arm. Based on these observations, both force production and moment arm influenced torque generation, and this was affected by progressive rTSA lateralization. It should be noted that these findings are limited to the specific rTSA implantation that was modeled, and results may vary for different design considerations like neck-shaft angle of the humeral stem or glenoid sphere diameter. Additionally, potential post-operative adaptations to the muscle architecture (e.g., optimal fiber length or pennation angle) were not taken into consideration.

SIGNIFICANCE/CLINICAL RELEVANCE: rTSA lateralization influenced the torque generated by the middle deltoid, infraspinatus, and subscapularis muscles by altering the force-production capacity and moment arm of the muscles. Overall, infraspinatus and subscapularis torque generation were directly increased with progressive lateralization whereas middle deltoid torque generation exhibited force/moment arm trade-offs during humeral elevation due to rTSA lateralization. These findings underscore the importance of considering rTSA lateralization strategies to optimize postoperative muscle biomechanics.

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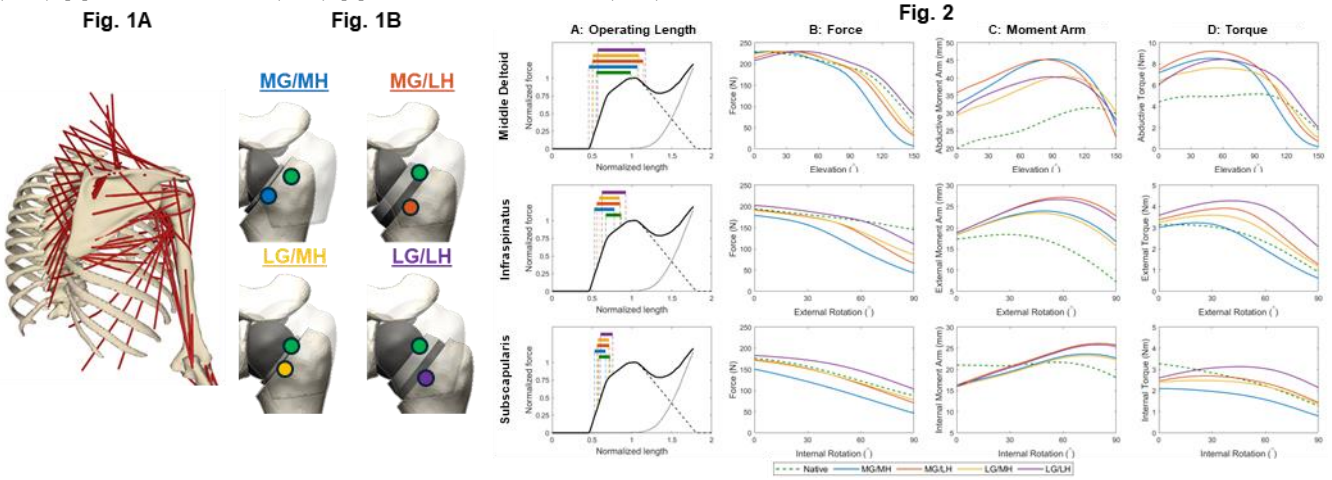

Figure 1: A: Musculoskeletal model. **B:** Implant alignment of the rTSA configurations. The green dot represents the humeral head center of the native shoulder, and the colored dots represent the post-operative humeral head center **Figure 2**: **A:** Operating length, **B:** force-production capacity, **C:** moment arm, and **D:** torque of the middle deltoid (top), infraspinatus (middle), and subscapularis (bottom). For the operating lengths plot (**A**), the dashed and dotted black lines represent the active and passive length-force curves for a Hill-type muscle, respectively, and the solid black line represents the overall length length-force curve for a Hill-type muscle. Length data were normalized by the optimal fiber length of the muscle.