ESTIMATION OF MUSCLE AND JOINT REACTION FORCES AT THE GLENOHUMERAL JOINT DURING ARM ABDUCTION: A MUSCULOSKELETAL MODELING APPROACH

Takashi Yanagawa (1), Marcus G. Pandy (2), Kevin B. Shelburne (1), Richard J. Hawkins (1), Michael R. Torry (1)

[1]Biomechanics Research Laboratory
Steadman-Hawkins Foundation
Vail, Colorado

[2]Department of Biomedical Engineering
University of Texas at Austin
Austin, Texas

INTRODUCTION

Shoulder motion involves integrated and multi-degree of freedom actions of the sternoclavicular, acromioclavicular, glenohumeral (GH) and scapulothoracic joints. Several studies have employed numerous methods to estimate the GH joint reaction forces (GHJRFs) during arm abduction. These studies have reported GH joint reaction forces in the range of 40-90% body weight (BW) and these forces tend to increase with abduction angle and peak when the arm is between 80°-90° in the scapular plane [1,2]. Throughout abduction the middle deltoid has been shown to be the most influential with regard to the magnitude of the GHJRFs. Studies have shown rotator cuff muscles to function as GH stabilizers and torque generators. In light of the complex relationship between joint stability and motion as mediated by the rotator cuff muscles, studies have attempted to isolate the rotator cuff importance to GH loads [2]. Parson's et al. described peak GHJRFs at 337 ± 88 N at 85° for an intact shoulder determined that the supraspinatus is relatively unimportant in causing GHJRFs. However, the intricacy of the shoulder and the inherent limitations of mechanical testing systems to reproduce the GH articulation have limited the quantitative analysis of GH joint reaction forces in vitro. This is most apparent when considering all in vitro studies to date have excluded many large muscles (e.g., latissimus dorsi, pectoralis major) that are active during shoulder abduction, and thus may contribute to the GH joint loads. Also, in vitro studies fixate the scapula or humerus during testing, thus negating the effect scapular rotation may have on increasing the mechanical advantage of the GH musculature, and these studies often combine multiple muscles into a single unit with the same line of action. Computer modeling and simulation of the upper extremity offers advantages in overcoming some of the limitations inherent to in vitro testing of the GH joint. The objective of this study was to utilize a musculoskeletal model of the upper extremity to estimate the individual muscles forces required to maintain a static abducted arm position, and to calculate the concomitant GHJRFs associated with this exercise.

METHODS

Muscle forces and GHJRFs during isometric shoulder abduction exercise were calculated using a detailed musculoskeletal model of the upper extremity (UE) that has been described in detail previously [3-5]. The model includes all of the major articulations from the shoulder girdle proceeding distally to the wrist [Fig. 1].

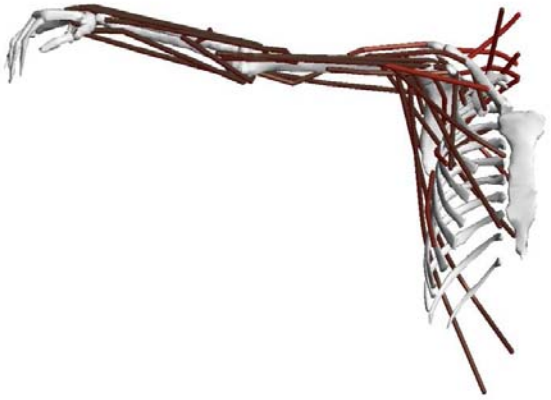

Figure 1: UE model with abducted position

Thirteen degrees of freedom are used to describe the orientations of the following seven bones: clavicle, scapula, humerus, radius, ulna, carpal bones, and hand. The joints of significance in this investigation, the sternoclavicular joint, the acromioclavicular joint, and the glenohumeral joint – are each modeled as a three degree-of-freedom ball-and-socket joint. The articulation between the scapula and thorax is based on the model reported by van der Helm (1994). Forty-two muscle bundles representing the actions of 26 muscle groups of the UE actuate the model [6]. The force generating property of each muscle-tendon actuator in the model is calculated from a Hill-type model of muscle force. Each muscle is divided into separate bundles according to the groupings of muscle fascicles [7]. Shoulder

abduction exercise was simulated with the humerus abducted to 90° relative to the torso and horizontally abducted to 20° relative to the coronal plane. The elbow of the arm was extended and no additional weight or external forces were applied. The muscle forces necessary to hold the arm abducted in the presence of gravity were found by solving a static optimization problem that minimized the sum of the squared muscle stresses [8].

RESULTS

Components of GHJRF in scapula frame are shown in figure 2. The resultant of GHJRF was 578 N, which is higher than reported previously [1,2]. Individual muscle force contributions to the GHJRF components are presented in figures 3, and are expressed in scapula frame and humerus frame, respectively. The clavicle portion of pectoralis major (PMajC), the middle deltoid (DeltA) and the posterior deltoid (DeltS) contributed most notably to the joint reaction force. The rotator cuff muscles (Supr, Infr, Subs, TMin) did not contribute considerably to the GHJRF.

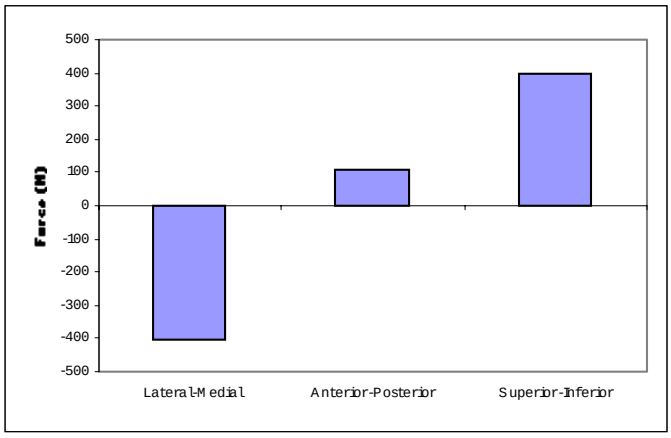

Figure 2: Components of GHJRF expressed in scapula frame

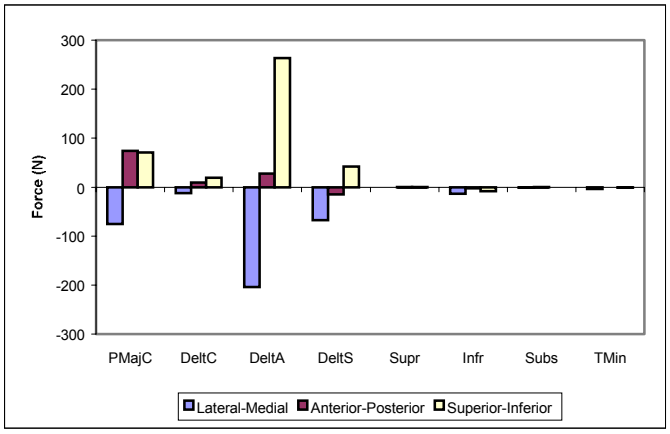

Figure 3: Muscle contributions of GHJRF

DISCUSSION

The present study employed all the muscles that span the GH joint and was able to differentiate their contributions to the GHJRF during humeral abduction. The present study has identified PMajC as contributing to the GHJRF. Contrary to previous studies [1,2], the rotator cuff muscles bear very little force while maintaining the humerus in 90° abducted position. The differences between the present study and previous studies may be due to numerous factors including: 1) the manner by which joint stability and joint motion are represented in the optimization routine of the UE model, 2) the number of degrees of freedom (the UE model does not translate), and 3) the estimation of scapula-humeral-thoracic position can be debated.

CONCLUSION

Technical challenges in vitro testing have limited the amount muscles that may be included in their analysis. The higher GHJRF observed in this study may be due to the inclusion of more muscles in the model and heavier arm mass. The inherent differences between computational models and in vitro models should be considered when making direct comparisons.

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