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Technical note

The sensitivity of shoulder muscle and joint force predictions to changes in joint kinematics: A Monte-Carlo analysis

Wen Wu, Peter Vee Sin Lee, David C. Ackland*

Department of Biomedical Engineering, University of Melbourne, Parkville, Victoria 3010, Australia

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ABSTRACT

Kinematics of the shoulder girdle obtained from non-invasive measurement systems such as video motion analysis, accelerometers and magnetic tracking sensors has been shown to be adversely affected by instrumentation measurement errors and skin motion artefact. The degree to which musculoskeletal model calculations of shoulder muscle and joint loading are influenced by variations in joint kinematics is currently not well understood. A three-dimensional musculoskeletal model of the upper limb was used to evaluate the sensitivity of shoulder muscle and joint force. Monte-Carlo analyses were performed by randomly perturbing scapular and humeral joint coordinates during abduction and flexion. Muscle and joint force calculations were generally most sensitive to changes in the kinematics of the humerus in elevation and of the scapula in medial-lateral rotation, and were least sensitive to changes in humerus plane of elevation and scapula protraction-retraction. Overall model sensitivity was greater during abduction than flexion, and the influence of specific kinematics perturbations varied from muscle to muscle. In general, muscles that generated greater force, such as the middle deltoid and subscapularis, were more sensitive to changes in shoulder kinematics. This study suggests that musculoskeletal model sensitivity to changes in kinematics is task-specific, and varies depending on the plane of motion. Calculations of shoulder muscle and joint function depend on reliable humeral and scapula motion data, particularly that of humeral elevation and scapula medial-lateral rotation. The findings in this study have implications for the use of kinematic data in musculoskeletal model development and simulations.

1. Introduction

Estimates of muscle and joint function using musculoskeletal modelling depend greatly on prescribed joint kinematics, since the positions of bone segments influences their centre of mass (COM) locations and net joint moments, as well as the force-generating properties of muscles including muscle-tendon lengths, lines of action, and moment arms. Contemporary motion measurement methods commonly employ high-speed video stereophotogrammetry [1], magnetic sensors [2], accelerometers, and gyroscopes [3,4]. These devices can detect gross movements such as arm flexion angles; however, skin-motion artefact creates errors in bone position estimation, particularly in glenohumeral joint translation, scapula motion and humeral axial rotation [5]. Kinematics studies demonstrate average skin-motion artefact errors of 7° for the scapula during abduction [6], and humeral axial rotation errors of up to 30° for maximum axial rotation tasks [7]. Bi-plane fluoroscopy has been used to track glenohumeral joint translations and rotations to the accuracy of less than 0.5 mm and 0.5° [8], respectively, but is costly to use and associated with ionizing radiation.

While motion measurement accuracy at the shoulder has been documented [6,7], the influence of changes in joint kinematics on model calculations of muscle and joint loading has not been quantified. As a consequence, the degree to which both scapular and humeral position measurement errors affect estimations of muscle and joint function is not well understood. The objective of the present study was to use Monte-Carlo analyses to evaluate the influence of changes in scapula and humerus position on musculoskeletal model estimates of shoulder muscle and joint force.

2. Methods

2.1. Upper limb motion tasks

Six male participants (25–38 years old, 170–175 cm, 56–85 kg) with no history of upper-limb pathology were recruited.

* Corresponding author.
E-mail address: dackland@unimelb.edu.au (D.C. Ackland).

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Participants performed coronal plane abduction and sagittal plane flexion at a speed of 25°/s. Three-dimensional trajectories of retro-reflective markers attached to subjects were simultaneously measured using an 8-camera video motion analysis system (Vicon, Oxford Metrics, UK) [9] (see Supplementary Material for details). Ethical approval for this study was obtained, as well as subjects' written informed consent.

2.2. Musculoskeletal model

A generic, 5-segment, 10-degree-of-freedom (DOF) musculoskeletal model of the upper-limb was developed as described previously [9]. The elbow was modelled as a 2-DOF universal joint, the glenohumeral and acromioclavicular joints as 3-DOF constrained ball and socket joints, and the sternoclavicular joint as a 2-DOF universal joint. The model was actuated by 26 Hill-type muscle-tendon units representing the major axioscapular, axiohumeral and scapulohumeral muscle groups, and has been previously validated (see Supplementary Material).

2.3. Monte-Carlo analyses

Upper limb joint kinematics during the tasks, including independent scapular and humeral motion, were calculated for each subject using inverse kinematics [9]. The average joint kinematics across all 6 subjects was used in nominal simulations of abduction and flexion to calculate shoulder muscle forces and glenohumeral joint forces. A Monte-Carlo analysis was then performed to evaluate the sensitivity of muscle and joint force calculations to perturbations in scapula and humeral kinematics. To reduce computation time, each motion trajectory was divided into seven evenly-spaced time points. For the Monte-Carlo analysis, each scapular and humeral joint coordinate at the seven time points was randomly perturbed by a value within a fixed range of ±13° to obtain a new time-history of joint kinematics [10]. This nominal perturbation range represented the standard deviation of measured motion across all subjects and tasks performed, and to normalize the analysis, was employed for each joint coordinate perturbation. Muscle and joint forces were subsequently recalculated using the perturbed kinematics, with body velocities and accelerations updated accordingly. Random perturbed simulations were subsequently repeated in an iterative manner until convergence, as described previously [11]. For perturbations of scapular motion, the orientation of the humerus relative to ground was not changed, and vice versa. Additional Monte-Carlo analyses were performed by simultaneously perturbing the three joint coordinates associated with the scapula and humerus.

3. Results

The changes in muscle forces that occurred when perturbing scapula and humeral kinematics were highly muscle-specific. In most cases, muscles that generated higher muscle forces, including the middle deltoid and subscapularis, were more sensitive to kinematics changes (Fig. 1). With the exception of humeral elevation perturbations, muscle force sensitivity increased with elevation angle and therefore torque demand.

Muscle force calculations during abduction and flexion were more sensitive to changes in humeral elevation and scapula medial-lateral rotation and least sensitive to changes in humerus plane of elevation and scapula protraction-retraction. Simultaneously perturbing all three joint coordinates associated with the humerus resulted in larger muscle force changes when compared to perturbing all three scapula joint coordinates (Fig. 2).

The sensitivity of muscle force calculations to changes in kinematics was task-dependent. For example, the middle deltoid, subscapularis and infraspinatus forces were more sensitive to perturbations in humeral elevation in abduction than flexion, while the superior pectoralis major force was more sensitive to changes in humeral elevation in flexion than abduction.

The sensitivity of joint force calculations to kinematics changes was direction dependent (Fig. 3). The compressive component of joint force was more sensitive to the kinematics changes (mean RMS difference: 6.98%BW) than the anterior and superior components (mean RMS difference: 2.52%BW and 2.23%BW, respectively). Joint force calculations were more sensitive to changes in humeral position than scapula position, with the exception of the superior component of joint force during abduction. Glenohumeral joint force was more influenced by perturbations in the humeral elevation coordinate than any other humeral or scapular joint motion coordinate, and joint force calculations were more sensitive in abduction than flexion overall (Fig. 3).

4. Discussion

The present study showed that model calculations of muscle and joint loading are more sensitive to changes in humeral elevation than any other humeral or scapular joint motion. Perturbations in humeral elevation affected force calculations substantially since the net glenohumeral joint moment is highly dependent on arm COM position and humeral motion with or against gravity. This was particularly evident at lower elevation where perturbations in humeral elevation angles resulted in a greater change in the lever of the arm COM about the glenohumeral joint centre (and therefore glenohumeral joint moment changes) than those at high elevation angles (Fig. 1). As a consequence, considerable muscle force variations were observed at lower elevation when the humeral elevation coordinate was perturbed in isolation. Shoulder muscle and joint force calculations also demonstrated high sensitivity to changes in scapula medial-lateral rotation, since this motion caused substantial changes in shoulder muscle-tendon unit lengths, which affected the operating region on the muscles' force-length curves and therefore the force-producing capacity of these actuators [12]. This finding suggests that the 'gliding' movement of the scapula on the thorax, a highly subject-specific motion critical for upper limb mobility [13,14], may be an important predictor of muscle and joint force, second only to humeral elevation.

The sensitivity of musculoskeletal model behaviour to joint kinematics changes was muscle-specific and task-dependent. A muscle was more sensitive to perturbations in kinematics when a given joint motion had a greater influence on the muscle's recruitment. For example, the anterior deltoid was more sensitive to changes in the plane of humeral elevation than humeral elevation, since plane of elevation perturbations resulted in substantial changes in its elevation moment arm which influenced its torque capacity and activation. Tasks requiring higher muscle and joint loading were associated with greater model sensitivity to kinematics changes. For example, muscle and joint forces were generally higher during abduction than flexion, with higher model sensitivity observed in abduction (Fig. 1).

Compressive glenohumeral joint force was affected more by joint kinematics perturbations than anterior or superior glenohumeral joint force, since most shoulder muscles contribute more compressive joint force than shear. Since perturbations in humeral elevation affected muscle recruitment more than other joint coordinate changes, joint force calculations were also highly sensitive to humeral elevation. In addition, the results demonstrate that scapula kinematics, particularly scapula anterior-posterior