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Comparison of model-predicted and measured moment arms for the rotator cuff muscles

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Abstract

Background— The ability of mathematical models of the shoulder to accurately replicate physiological muscle moment arms is unknown. The purpose of this study was to compare model-predicted and experimentally measured moment arms for the rotator cuff muscles during arm elevation.

Methods— Moment arms obtained from 6 mathematical models and 7 experimental studies were compared for the supraspinatus, infraspinatus, teres minor, and subscapularis for elevation in the scapular plane.

Results— All of the included models generated moment arms that generally fell within the range of experimentally measured data.

Interpretation— The quantitative agreement between model-predicted and experimentally measured moment arms supports the use of the included models for biomechanical shoulder analyses.

Keywords

shoulder; moment arms; computational model

INTRODUCTION

Mathematical models of shoulder and upper extremity muscles are useful for many applications, including analysis of tendon transfers (Magermans *et al.*, 2004), rehabilitation (Labriola *et al.*, 2005), finite element modeling of prosthesis components (Stone *et al.*, 1999), and ergonomics (Laursen *et al.*, 2003). EMG-driven (Laursen *et al.*, 1998) and optimization-based models (Hogfors *et al.*, 1987,1991,1995;van der Helm, 1994a,1994b) have been developed for estimating muscle forces around the shoulder. A critical component of optimization-based methods is the accurate determination of muscle moment arms as muscle force predictions have been shown to be highly sensitive to these parameters (Raikova and Prilutsky, 2001).

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There have been several experimental investigations of elevation moment arms for the rotator cuff muscles (Graichen *et al.*, 2001; Howell *et al.*, 1986; Kuechle *et al.*, 1997; Liu *et al.*, 1997; Nyffeler *et al.*, 2004; Otis *et al.*, 1994; Poppen and Walker, 1978), as these muscles are critical for normal shoulder function. Although some models have used empirical measurements of muscle moment arms (Hughes and An, 1996, 1997, 1999; Langenderfer *et al.*, 2006; Poppen and Walker, 1978), many modern shoulder models apply mathematical representations of musculoskeletal geometry (Dickerson *et al.*, 2005, 2006; van der Helm, 1994a, 1994b). One advantage of this approach is that the models can analyze arm positions other than those for which moment arm data were experimentally collected. However, the resulting accuracy of the models to predict muscle moment arms is unclear.

The objective of this paper was to compare model predicted moment arms of the rotator cuff muscles to experimentally measured moment arms reported in the literature. Our comparison was limited to elevation in the scapular plane because of the availability of experimental data.

METHODS

A structured literature review process, which is standard practice when conducting a meta-analysis (Petitti, 2000), was followed to identify published experimental data on rotator cuff muscle moment arms. Four inclusion criteria were defined: (1) experimental measurement of moment arms of either the supraspinatus, infraspinatus, teres minor, or subscapularis, muscles *in vivo* or in cadavera; (2) moment arm data presented for abduction in the plane of the scapula; (3) data presented in text, tabular, or graphical format; and (4) clearly described experimental method. A protocol was developed for selecting papers, which included searching Medline and PubMed using keywords rotator cuff, shoulder, moment arm, lever arm, mechanical advantage, and muscle line of action. Book chapters were also consulted for references to primary sources of moment arm data. References in all documents were scrutinized for additional data sources. Forty-two papers were identified and each full paper was checked for inclusion criteria by two authors (AGM and CJG). Ten papers met the inclusion criteria; however, only seven were used because some data sets from independent studies were published in multiple manuscripts.

The moment arms included in the comparison were for arm elevation in the scapular plane at glenohumeral angles (GHAs) of 30° and 60° with 0° of humeral axial rotation for the supraspinatus, infraspinatus, teres minor, and the subscapularis. Experimentally measured moment arm data were obtained from studies by Graichen *et al.* (Graichen *et al.*, 2001), Howell *et al.* (Howell *et al.*, 1986), Kuechle *et al.* (Kuechle *et al.*, 1997), Liu *et al.* (Liu *et al.*, 1997), Nyffeler *et al.* (Nyffeler *et al.*, 2004), Otis *et al.* (Otis *et al.*, 1994), and Poppen and Walker (Poppen and Walker, 1978). The methods used in these studies are presented in Table 1. Model-predicted moment arm data were obtained from the use of the Dickerson model (Dickerson *et al.*, 2005, 2006), Holzbaur model (Holzbaur *et al.*, 2005), and Delft Shoulder and Elbow Model (DSEM) (van der Helm, 1994a, 1994b); these models are available to the biomechanics community. It should be noted that the Dickerson model is an implementation of the model developed by Hogfors and co-workers (Hogfors *et al.*, 1987, 1991, 1995). For the other included models, moment arm data were extracted from published or dissertation data from the Favre model (Favre *et al.*, 2005), Garner model (Garner and Pandy, 2001), and Newcastle model (Charlton, 2003); the availability of these models is not known.

Moment arms were extracted from published figures for the studies performed by Graichen *et al.*, Kuechle *et al.*, Liu *et al.*, Nyffeler *et al.*, Otis *et al.*, and Poppen and Walker as well as for the Garner and Newcastle models. For the study by Howell *et al.* and for the Favre model, moment arms were taken from the published article text and tables, respectively.

Graichen *et al.*, Howell *et al.*, and Poppen and Walker reported moment arms with respect to arm elevation angle, whereas the current study compares moment arms with respect to GHA. The arm positions of these studies were converted using a 2:1 ratio of arm elevation angle to glenohumeral angle as reported by Inman *et al.* (Inman *et al.*, 1944). Thus, GHAs of 30° and 60° correspond to arm elevation angles of 45° and 90°, respectively. The experimentally measured moment arms are presented in Tables 2 and 3 for 30° and 60° GHA, respectively. Two studies divided each rotator cuff muscle into multiple muscle elements and measured each muscle element moment arm (Nyffeler *et al.* and Otis *et al.*). Thus, ranges of values were obtained and are presented for each individual muscle element in the tables.

Moment arms from the Holzbaur and Dickerson models and the DSEM were computed directly with the respective models. The Holzbaur model output moment arms with respect to arm elevation angles that were converted to GHAs using the calculated scapulohumeral rhythm of the model. A superior-inferior vector was aligned and attached to the medial border of the scapula; the GHA was defined to be the angle between said vector and the long axis of the humerus. The scapulohumeral rhythm was calculated and the moment arms at the GHAs of interest were computed. For the Dickerson model, the position of the humerus was defined with respect to the torso. Arm position was defined relative to a starting position extracted from the geometric model of Hogfors *et al.* (Hogfors *et al.*, 1987) (humerus abducted to 90°, with epicondyles parallel to the gravity vector, the thumb pointed up and elbow range of motion in the horizontal plane). Three sequential Euler rotations (3, -2, 1) defined humeral position relative to the scapula in order to ensure consistency with the shoulder rhythm formulation used (Hogfors *et al.*, 1991). Glenohumeral angles were confirmed following humeral positioning as matching those of the empirical data used. For the DSEM, the humerus was positioned in 30° and 60° elevation with respect to the scapular vector in the scapular plane, with zero degrees axial rotation. Moment arms were extracted in the local humeral system of the model.

RESULTS

In general, all of the models evaluated generated moment arms that fell within the range of experimentally measured data for the muscles reported by each. The moment arms predicted by each model are shown together with the range of experimentally measured moment arms in Figure 1 (a–h) for each rotator muscle at 30° and 60° GHA. The Favre, Dickerson, Holzbaur models and the DSEM contained muscle elements for all four rotator cuff muscles. The Favre model predicted both the infraspinatus and supraspinatus abduction moment arms within the experimental range. However, for the subscapularis and teres minor, the predicted moment arms tend towards a greater adduction function than that of the experimental data. The Dickerson model produced moment arms in the experimental data range for all postures and muscles except for supraspinatus at 60° GHA (over prediction by 0.05 mm) and the teres minor at 30° GHA. Predictions from the Holzbaur model wholly agreed with the empirical data except for underpredicting the teres minor adduction moment arm at 60° GHA. The DSEM has high anatomical fidelity with multiple muscle elements for each muscle, and therefore produces a range of predicted moment arms for each muscle. In several situations, some muscle elements agree with experimental ranges, while others do not. For example, approximately half of the muscle elements for the subscapularis are within the range. Moreover, substantial adduction function was predicted for some muscle elements, while a substantial abduction function was predicted for others. The Garner model predicted moment arms within the experimental range for the supraspinatus and subscapularis, although data was unavailable for the infraspinatus and teres minor. The Newcastle model accurately predicted subscapularis moments arms, however, at 60° GHA it predicted higher abduction moment arms for both the supraspinatus and infraspinatus. No data were available for the teres minor in the Newcastle model.

DISCUSSION

This study compared rotator cuff moment arms obtained from multiple shoulder models to those reported in several sets of experimental data. The moment arms from the models showed overall agreement and were within the range defined by the empirically measured data. The experimental data included represent the body of literature concerning moment arms for the arm positions of interest, as these two arm positions are clinically relevant.

The Garner and Newcastle models did not publish moment arm data for all muscles at both arm positions considered. Further, published data concerning experimentally measured moment arms did not always include data on all muscles in both positions. Discrete positions were selected due to the limited literature concerning experimental studies. The experimental studies were performed independently; thus, variations in methodology and in the arm positions at which moment arms were measured are possible. Some studies (Graichen *et al.*, 2001; Howell *et al.*, 1986; Poppen and Walker, 1978) reported measured moment arms with respect to arm elevation angle, whereas the current comparison uses glenohumeral angle. Conversion of these angles is subject to variations in subject-specific scapulohumeral rhythm. The model moment arms were either computed (Dickerson and Holzbaur models and DSEM) or extracted (Garner, Favre, and Newcastle models) from published or dissertation data, and some variation in the arm positions of the models is possible. The included studies did not report anthropometric specimen data, and, with the exception of the Dickerson model, the models either did not report or do not allow for subject scaling. Therefore, this comparison does not account for potential anthropometric variation, which may alter the results. Finally, the method of subdivision of muscles into functional mechanical elements differed across models and experiments and this may have resulted in discontinuities between the data sets. These limitations should be considered as they can influence experimental and model-predicted moment arms. It should also be noted that variation in moment arm values would cause large variation in torque calculations. Despite these limitations, however, the performance of the models in predicting the empirical data confirms the robustness of the modeling approaches used and informs users of the models as to their utility.

The quantitative agreement between model-predicted and experimentally measured moment arms supports use of the included models for biomechanical analyses of the rotator cuff muscles of the shoulder. The comparison between computational models and published empirical data is important because moment arms are a critical factor in the outputs of muscle force prediction models.

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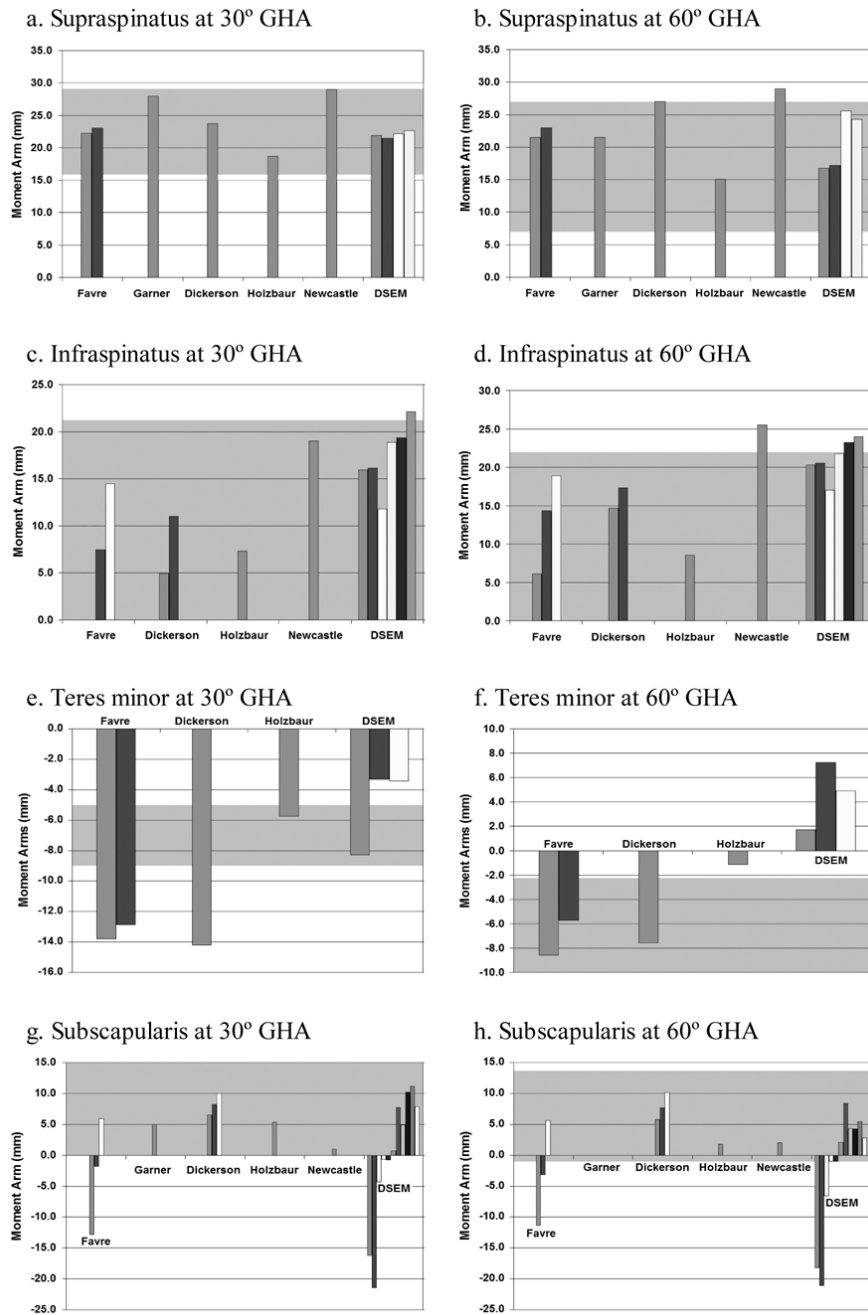


Figure 1. Model predicted rotator cuff moment arms
 Model predicted muscle (or muscle element if applicable) moment arms for the supraspinatus (a,b), infraspinatus (c,d), teres minor (e,f), and subscapularis (g,h) at 30° and 60° GHA compared to the range of experimentally measured moment arms (shaded area). For models which have multiple muscle elements, the moment arms are presented (left to right) using the following conventions: supraspinatus – anterior to posterior muscle elements; infraspinatus, teres minor, and subscapularis – inferior to superior muscle elements.

Table 1

Moment arm measurement method used in each study

Study	Method
Graichen <i>et al.</i> , 2001	3-D measurement using reconstruction from MRI
Howell <i>et al.</i> , 1986	Roentgenographic measurement
Kuechle <i>et al.</i> , 1997	Tendon excursion/joint displacement method
Liu <i>et al.</i> , 1997	Tendon excursion/joint displacement method
Nyffeler <i>et al.</i> , 2004	Tendon excursion/joint displacement method
Otis <i>et al.</i> , 1994	Tendon excursion/joint displacement method
Poppen and Walker, 1978	Radiographic measurement

Table 2

Experimentally measured rotator cuff abduction moment arms at 30° glenohumeral abduction in the scapular plane

Study	Supraspinatus	Infraspinatus	Teres minor	Subscapularis
Graichen <i>et al.</i>				
Howell <i>et al.</i>	25.0	0.0		
Kuechle <i>et al.</i>	16.0	4.0	-5.0	3.0
Liu <i>et al.</i>	29.0	11.0		6.0
Nyffeler <i>et al.</i>	27.5	8.5, 15.5, 21.5 [†]	-9.0	0.0, 10.0, 16.0 [†]
Otis <i>et al.</i>				
Poppen and Walker				
Range	16.0 to 29.0	0.0 to 21.5	-9.5 to -5.0	0.0 to 16.0

* moment arms measurements in mm;

[†] inferior, middle, superior muscle elements, respectively

Table 3

Experimentally measured rotator cuff abduction moment arms at 60° glenohumeral abduction in the scapular plane

Study	Supraspinatus	Infraspinatus	Teres minor	Subscapularis
Graichen <i>et al.</i>	21.0			
Howell <i>et al.</i>	25.0	0.0		
Kuechle <i>et al.</i>	7.0	2.0	-13.0	11.0
Liu <i>et al.</i>	23.0	10.0		1.0
Nyffeler <i>et al.</i>	22.5	13.0, 18.0, 22.0 [‡]	-4.0	-1.0, 8.0, 11.0 [‡]
Otis <i>et al.</i>	25.1, 27.0 [‡]	5.4, 8.4, 16.9 [‡]	-2.2	4.3, 7.3, 13.6 [‡]
Poppen and Walker	21.0			-1.0
Range	7.0 to 27.0	0.0 to 22.0	-13.0 to -2.2	-1.0 to 13.6

* moment arms measurements in mm;

[‡] inferior, middle, superior muscle elements, respectively

[‡] anterior, posterior muscle elements, respectively