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A probabilistic orthopaedic population model to predict fatigue-related subacromial geometric variability

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ABSTRACT

Fatigue-related glenohumeral and scapulothoracic kinematic relationships, in addition to morphological characteristics of the scapula and humerus, affect the dimensions of the subacromial space. Each exhibits considerable interpersonal variability, which if only considering the mean, can lead to misleading population estimations of subacromial impingement risk, particularly for outliers. Additionally, the relative influence of each parameter on subacromial space variability is unclear. Applying empirically-derived morphological and kinematic distributions ($n=31$), this research used Advanced Mean Value and Monte Carlo probabilistic modeling approaches to predict the distribution of the minimum subacromial space width (SAS) and establish which parameters contributed more to modulating the SAS. The predicted SAS differed by 8 mm between 1% and 99% confidence intervals. While the SAS was not influenced by muscle fatigue, the space reduced with arm elevation to magnitudes between 4.5 and 5 mm. This reduction resulted in an estimated 65–75% of the population at risk for tissue compression at elevation angles $\geq 90°$ when considering the interposed tissue thickness. Morphological parameters, notably glenoid inclination, showed higher relative importance for modulating the predicted SAS across conditions, while kinematic parameters (humeral head translation, scapular orientation), which differed by elevation angle and fatigue state, demonstrated less consistent importance levels across experimental conditions. Overall, the findings reinforce the shoulder health risks related to overhead activities, as they pose an increased likelihood of mechanical rotator cuff tendon compression. Further, probabilistic methods are highly innovative, in that they are capable of determining relative parameter importance and subsequently identifying key injury risk factors. As glenoid inclination is difficult to diagnose and treat, and is associated with superior humeral head translation, interventions to improve rotator cuff strength and glenohumeral stability are recommended, particularly in populations exposed to overhead postures.

1. Introduction

Computational models in biomechanics are often used to evaluate parameters related to musculoskeletal injury risk, however model assumptions must be considered. Incorporating variability into predictive models is crucial for capturing physiological realism. Each variable or parameter that contributes to the overall model predictions has an associated level of uncertainty. Thus, relying on representative population mean values, as is the case with deterministic models, fails to capture this variability which can subsequently result in misleading outcomes (Langenderfer et al., 2006; Laz and Browne, 2010). Probabilistic approaches, including Advanced Mean Value (AMV) and Monte Carlo, evaluate the influence of model parameter uncertainty on the predicted outputs by representing each parameter as a probability distribution. AMV is a probabilistic approach that uses a combination of reliability and optimization-based approaches to predict the output at specified discrete probability levels (Wu et al., 1990). Monte Carlo iteratively calculates many deterministic solutions to construct an entire cumulative distribution function (CDF) for the predicted output. AMV is computationally efficient and accurately converges to the Monte Carlo solution, which is considered the gold standard (Easley et al., 2007; Langenderfer et al., 2008, 2009; Laz and Browne, 2010). Additionally, as AMV simulations require a transformation of each parameter into a non-dimensionalized standard normal solution space, it permits calculation of importance factors. These factors describe the relative importance of each parameter in modulating the predicted output. Despite demonstrating critical utility for characterizing biological tissue variation, the overall use of probabilistic modeling in biomechanics remains limited.

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Table 1
Morphological and Kinematic Parameter Input.

Morphological Parameter Input	μ	σ
Glenoid inclination (deg)	95.0	5.9
Lateral acromial angle (deg)	79.9	9.3
Acromial anterior slope (deg)	18.0	10.9
Acromial tilt (deg)	31.5	4.7
Acromion index	0.62	0.08
Subacromial tissue thickness (mm)	6.1	0.8

Kinematic Parameter Input

β (deg)	Humeral Head Position (mm)			
	μ		σ	
	Pre	Post	Pre	Post
0	−0.4	−0.6	1.3	1.6
30	0.7	0.5	1.1	1.4
60	1.4	1.4	1.2	1.0
90	2.1	1.8	0.8	0.9
120	2.5	2.4	0.9	1.0

β (deg)	Scapular upward–downward rotation (deg)				Scapular anterior–posterior tilt (deg)				Scapular internal–external rotation (deg)			
	μ		σ		μ		σ		μ		σ	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
0	−0.3	0.4	5.5	6.3	19.3	20.3	7.3	8.3	−31.8	−34.8	6.7	8.3
30	2.6	4.9	7.1	8.0	20.1	19.7	7.4	9.1	−31.3	−32.9	6.3	7.7
60	11.0	12.3	8.3	7.5	20.0	20.8	9.5	9.7	−32.1	−33.0	7.1	7.0
90	18.1	21.7	11.9	9.1	20.1	20.6	11.0	10.9	−33.5	−34.9	8.4	7.9
120	28.6	34.1	13.4	13.8	17.5	18.3	13.9	14.5	−39.0	−36.7	9.8	11.0

Morphological Input: Mean (μ) and Standard Deviation (σ) for each of the measured parameters. Kinematic Input: Mean (μ) and Standard Deviation (σ) for each of the measured parameters for each condition (five humerothoracic elevation angles (β) and two fatigue states (Pre/Post)). Positive kinematic orientations: superior humeral head translation, scapular upward rotation, scapular anterior tilt, scapular external rotation. All morphological parameters were identical across all conditions.
Note: Input data included in this table are identical to experimental outputs presented in Chopp-Hurley et al. (in press-a, in press-b).

The risk of developing subacromial impingement syndrome (SAIS), and subsequent tissue damage, has been attributed to several bone and tissue morphological characteristics, in addition to activity-induced kinematic alterations. Specifically, anatomical variation in the shapes of the acromion process, humerus and glenoid cavity has been related to SAIS and/or rotator cuff pathologies (Balke et al., 2013; Hughes et al., 2003). Additionally, altered glenohumeral and scapulothoracic kinematics, that may follow muscular fatigue or injury, can reduce the size of the subacromial space, subsequently leading to mechanical impingement of the interposed tissues (Chopp et al., 2010; Chopp and Dickerson, 2012; Deutsch et al., 1996; Ludewig and Reynolds, 2009). The marked interpersonal variability that exists for each of these characteristics coupled with the clinical relevance of small changes in subacromial space width magnitude (~1 mm) (Michener et al., 2015) demonstrates the essential need to apply probabilistic methods to effectively evaluate population SAIS risk, as often minor perturbations in inputs and/or model parameters can have a remarkable influence on the predicted outputs (Chopp-Hurley et al., 2014; Easley et al. 2007; Langenderfer et al., 2006, 2008, 2009; Pal et al 2007).

The many parameters contributing to subacromial space reduction, and their consistent interpersonal variability, prompted the application of probabilistic methods to evaluate the distribution of subacromial space geometry resulting from parameter variation. The primary objectives of this research were to develop a probabilistic model to predict the distribution of the minimum subacromial space width (SAS) among a young, healthy male population based on varying empirically measured morphological characteristics and fatigue-related glenohumeral and scapulothoracic kinematics, and to determine the relative parameter importance in modulating the predicted SAS. Additionally, a second probabilistic impingement risk model was developed to calculate the probability of measured subacromial tissue thicknesses exceeding the predicted SAS. It was hypothesized that superior humeral head translation would be a greater contributor to subacromial space reduction than three-dimensional scapular orientation following fatigue due to reported fatigue-initiated glenohumeral and scapulothoracic kinematics (Chen et al., 1999; Chopp et al., 2010, 2011; Chopp-Hurley and Dickerson, 2015; Cote et al., 2009; Ebaugh et al., 2006; McQuade et al., 1998; Teyhen et al., 2008). It was also hypothesized that morphological parameters related to the acromion and glenoid shape (Balke et al., 2013; Hughes et al., 2003; Toivonen et al., 1995) would be as important as the kinematic factors, due to their previously established relationship with rotator cuff damage and/or SAIS. Lastly, it was anticipated that both predicted SAS and SAIS risk would be highly variable among the measured population.

2. Methods

A subacromial geometry model was created with two implementations: probabilistic and deterministic. The probabilistic implementation was developed using NESSUS probabilistic analysis software (SwRI, San Antonio, TX), such that nine parameters related to the morphology and kinematic relationships of the humerus, scapula and torso, were defined by modifying each parameter within an existing deterministic implementation. This implementation interfaced with the deterministic, created in Matlab® (Mathworks®, Natick, MA), to apply defined