FUNCTIONAL IDENTIFICATION

OF SHOULDER JOINT CENTERS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Analysis of upper extremity kinematics is difficult due to the lack of bony landmarks on the upper arm and shoulder. The medial and lateral epicondyles provide two potential bony landmarks for the upper arm, and the shoulder joint center provides a potential third landmark. Two methods commonly used to estimate the location of the shoulder joint center are the constant offset method (Rab, Petuskey, and Bagley, 2002) and the spherical fit method (Hicks and Richards, 2005). The constant offset method is susceptible to error due to variability of human geometry. The spherical fit method has been shown to be more accurate than constant offset methods for the hip; however, the methods have not been compared for the shoulder joint center. The objective was to compare the accuracy of the shoulder joint centers found using the functional spherical fit method as well as the constant offset method proposed by Rab, Petuskey, and Bagley (2002) relative to a physical measure of the shoulder joint center found using ultrasound. The physical measure was compared to the centers found with the constant offset method and functional identification for four positions: adduction-ER, 90º abduction-ER, 180º abduction-ER, and 90º flexion, IR. The centers were found for each method using the elevation of the humerus as a constraint. Specifically, motion trial data was analyzed at maximum elevation limits ranging from -30º below horizontal to 80º above horizontal at 10º intervals. Results indicated that the angle of elevation when using the spherical fit should be limited to zero degrees relative to the horizontal in order to minimize error. Using this minimized difference, the functional identification is most accurate in the adduction-ER position. Since

both estimation methods are relative to the acromion marker, both are susceptible to errors in the other positions. In positions that require abduction, the scapula displays posterior tilt, resulting in the acromion rotating behind the glenoid cavity and causing the estimated centers to become posterior to the actual shoulder joint center. Conversely, in the 90º flexion-IR position, the scapula tilts anteriorly, causing the acromion to rotate in front of the glenoid cavity and produce estimated centers anterior to the actual shoulder joint center. Therefore, although the functional identification is more accurate in the adduction-ER position, both methods are characterized by substantial errors when implemented through a full range of motion.

Chapter 1

INTRODUCTION

In order to analyze human kinematics, at least three points are needed on each body segment to determine a segment's orientation in space and calculate kinematics and kinetics[1]. Markers are typically placed where skin movement is minimized -- on bony landmarks -- in order to decrease error due to skin artifact, which has been shown to contribute to ninety percent of kinetic uncertainty in upper extremity joints while walking[, 2,3]. However, only two bony landmarks are feasible on the upper arm due to muscles covering all other possibilities[4]. Therefore, it is necessary that an effective, accurate method be determined in order to find the shoulder joint rotation center and provide a third point – a suggestion being the shoulder joint center since it will provide a common point connecting the upper arm and trunk[1]. This point, the shoulder joint center, resides at the geometric center of the humeral head[5].

Among the current methods used to estimate the shoulder joint center are constant offset methods, which describe the rotation center relative to surface markers using constant ratios that are usually based on a percentage of the distance between the right and left acromioclavicular joints[6]. These methods assume constant ratios of bony geometry and require normal geometry of the scapula [7]. Recent studies have found these methods to produce inaccurate and unreliable results due to palpation errors, unaccounted variability in scapular geometry, and limitations in the methods themselves[1, 8].

A similar problem with constant offset methods was found when estimating the hip joint; however a recent study showed that for the hip joint, a spherical fit algorithm was more accurate than constant offset methods[9]. This spherical fit algorithm, also known as a functional method, fits a sphere to a cluster of points created by tracking the motion of a marker on the distal segment as it moves relative to the proximal segment, thus allowing for the individualized functional identification of the joint rotation center. Studies have shown that, when applied to the shoulder joint center, spherical fit algorithms are more reliable between observers as well as between trials than constant offset methods[8].

The functional identification method is a potential solution to the inaccuracy and non-individualization of the constant offset methods for estimating the shoulder joint centers; however, studies have yet to assess the accuracy of this method for the upper extremities. The objective of this study was to determine the shoulder joint center using the constant offset methods devised by Rab, Petuskey, and Bagley (2002) as well as the functional identification method described by Hicks and Richards (2005). The location of these points was compared to physical measure of the shoulder center location obtained using ultrasound. The accuracy of each method was assessed by comparing the linear differences between these points.

Chapter 2

METHODS

Fifteen healthy, average-weight adults (6 males and 9 females, mean age 26.7 ± 12.4 years, range 21-64) served as subjects for this study, using only their left arm for trials. Testing for each subject occurred in the Human Performance Laboratory at the University of Delaware. Motion data was captured in a calibrated volume using an 8 camera Motion Analysis system operating at 60 Hz. Ultrasound data was collected using a SonoSite180 ultrasound unit operating at 10 MHz.

Cube-shaped markers measuring 7mm across were placed on the subject in the following locations: the spinal process of the 7^{th} cervical vertebra, the spinal process of the 8th thoracic vertebra, the suprasternal notch, the xiphoid process, the acromioclavicular joint, the lateral epicondyle, and the medial epicondyle. The center of the upper trunk was then defined as the midpoint between the 7^{th} cervical vertebra and the suprasternal notch, and the center of the lower trunk was defined as the midpoint between the spinal process of the 8^{th} thoracic vertebra and the xiphoid process. A local coordinate system was created using the acromion marker as the origin. The axes were created as follows: X was directed lateral from the upper trunk to the acromion, Z was computed by performing the negated cross product of X onto a temporary vector from the center of the upper trunk to the center of the lower trunk, and Y was computed by performing a cross product of the X-axis and Z-axis creating an inferior axis,. Three markers were also placed on the ultrasound probe in order to capture the position and orientation of the ultrasound during trials; one toward the medial side, one toward the lateral side, and one toward the back of the probe. The subject then completed a dynamic trial and a series of static trials in order to determine the location of the shoulder joint center using each method. Static trials were the performed in order to determine the actual shoulder joint center with the upper arm in several positions relative to the trunk. A motion trial was used to determine the location of the shoulder joint centers using spherical fit and constant offset methods.

The markers on the ultrasound probe were used to create a coordinate system that provided the position and orientation of the ultrasound probe and enabled the ultrasound data to be described in the calibrated laboratory volume. This was accomplished by relating the markers on the probe that were used for subject data collection (technical markers) to a temporary set of probe markers that were positioned in the sensor plane and had two markers aligned on each end of the leading edge of the ultrasound probe (temporary markers). In this manner, the temporary markers were easily recreated from the technical markers used during data collection, and the data from the ultrasound images was then processed relative to the orientation and position of the reconstructed temporary markers.

The static trials consisted of the subject sitting on a chair in the center of the calibrated region while data was collected in each of the following positions: 1) External rotation and adduction, 2) External rotation and 90 degrees abduction, 3) External rotation and 180 degrees abduction, 4) Internal rotation and 90 degrees flexion. While in each position, the ultrasound was oriented in both vertical and horizontal positions at the shoulder joint, thus providing two trials of ultrasound and marker data. The horizontal orientation distinguished the rotation center, indicated on the ultrasound by the midpoint of the humeral head arc, along the anterior-posterior and medial-lateral axes. The vertical orientation was used to determine the rotation center on the inferior-superior axis. Once the arc identifying the surface of the humeral head was centered on the ultrasound image, the image was frozen and the motion analysis system simultaneously captured the location of the markers. The depth of the humeral head outline was then measured using the ultrasound unit and saved onto a computer using an ADS Tech VideoXpress Version 2.2. The depth of the humerus and position of the probe was used to locate the shoulder joint center relative to markers on the probe (Figure 1).

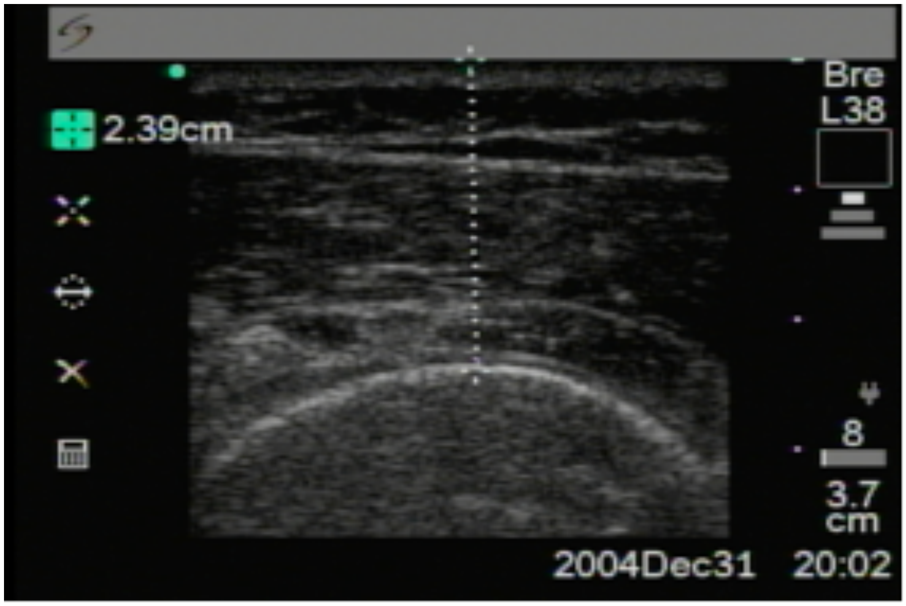

Figure 1 Ultrasound image of the humeral head in the horizontal plane

The images from the ultrasound were analyzed with a custom LabView program that determined a circle using four points fitted to the humeral outline (Figure 2). The center of the humeral head was then determined by adding the radius of this circle to the humeral depth found using the ultrasound. By knowing the direction and magnitude of the vector originating at the ultrasound probe, and knowing the position of the probe in the volume, the global position of the shoulder joint center was identified. This ultrasound-determined shoulder joint center, referred to in the remainder of this paper as the US measure, provided a standard with which to assess the accuracy of each method of estimation.

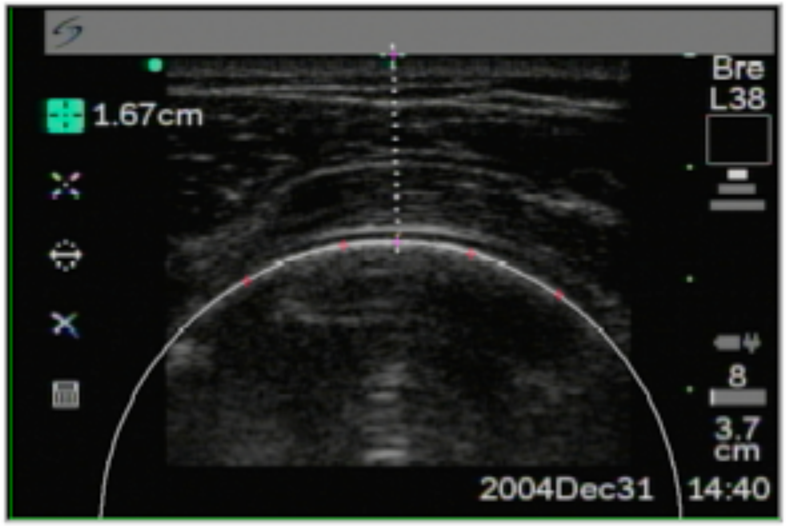

Figure 2 Ultrasound Image with Circular Fit

After all static trials were completed, subjects performed a dynamic trial consisting of two cycles of each following motions in a single trial: 1) Abduction and adduction, 2) Horizontal adduction and abduction, and 3) Circumduction. Subjects were instructed to complete these movements slowly through a comfortable range of motion. This trial was used to track the elbow joint center found by averaging the location of the medial and lateral epicondyles relative to the acromion marker in the shoulder coordinate system. The path created by the elbow center created a sphere around the shoulder joint, in which the center of the sphere would correspond to the shoulder joint center.

Shoulder joint centers were determined using the functional identification method described by Hicks and Richards (2005) as well as the constant offset method developed by Rab, Petuskey, and Bagley (2002). The shoulder joint centers from the functional identification method and constant offset method were found using data from the dynamic trial. These centers were found in the shoulder coordinate system for every frame and then averaged over the entire trial. The centers were found for each method using the elevation of the humerus as a constraint in order to limit the movement of the deltoid over the acromion. Specifically, motion trial data was analyzed at maximum elevation limits ranging from -30º below horizontal to 80º above horizontal at 10º intervals. The linear differences between the estimated shoulder joint centers and the actual shoulder joint center found using the ultrasound as well as the differences in each plane were then determined. A two-way repeated measures analysis of variance and Tukey HSD test was used to compare each method.

Chapter 3

RESULTS

The linear differences between the estimated joint centers and the US measure were compared for each position and maximum elevation angle in order to determine the elevation angle of which a minimal difference resulted. The limited angle of elevation made no difference in the accuracy of the constant offset method. For the functional identification, however, the optimal angle of elevation was 0 degrees relative to the horizontal for each position (Figure 3).   This approximated an abduction angle of 90 degrees.

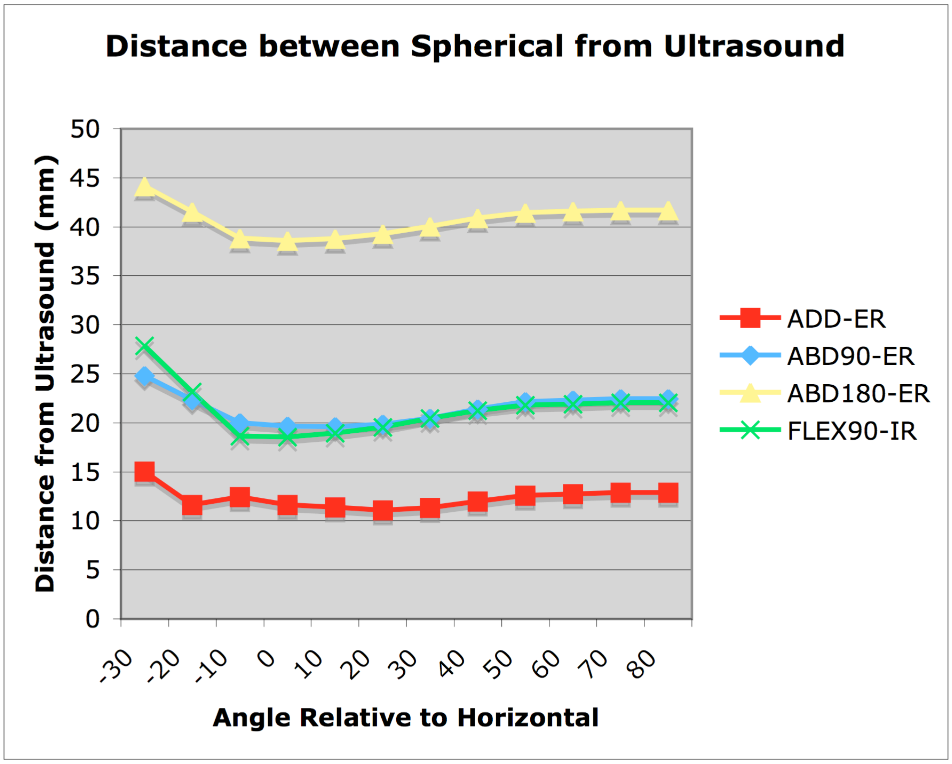

Figure 3 Difference between Spherical Fit and Ultrasound for each angle

Comparing the linear differences in the adduction-ER position with an elevation constraint angle of 0 degrees, the mean linear difference between the spherical fit estimate and the US measure was 1.16 cm. This difference was significantly less than the difference between the shoulder joint center found using the constant offset method and the US measure (2.56 cm) (Table 5). There were no significant differences between the spherical fit and constant offset estimates in the other three positions. In 90º abduction-ER, the mean linear difference for the sphere fitting was 1.97 cm compared to 2.43 cm for the constant offset method. In 180º abduction-ER, the spherical fit estimate resulted in a mean linear difference of 3.68 cm compared to 3.52 cm linear difference for the constant offset method. In 90º flexion-IR, the spherical fit estimate produced a mean linear difference of 1.85 cm, while the constant offset method produced a mean linear difference of 1.70 cm. The difference between the center found with the spherical fit and constant offset was approximately 2.1 cm in each position.

Table 5 Mean Linear Differences Between Ultrasound Measures and Shoulder Center Estimates with a 0º Limited Angle of Elevation

	US vs. Spherical (mm)	US vs. Constant Offset (mm)	Spherical vs. Constant Offset (mm)
Adduction-ER	11.652 (± 3.920)	25.569 (± 6.478)	20.998 (±7.498)
90º Abduction-ER	19.657 (± 7.184)	24.253 (±7.151)	20.998 (±7.498)
180º Abduction-ER	38.581 (± 11.164)	35.238 (± 12.361)	20.998 (±7.498)
90º Flexion-IR	18.539 (±7.601)	16.990 (±8.428)	20.998 (±7.498)

The differences between positions determined using ultrasound and each method of estimation were also calculated for each anatomical axis in each position (Table 6). In the adduction-ER position, minimal error in any axis occurred for the spherical fit with the estimated center 0.43 cm lateral, 0.39 cm inferior, and 0.05 cm anterior of the US measure. For the constant offset method in this position, the estimated center was 2.19 cm lateral, 0.76 cm inferior, and 0.44 cm anterior of the actual shoulder joint center. In 90 degrees abduction-ER, the estimated centers became more posterior, with a mean of 1.7 cm for the spherical fit and 1.3 cm for the constant offset method. This difference in the posterior direction further increased in the 180 degrees abduction-ER, in which the mean difference was 3.47 cm for the spherical fit and 3.07 cm for the constant offset method. For the spherical fit, the estimated center remained slightly medial but also superior of the actual shoulder joint whereas the constant offset method produced an estimated center slightly lateral and superior of the actual shoulder joint center. In 90 degrees flexion-IR, estimated shoulder joints became more medial, superior, and anterior, with the spherical fit center was 1.2 cm medial, 0.08 cm superior, and 0.20 cm anterior and the constant offset center 0.57 cm lateral, 0.42 cm superior, and 0.60 cm anterior of the US measure.

Table 6 Difference between Ultrasound Measures and Shoulder Center Estimates for each anatomical axis

	US vs. Spherical Fit (mm)			US vs. Constant Offset (mm)		
	Lateral Medial	Inferior Superior	Anterior Posterior	Lateral Medial	Inferior Superior	Anterior Posterior
Adduction-ER	4.26 Lateral	3.85 Inferior	0.47 Anterior	21.93 Lateral	7.64 Inferior	4.44 Anterior
90º Abduction-ER	3.46 Medial	1.35 Inferior	17.00 Posterior	14.21 Lateral	5.24 Inferior	13.03 Posterior
180º Abduction-ER	9.89 Medial	4.77 Superior	34.71 Posterior	7.77 Lateral	0.98 Superior	30.74 Posterior
90º Flexion-IR	11.97 Medial	8.03 Superior	2.04 Anterior	5.70 Lateral	4.24 Superior	6.01 Anterior

Chapter 4

DISCUSSION

The results indicated that upper arm movement used to estimate the functional joint center should be limited to a 0 degree or horizontal angle of elevation in order to minimize error with the spherical fit algorithm. Error due to elevation was expected since an angle of elevation above 120 degrees has been shown to produce marker movement and error[10]. When the arm exceeds this angle, the deltoid and surrounding tissue cover the acromion altering the marker position relative to the acromion process.

At the zero degree angle of elevation, the results of the linear differences and differences in each plane suggested that the functional identification is more accurate than the constant offset method in the adduction-ER position. This method produced a lower linear difference and lower differences on each of the axes. This is consistent with the hip joint, in which Hicks and Richards[9] found that the spherical fit was more accurate than the constant offset method. The difference between the spherical fit center and constant offset method remained relatively constant since joint center estimates from both methods were dependent on the position of the acromion marker. Both methods are susceptible to errors of similar magnitude and direction due to soft tissue movement and scapular tilt, and consequently there was no significant difference between methods in 90 degrees abduction-ER position, 180 degrees abduction-ER position, and 90 degrees flexion-IR.

In positions where abduction exceeds 90 degrees, the soft tissue likely allows movement of the acromion marker relative to the acromion process. The deltoid crossing the acromion can create a small amount of superior displacement in the 180º abduction-ER position and 90º flexion-IR position. In fact, one study showed that markers placed on the acromion can deviate up to 39 mm for full elevation[10]. Relative to adduction-ER, the scapula displays posterior tilt in the 90 degrees abduction-ER position. As a result, the acromion rotates behind the glenoid cavity. Since both methods position the joint center in a trunk-dependent coordinate system that is relative to the position of the acromion marker, this scapular tilt results in the posterior discrepancy between the estimated and actual shoulder joint centers. This posterior difference increases in the 180 degrees abduction-ER position due to an increase in posterior scapular tilt. In the 90 degrees flexion-IR position, the scapula displays anterior tilt, resulting in the acromion rotating in front of the glenoid cavity. This causes the estimated centers, both relative to the acromion, to become anterior to the actual shoulder joint center. This is expected since external rotation causes the acromion to move posteriorly and internal rotation causes the acromion to move anteriorly[11]. Previous studies have indicated that, with abduction, a posterior tilt of up to 30 degrees occurs between rest and maximal elevation[12]. Thus, in addition to accounting for soft tissue movement, a method that utilizes a trunk-dependent coordinate system to determine the virtual location of the shoulder joint center needs to account for scapular tilt in order to provide an accurate shoulder joint center through a full range of motion.

REFERENCES

1. Wu, G., van der Helm, Frans C.T., (DirkJan) Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., et al. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38*(5), 981-992.

2. Reimer, E., Hsiao-Wecksler, X., Zhang. (2008). Uncertainties in inverse dynamics solutions: comprehensive analysis and an application to gait. *Gait & Posture, 27*(4), 578-588.

3. Roux, E., Bouilland, S., Godillon-Maquinghen, A., & Bouttens, D. (2002). Evaluation of the global optimisation method within the upper limb kinematics analysis. *Journal of Biomechanics, 35*(9), 1279-1283.

4. Veeger, H. E. J., van der Helm, F. C. T., Chadwick, E. K. J., Magermans, D. (2003). Toward standardized procedures for recording and describing 3-D shoulder movements. *Behavior research methods, instruments & computers, 35*(3), 440-446.

5. Veeger, H. E. J. (2000). The position of the rotation center of the glenohumeral joint. *Journal of Biomechanics, 33*(12), 1711-1715.

6. Rab, G., Petuskey, K., & Bagley, A. (2002). A method for determination of upper extremity kinematics. *Gait & Posture, 15*(2), 113-119.

7. Meskers, C. G. M., Vermeulen, H. M., de Groot, J. H., van der Helm, F. C. T., & Rozing, P. M. (1998). 3D shoulder position measurements using a six-degree-of-freedom electromagnetic tracking device. *Clinical Biomechanics, 13*(4-5), 280-292.

8. Stokdijk, M., Nagels, J., & Rozing, P. M. (2000). The glenohumeral joint rotation centre in vivo. *Journal of Biomechanics, 33*(12), 1629-1636.

9. Hicks, J. L., & Richards, J. G. (2005). Clinical applicability of using spherical fitting to find hip joint centers. *Gait & Posture, 22*(2), 138-145.

10. Karduna, A. R., McClure, P. W., Michener, L. A., Sennett, B. (2001). Dynamic measurements of three-dimensional scapular kinematics: a validation study. *Journal of Biomechanical Engineering, 123,* 184-190.

11. Wilk, K. E., Reinold, M. M., & Andrews, J. R. (2008). *The athlete's shoulder, 2nd edition*. Philadelphia, PA: Elsevier Health Sciences.

12. McClure, P. W., Michener, L. A., Sennett, B. J., & Karduna, A. R. (2001). Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *Journal of Shoulder and Elbow Surgery, In Press, Corrected Proof.*