A COMPARISON OF NON-INVASIVE METHODS FOR ESTIMATING SCAPULAR KINEMATICS IN TYPICALLY DEVELOPING ADOLESCENTS

by

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ABSTRACT

Typical shoulder motion depends on proper contributions of both the scapulothoracic (ST) and glenohumeral (GH) joints. Abnormal scapular kinematics are related to a variety of shoulder pathologies such as impingement syndrome and rotator cuff tears. Identification of scapular dyskinesis and evaluation of subsequent interventions depend on the ability to properly measure ST and GH motion.

In upper extremity literature, the recommended dynamic measurement method is the acromion marker cluster (AMC). While it enjoys widespread use, this approach yields large errors at higher levels of humeral elevation and has also been shown to be inaccurate in populations with pathological upper extremity motion. Recently, an approach that develops individualized regression equations has been proposed as an alternative to the AMC. This technique utilizes the relationship between ST orientation, humerothoracic (HT) orientation and acromion process (AP) displacement derived from a set of static positions to predict ST orientations from HT and AP measures in motion. These individualized regressions demonstrated promising results for healthy adults; however, this method has not been validated on children or in populations with pathological motion. Furthermore, this approach has not yet been compared to the more conventional AMC.

This study compared the AMC to the regression approach in typically developing adolescents performing a series of functional tasks. The accuracy of each method was evaluated against palpated ST angles and error trends were examined for relationships to the amount of HT motion. Following the static accuracy evaluation, measurements by the AMC were compared across both static and dynamic conditions. Finally, the two methods were compared during dynamic execution of the functional

tasks, and differences were evaluated in the context of the previous analyses and also with respect to the amount of HT motion.

The results of this study revealed that the regression approach yielded smaller errors than the AMC along each axis of motion and in every position. The performance of the regression approach suffered, however, when applied to positions outside of the range of motion present in the set of positions used to build the equations. The AMC demonstrated significant errors in capturing motion about the ST internal rotation axis and a trend toward overestimation of ST posterior tilt. These directional biases were exacerbated from static to dynamic conditions. In motion, the AMC and regression methods differed considerably in many subjects. On average, the AMC produced higher upward rotation angles, lower internal rotation angles and higher posterior tilt angles than the regression approach. Upon examination of many individual trials with extreme differences, the regression approach was typically within one standard deviation of the corresponding static mean palpated angle, while the AMC often produced angles that exceeded two standard deviations from the static mean. Dynamic differences between methods were found to be related to the amount of AMC error in the corresponding static position. Additionally, the two methods diverged for ST internal rotation and posterior tilt with increased HT displacement. When the dynamic results were examined in the context of the static validation, it appeared that the regression approach outperformed the AMC for functional tasks in the adolescent population. These findings can inform future researchers as to the best choice of scapular kinematic measurement method and provide context for interpretation of scapular kinematics resulting from the use of either approach.

Chapter 1

INTRODUCTION

Background

Motion of the upper extremity requires coordination of each of the four joints that comprise the shoulder girdle: the sternoclavicular, acromioclavicular, scapulothoracic (ST) and glenohumeral (GH) joints. Clinical exams are typically limited to evaluating the motion of the humerus relative to the trunk. However, understanding the contribution of the individual joints is essential for the assessment and treatment of shoulder dysfunction. The range of motion of the scapula has been shown to be an important part of achieving functional arm motion, including humeral elevation [1], and daily activities such as reaching, hand behind the back, hair combing, feeding and brushing teeth [2]–[4]. In young populations that suffer from shoulder pathology, such as injured athletes or children with brachial plexus birth palsy, the motion of each underlying joint is often the target of surgical or therapeutic treatment [5], [6]. In general, diagnosis of shoulder dysfunction and evaluation of interventions require consideration of scapular movement patterns. Abnormal motion of the ST joint has been implicated in a variety of shoulder pathologies, ranging from instability to impingement syndrome and even rotator cuff tears [7]–[10].

Scapular kinematics are particularly relevant in the adolescent population. Injury occurrence surges in high school throwing athletes due to the increase in frequency and intensity of training [11], and scapular dyskinesis is often implicated in the risk of injury [12], [13]. Rehabilitation specifically targets the restoration of GH range of motion and ST strength and stability [14], and thus decisions regarding return to play depend on the ability to accurately measure the motion of the entire shoulder complex. In addition to the sports medicine considerations, the extreme musculoskeletal growth that occurs in adolescence increases the prevalence of orthopedic injuries such as physeal fractures [15], [16] and disorders such as scoliosis [17] that may have implications for shoulder motion. Accordingly, accurate measurement of scapular motion is essential to the evaluation and treatment of shoulder dysfunction in the adolescent population.

While the need for consideration of ST and GH joint contributions is clear, the body of upper extremity research is still largely limited to humerothoracic (HT) motion. This is a direct consequence of the difficulty of measuring the entire shoulder complex, in particular, the scapula. The complicated geometry of the scapula and its translation beneath the skin during movement make traditional surface marker motion capture challenging. The literature details several different measurement techniques, but none are without limitation and many are considered inaccurate. Bone pins are generally accepted as the reference standard for measuring ST motion [18]–[20], but the invasive nature of this approach is not appropriate for children or patient populations. Furthermore, even for use in healthy adults, it has never been determined whether the insertion of pins through the skin into the scapula influences the pattern of scapular movement. Biplane fluoroscopy or other imaging techniques eliminate the skin-pinning problem, but require radiation exposure [21], [22].

Several non-invasive approximations have been proposed and validated with varying degrees of accuracy. The most common approach, and the current literature recommendation, is the acromion marker cluster (AMC) [23]. The AMC (or acromion marker sensor if used in conjunction with an electromagnetic tracking system) is a non-anatomical coordinate system attached to the acromion process. By calibrating the orientation of this device to the orientation of the anatomical scapula in one or more static positions, the device can track scapular orientation during motion [18], [24], [25]. This approach is easy to implement and has been shown to yield accurate results in healthy adults within a moderate ranges of humeral elevation. At higher levels of humeral elevation (greater than 120 degrees), however, AMC errors can reach clinically significant levels, as high as 25 degrees [18].

Throughout the literature, the evaluation of the AMC's accuracy has been fragmented and mostly limited to elevation or planar motion [23]. The AMC has never been validated for a comprehensive set of functional motions, even in typically-developing populations. Additionally, studies in populations other than healthy adults have demonstrated that the AMC has significant limitations when measuring pathological shoulder motion. In children with brachial plexus birth palsy, the AMC produced errors that were often greater than the measured motion [26]. Similarly, in children with hemiplegic cerebral palsy, the AMC significantly underestimated scapular upward rotation and protraction [27].

A novel non-invasive alternative has been recently proposed with encouraging results. Nicholson et. al [28] developed individualized regression equations that predicted ST orientation based on its relationship to HT orientation and acromion process (AP) position derived from a set of static calibration positions. The approach was validated for nine healthy adults using biplane fluoroscopy, and yielded average root mean square (RMS) errors below eight degrees for all axes of ST motion. Additionally, this study validated an unprecedented range of motion, incorporating the traditional planar movements of elevation and rotation, but also functional movements such as hand to mouth, hand to nape, hand to spine and a forward reach. The results of this study support the application of this approach in healthy adults. Furthermore, the individualized nature of the equations suggests this technique may be useful in pathological populations that may not follow a normal pattern of ST motion. Still, the approach has only been validated in a normal adult population.

The AMC and regression methods have not yet been compared in any population. Furthermore, neither has been evaluated for use in adolescents. As discussed previously, measurement techniques that can be used for dynamic validation are invasive. This creates an ethical and practical challenge, particularly for the adolescent population. In contrast, static validation, using palpation as a reference, is an alternative approach to evaluating the performance of measurement techniques. Palpation is considered the silver standard of scapular orientation measurement [29] and has been shown to be accurate to within two degrees [30].

The primary goal of this study was to validate and compare two non-invasive methods of estimating scapulothoracic motion in typically-developing adolescents. Both methods have been proposed as justifiable candidates for marker-based measurement. By comparing the estimated ST angles to palpated ST orientations in several functional positions and interpreting the static results for dynamic conditions, we sought to determine which, if either, technique was most suitable for adolescent subjects. The expected outcomes from this study were 1) an evaluation of two non-invasive approaches to measuring ST motion in typically-developing adolescents and 2) an easily replicable validation approach that could be used in other vulnerable populations where accurate measurement of ST and GH motion is of interest.

Specific Aims and Hypotheses

Aim 1. Evaluate the accuracy of the regression approach and the acromion marker cluster in static positions

ST orientations in five positions within a functional range of upper extremity motion were estimated by both approaches. Estimated angles were compared to ST angles determined by palpation.

Hypothesis 1.1: RMS differences between the palpated ST orientations and the regression-predicted ST orientations will be smaller than differences between the palpated ST orientations and the AMC-estimated ST orientations.

Hypothesis 1.2: For each axis of motion, errors in angles estimated by the AMC will be related to the amount of HT angular displacement from a neutral resting position.

Hypothesis 1.3: For each axis of motion, errors in angles estimated by the regression approach will be independent of the amount of HT angular displacement from a neutral resting position.

Aim 2: Compare the angles estimated by the regression approach and the acromion marker cluster during motion

While this study did not utilize a gold standard for a dynamic evaluation of accuracy, we directly compared angles produced by each measurement approach during motion. We determined how angles produced by the AMC changed from static to dynamic conditions. We also examined how differences between the AMC and the regression approach during motion were related to the overall amount of HT motion, as well as how differences were related to the errors that were observed during static validation.

Hypothesis 2.1: The AMC will produce ST angle estimates that are consistent across both static and dynamic conditions.

Hypothesis 2.2: RMS differences between the two methods across the motion trials will be related to the errors observed in the static validation of the corresponding position.

Hypothesis 2.3: For each axis of motion, differences between the two methods will be correlated with the amount of HT displacement from a neutral resting position.

Innovation

This study is the first to compare the AMC and the regression approach for measuring ST orientation. Both methods are non-invasive and easy to implement, and thus a direct comparison is warranted. Furthermore, this is the first study in which the AMC was evaluated for a broad range of motion within the same set of subjects. Hence, the interpretation and application of our results is not limited to humeral elevation or other planar motions, as is the case with most of the literature. For an investigator looking to make an informed choice on which method is more suitable for the intended research question, our comparison of the two methods across different functional positions demonstrates when each method fails under certain conditions and provides an overall evaluation of each approach.

Finally, this study is the first to evaluate methods for measuring ST orientation specifically in adolescents. Scapular motion is an important consideration for sports medicine and upper extremity orthopedic diseases in the developing adolescent. The results from this study can inform future research investigations as to the appropriate choice of measurement technique.

Chapter 2

A STATIC COMPARISON OF TWO NON-INVASIVE METHODS FOR MEASURING SCAPULAR ORIENTATION IN FUNCTIONAL POSITIONS

Introduction

The range of motion of the scapula has been shown to be an important factor for achieving functional arm motion including humeral elevation [1] and daily activities such as reaching, hand behind the back, hair combing, feeding and brushing teeth [2]–[4]. Abnormal motion of the scapulothoracic (ST) joint has been implicated in a variety of shoulder pathologies, ranging from instability to impingement syndrome and even rotator cuff tears [7]–[10].

Scapular kinematics are particularly relevant in the adolescent population. Injury occurrence surges in high school throwing athletes due to the increase in frequency and intensity of training [11], and scapular dyskinesis is often implicated in the risk of injury [12], [13]. Rehabilitation specifically targets the restoration of glenohumeral (GH) range of motion and ST strength and stability [14], and thus decisions regarding return to play depend on the ability to accurately measure the motion of the entire shoulder complex. Additionally, orthopedic disorders (e.g. scoliosis) that develop primarily in adolescence can involve abnormal scapular motion [31]. Accordingly, accurate measurement of scapular motion is essential to the evaluation and treatment of shoulder dysfunction in the adolescent population.

While the need for consideration of ST joint motion is clear, the available measurement approaches are fraught with limitations. Bone pins are generally accepted as the gold standard for measuring ST motion [18]–[20], however the invasive nature of this approach is not appropriate for children or patient populations. Biplane fluoroscopy or other imaging techniques are alternative reference standards, but require radiation exposure [21], [22]. Several non-invasive approximations have been proposed and validated with varying degrees of accuracy. The most common approach, and the current recommendation in the literature, is the acromion marker cluster (AMC) [23]. The AMC is a non-anatomical coordinate system attached to the acromion process (AP). By calibrating the orientation of this device to the orientation of the anatomical scapula in some static position, the device can track scapular orientation during motion [18], [24], [25]. This approach is easy to implement and has been shown to yield accurate results within a moderate range of humeral elevation in healthy adults. However, at higher levels of humeral elevation (greater than 120°), AMC errors can reach clinically significant levels, as high as 25° [18].

Throughout the literature, the evaluation of the AMC's accuracy has been fragmented and mostly limited to elevation or planar motion [23]. The AMC has never been validated for a comprehensive set of functional motions, even in typically-developing populations. Furthermore, studies in populations other than healthy adults have demonstrated that the AMC has significant limitations when measuring pathological shoulder motion. In typically-developing children and children with hemiplegic cerebral palsy, the AMC significantly underestimated scapular upward rotation and internal rotation [27]. These trends persisted in children with brachial plexus birth palsy, and for these subjects, the AMC produced large errors that were often greater than the measured motion [26].

A novel non-invasive alternative has been recently proposed with encouraging results. Nicholson et. al [28] developed individualized regression equations that predicted ST orientation based on its relationship to humerothoracic (HT) orientations and acromion process (AP) positions derived from a set of static calibration positions.

The approach was validated for nine healthy adults using biplane fluoroscopy and yielded average root mean square (RMS) errors below eight degrees for all axes of ST motion. Additionally, this study validated an unprecedented range of motion, incorporating the traditional planar movements of elevation and rotation, but also functional movements such as hand to mouth, hand to nape, hand to spine and a forward reach. The results of this study support the application of this approach in healthy adults. Furthermore, the use of individualized inputs for the regression equations suggests this technique may be useful in pathological populations that may not utilize a typical pattern of ST motion. Still, the approach has only been validated in a normal adult population.

While both methods are candidates for non-invasive measurement of ST motion, the AMC and regression methods have not yet been compared in any population. Furthermore, neither has been evaluated for use in adolescents. As discussed earlier, the available gold standard measurement methods that can be used for dynamic validation are invasive. This creates an ethical and practical challenge, particularly for the adolescent population. In contrast, static validation, using palpation as a reference, is an alternative approach to evaluating the performance of measurement techniques. Palpation is considered the silver standard of scapular orientation measurement [29] and has been shown to be accurate to within two degrees [30].

In this study, we propose a validation and comparison of the AMC and regression methods for measuring ST orientation in the adolescent population. Both methods have been suggested as justifiable candidates for marker-based measurement of shoulder motion. By comparing the ST angles estimated from each method to palpated ST orientations in several functional positions, we can determine which, if either, method is most suitable for adolescent subjects and whether either method fails under certain conditions. We hypothesized that the regression approach would outperform the AMC in the adolescent population and that performance of the AMC would be related to the amount of HT displacement, while regression performance would be independent of HT motion.

Methods

Subjects

Eighteen healthy adolescents (average age: 14.9 ± 1.8 years, 6 males, 12 females) were recruited, and assent and parental permission were obtained in accordance with the procedures established by the University of Delaware institutional review board. Subjects were excluded if they had history of shoulder pathology or surgery.

Motion Capture

Subjects sat on a backless chair in a comfortable position. A 12 camera Motion Analysis (Santa Monica, CA) system operating at 60 Hz was used for motion capture. Throughout the trials, the subjects wore three-dimensional (3D) retro-reflective markers at the following locations:

Thorax: sternal notch, T1 spinous process, T8 spinous process

Humerus: medial epicondyle, lateral epicondyle, posterolateral humerus

An AMC was placed on the AP in accordance with the recommendations of Warner et al [25]. The subjects proceeded to hold each arm in a series of 15 positions (Figure 1).

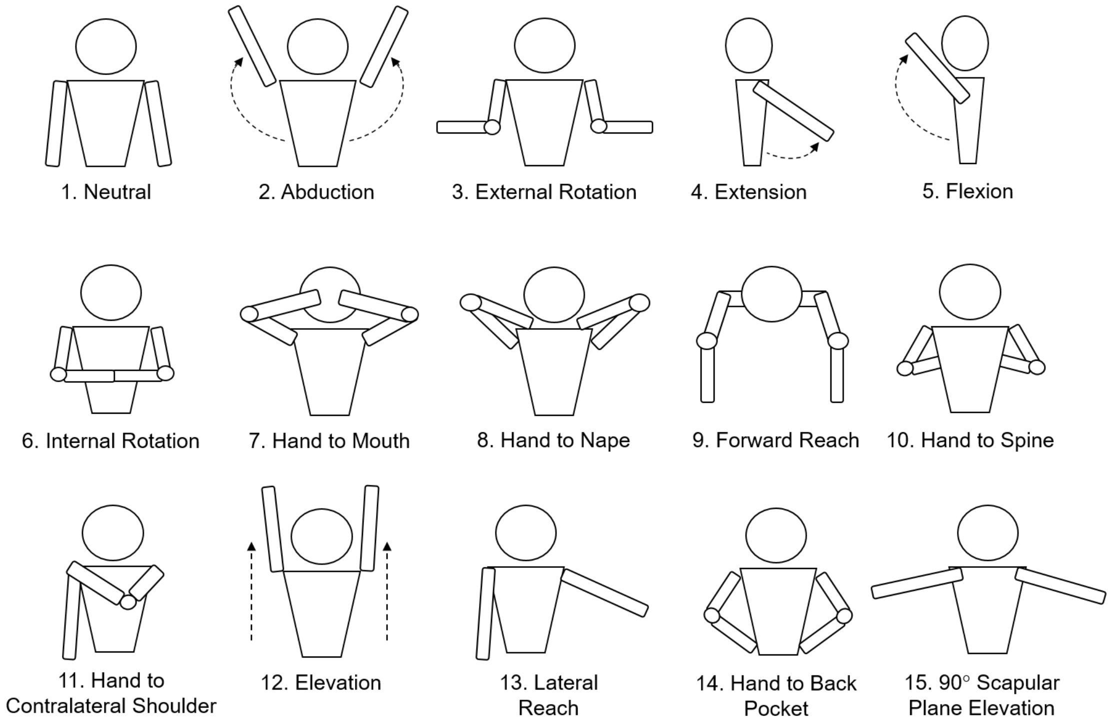

Figure 1 Positions for regression input (1-10) and testing of regression and AMC (11-15).

The first ten positions (neutral, full humeral abduction, external rotation, extension, flexion, internal rotation, hand to mouth, hand to nape, forward reach, and hand to spine) were used solely for development of the regression equations, while the remaining five positions (hand to contralateral shoulder, unconstrained full humeral elevation, lateral reach, hand to back pocket, and 90° elevation in the scapular plane) were designated the test positions for evaluation of the accuracy of the AMC and regression approaches. These test positions were selected to include motion that was both functional and robust enough in range to derive meaningful results from the evaluation of each technique's performance. At each position, the following anatomical landmarks on the scapula were palpated: trigonum spinae and inferior angle of the scapula. Two-dimensional (2D) retro-reflective markers were placed on the palpated locations (Figure 2) and removed once the position was captured for a duration of one second.

Figure 2 Marker placement for scapular coordinate system, demonstrated for the "Hand to Back Pocket" position.

As most of the cameras were placed behind the subject, 2D markers at these locations were visible to several cameras and provided accurate measures of 3D landmark position without an offset associated with 3D markers.

Calculation of Joint Angles and AP Position

Coordinate systems for the humerus and trunk were created using recommendations from the International Society of Biomechanics (ISB) [32]. The GH joint center was calculated by an individualized vertical offset from the acromion process as per the Rab method [33]. The scapular coordinate system was constructed as a slight modification of ISB recommendations. The center marker of the AMC (which was placed directly on the AP) was used in place of the acromial angle. ST angles were calculated as per the ISB-recommended YXZ Euler sequence [32]. Rotation about the X axis corresponded to scapular upward and downward rotation, rotation about the Y axis corresponded to internal and external rotation, and rotation about the Z axis corresponded to anterior and posterior tilt. HT angles were calculated by the helical method to avoid dependence on order of motion and any resulting singularities [34]. Helical angles were then resolved onto the anatomical axes. HT displacements from a neutral resting position were also calculated for each position. The position of the AP was calculated as the X (anterior/posterior) and Y (superior/inferior) position of the central AMC marker within the trunk coordinate system. All coordinate system calculations and subsequent calculation of joint angles and AP positions were performed using custom LabVIEW software (National Instruments, Austin, TX).

AMC Calibration

A non-anatomical coordinate system was constructed from the three markers of the AMC. The relationship (transformation matrix) between this coordinate system and the scapular coordinate system was calculated in both the neutral position and the abduction position. For each of the test positions, a transformation matrix was interpolated from the neutral and abduction matrices based on the humeral elevation angle, as calculated by a YXY Euler sequence. This approach is modeled after methods described in the AMC double calibration study proposed by Brochard et al. [35] and has been implemented in several other studies [36], [37]. The interpolated AMC to anatomical scapula transformation matrix was subsequently used to estimate scapular orientation from the orientation of the AMC during the test positions.

Calculation of Regression Equations

Predictive equations for ST angles were developed through a standard multiple linear regression, based on ST, HT, and AP data from positions 1-10, as per Nicholson et al. [28]. While the Nicholson study also included an unconstrained humeral elevation (position 11) as an input position for the regression equation, pilot work demonstrated that most healthy subjects achieved a very similar ending ST orientation in the abduction and the elevation positions, indicating that including both positions as regression inputs would be redundant. Instead, we elected to remove humeral elevation from the set of regression input positions and use it as a test position to evaluate the performance of both approaches in that position.

One equation was generated for each axis of ST motion, and each equation incorporated the same five predictor variables: the HT angles along each axis of motion (X, Y and Z) and the AP position along the X and Y axes. The position of the

AP along the Z (medial/lateral) axis was not considered, as displacement in this direction was expected to be negligible. The input data set contained only 10 different positions, however the capture of each position yielded 60 frames of data, incorporating camera noise and any motion from the subject. Ten positions each with 60 frames produced a total of 600 input data points, which was more than sufficient for the recommended ratio (20:1) of data points to predictor variables [38]. Coefficients for the regression equations were calculated using the LabVIEW General Linear Fit function (National Instruments, Austin, TX). These equations were applied for the five test positions, generating three ST angles (one for each axis of motion) from the measured HT angles and AP positions.

Evaluation of Accuracy

Both the left and right sides of each subject were considered, for a total of 36 scapulae. For the five test positions (positions 11-15), the ST angles estimated from both methods (AMC and regression) were compared to the ST angles calculated from the palpated scapular orientations. Root mean square (RMS) errors (differences between the regression or AMC estimated ST angles and the palpated ST angles) were calculated for each position along each axis.

The accuracy of the regression approach and the acromion marker cluster was evaluated statistically using a 3-way within-subjects analysis of variance (ANOVA). We considered factors of measurement method (palpation, AMC, and regression), position (each of the five test positions), and axis of ST motion (X, Y, and Z). In order to evaluate errors (i.e. differences from palpation) in the context of the amount of ST motion, we elected to compare the raw angles produced by the AMC and regression to the palpated angles instead of merely comparing AMC and regression errors. The overall accuracy was evaluated by the main effect of measurement method (i.e. was either regression or the AMC significantly different from palpation), and the influence of position or axis was examined with post-hoc t-tests, pending a significant interaction. Bonferroni corrections were applied to p values to account for multiple pairwise comparisons. All statistical analyses were performed in SPSS (SPSS v24, IBM, Armonk, NY) and experiment-wise significance level was set at $\alpha = 0.05$.

Relationship to HT Motion

AMC and regression measurement errors were also evaluated in the context of HT motion. Pearson product-moment correlations were assessed between errors (AMC minus palpation or regression minus palpation) and the calculated HT displacement for each subject in each position. Separate correlation analyses were performed for each axis of HT motion as well as each axis of ST angle error. Correlation strength was assessed according to the recommendations of Dancey and Reidy, where coefficients greater than or equal to 0.7 indicated a strong relationship, coefficients between 0.4 and 0.7 indicated a moderate relationship, coefficients between 0.1 and 0.39 indicated a weak relationship and coefficients less than 0.1 were considered to have zero relationship [39].

Results

Mean ST angles for each technique (as well as means and standard deviations of the palpated angles) are displayed for each position and each axis of motion in Figure 3. RMS errors for each position and axis are displayed in Figure 4. The regression approach generated smaller RMS errors for all axes in every position.

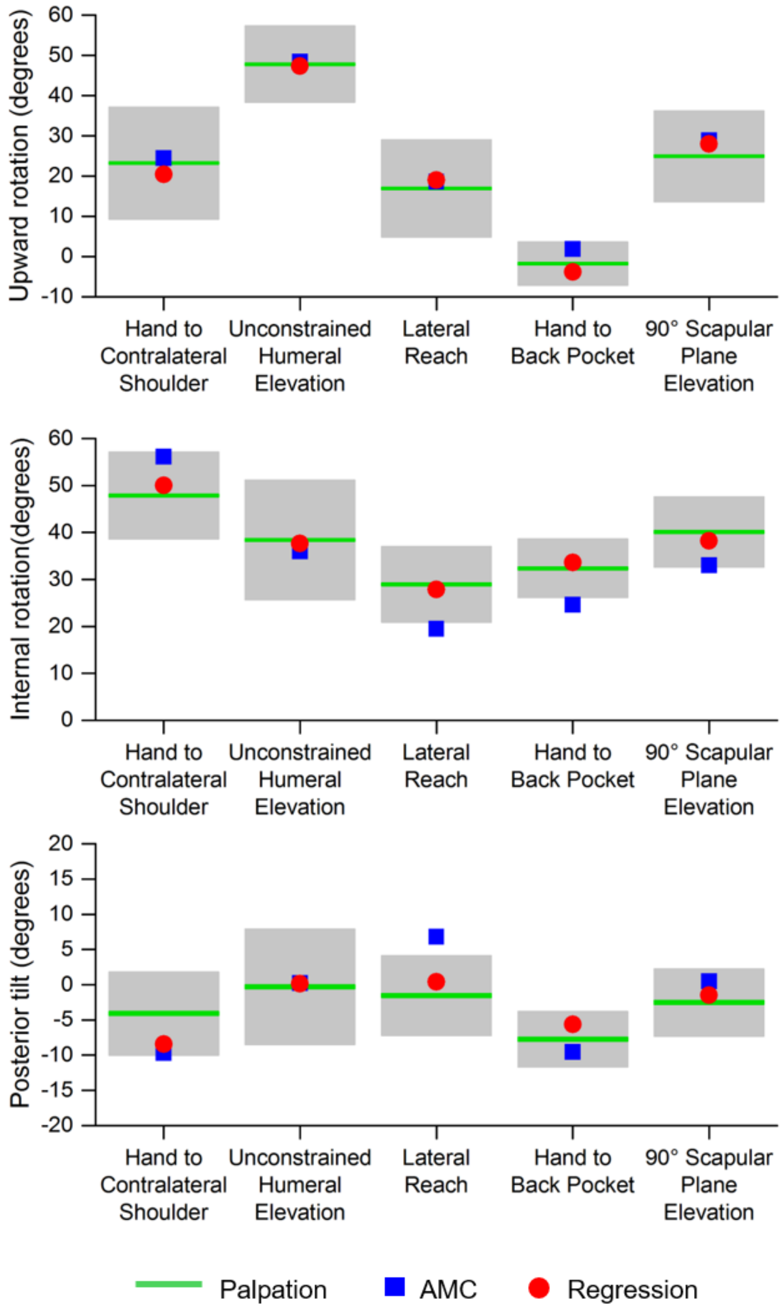

Figure 3 Mean ST angles for each method during each position and along each axis of ST motion. The grey shaded bars represent +/- one standard deviation of the palpated angles. The green line represents the mean palpated angles, the blue square represents the mean AMC angles and the red circle represents the mean regression angles.

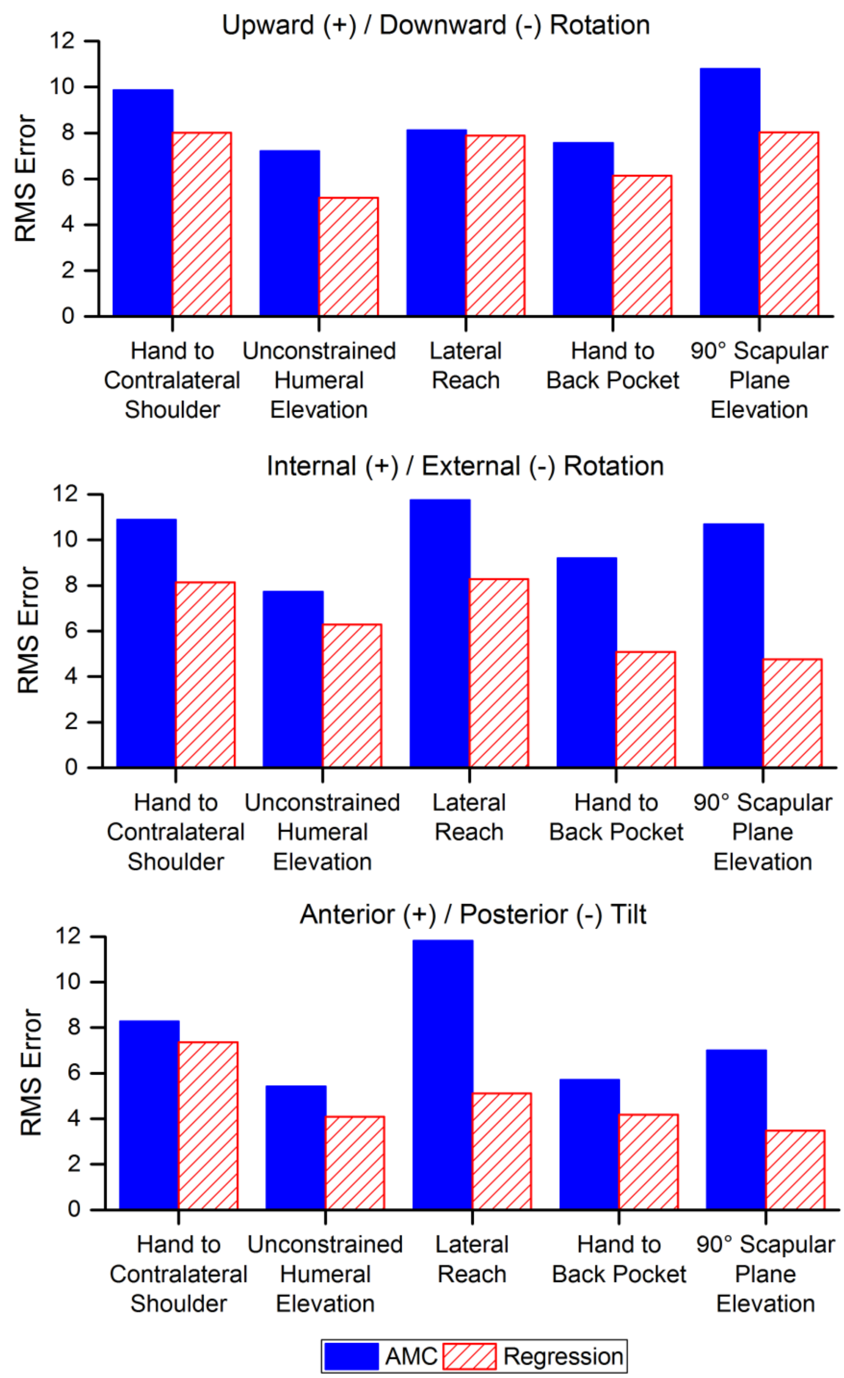

Figure 4 RMS errors for AMC and regression approaches in each position and for each axis of ST motion.

The ANOVA did not reveal an overall significant difference between the AMC, regression, and palpation angles ($F_{2,34}$ = 0.901 p = .416). However, significant interaction effects between measurement method and position ($F_{8,28}$ = 4.052, p = .003), measurement method and axis ($F_{4,32}$ = 9.292, p < .001), and measurement method, position and axis ($F_{16,20}$ = 7.999, p < .001) indicated that differences were present between approaches.

For the interaction of method and position, post-hoc testing revealed that in the hand to contralateral shoulder position, the regression approach produced significantly lower ST angles relative to palpation (Mean difference = 1.805°, p = 0.017). Alternatively, in the hand to back pocket position, the AMC approach produced significantly lower ST angles than both palpation (Mean difference = 2.003°, p = 0.002) and regression (Mean difference = 2.181°, p = 0.001).

For the interaction of method and axis, post-hoc testing revealed that along the X axis (ST upward rotation), the AMC produced significantly higher ST angles than regression (Mean difference = 2.682°, p = 0.013), however neither method was significantly different from palpation along this axis. Along the Y axis (ST internal rotation) the AMC produced significantly lower ST angles than both palpation (Mean difference = 4.710°, p < 0.001) and regression (Mean difference = 4.868°, p < 0.001).

The three-way interaction between measurement method, position and axis tested whether either method differed significantly from palpation along one particular axis in any particular position. Results are displayed in Table 1, with mean ST angle difference from palpation as well as p values.

Table 1 Results of the three-way interaction testing: mean difference from palpation (p value and significance) for each measurement technique across each position and axis of motion.

	Upward (+) / Downward Rotation		Internal (+) / External Rotation		Posterior (+) / Anterior Tilt	
Position	AMC	REGR	AMC	REGR	AMC	REGR
Hand to Contralateral Shoulder	1.2 (p = 1.00)	-3.2 (p = .098)	3.3 (p = .100)	2.1 (p = .268)	**-6.7 (p < .001)**	**-4.2 (p =.001)**
Unconstrained Humeral Elevation	0.5 (p = 1.00)	0.2 (p = 1.00)	-2.4 (p = .183)	-0.7 (p = 1.00)	0.5 (p = 1.00)	-0.4 (p = 1.00)
Lateral Reach	1.6 (p = .700)	1.6 (p = .711)	**-9.6 (p < .001)**	-1.1 (p = 1.00)	**8.3 (p < .001)**	1.9 (p = .072)
Hand to Back Pocket	**3.6 (p = .009)**	**-2.8 (p = .027**)	**-7.8 (p < .001)**	1.2 (p = .441)	-1.8 (p = 0.159)	**2.1 (p = .005)**
90° Scapular Plane Elevation	3.9 (p = .082)	1.8 (p = .671)	**-7.1 (p < .001)**	-0.7 (p = .927)	**4.4 (p = 0.011)**	1.0 (p = .237)

Differences are expressed as (AMC – Palpated) or (Regression – Palpated) i.e. a positive difference indicates overestimation. Significant differences are indicated in bold.

Correlations between ST angle errors and HT displacements are displayed in Table 2. The only relationships that demonstrated more than a weak correlation were the relationships between HT internal rotation displacement and AMC internal rotation error (R = 0.50) and between HT internal rotation displacement and AMC posterior tilt error (R = -0.56).

Table 2 Correlations between errors from each method (difference from palpation) and HT displacement along each axis of motion.

Method		HT abduction displacement	HT internal rotation displacement	HT flexion displacement
AMC	Upward (+) / Downward Rotation Error	-0.08	-0.02	-0.10
	Internal (+) / External Rotation Error	-0.02	**0.50**	0.20
	Posterior (+) / Anterior Tilt Error	0.24	**-0.56**	0.06
Regression	Upward (+) / Downward Rotation Error	0.08	-0.21	0.05
	Internal (+) / External Rotation Error	-0.10	0.19	-0.11
	Posterior (+) / Anterior Tilt Error	0.09	-0.25	-0.14

Correlations that are at least moderate according to the guidelines of Dancey and Reidy [39] are indicated in bold.

Discussion

The RMS error values ranged from 3.5° to 11.8°. These errors are within the range reported in the most recent review of the accuracy of ST measurement validation (1.8° to 14.2°) [23]. For all axes and positions, the regression approach yielded lower RMS errors than the AMC. The maximum AMC RMS error (11.8°) from this study is higher than those reported in prior AMC double calibration studies [35], [37]. However, this is the only study to evaluate the AMC double calibration through a full range of functional motion. Additionally, to our knowledge, this is the only study to validate any surface marker approaches to measuring ST motion in adolescents. In a prior AMC validation study, Lempereur et. al [27] reported slightly lower accuracy in children when compared to an identical study design in adults.

Similarly, the slightly higher errors in this study versus other AMC studies could potentially be due to an age effect.

Statistical testing indicated no significant main effect of measurement method. Still, as the main effect testing compared AMC, regression, palpation angles aggregated across all axes and positions, large positive differences along one axis or position could be offset by large negative differences along another, leading to a conclusion of insignificant overall difference. For this reason, examining the interaction effects can yield more relevant conclusions. Testing for interactions between measurement method and position and/or axes revealed that both the AMC and regression had limitations under certain conditions. The regression approach produced significantly lower ST angles in the hand to contralateral shoulder position. Based on the average ST orientation required for this position (upward rotation, internal rotation and slight anterior tilt), "lower" angles can be interpreted as the regression underestimating upward rotation and internal rotation, and overestimating anterior tilt. The maximum error across all subjects was 21.8° and the regression approach produced erroneous ST angles by more than 10° for 10% of all measurements in this position. While the AMC did not significantly underestimate or overestimate angles in this specific position, it still produced higher absolute errors, exceeding 10° for 31% of all measures.

With regard to the significant regression results, most of the error occurred on the anterior/posterior tilt axis, which was supported by post-hoc testing of the three-way interaction revealing a significant difference between regression and palpation along this axis in this position. Upon close inspection of the data, it appeared that for many subjects, the hand to contralateral shoulder position required more HT internal rotation than any of the regression input positions. For most subjects, the regression input position with the most HT internal rotation was the hand to spine position. That position was typically associated with ST anterior tilt. In contrast, during the hand to contralateral shoulder position, HT internal rotation occurred in conjunction with HT elevation and ST posterior tilt. While the regression approach is intended to incorporate HT angles along all axes in order to predict ST angles, the association of large HT internal rotation with ST anterior tilt from the input data set likely contributed to the overestimation of ST anterior tilt (and underestimation of posterior tilt) in the hand to contralateral shoulder position. This phenomenon illustrates the importance of optimizing the set of regression input positions to encompass the entire desired range of motion for testing.

Statistical testing also indicated that the AMC produced significantly lower angles (i.e. the AMC significantly underestimated ST angles) along the Y axis (internal/external rotation). The maximum error was 29.8° and the AMC underestimated ST Y angles by more than 10° for 23% of all ST Y measurements. In contrast, the regression approach underestimated ST Y angles by more than 10° for less than 5% of measurements. Additionally, the greatest RMS errors for the AMC occurred along this axis. While maximum errors from previous studies have mostly occurred around the upward rotation axis [23], the large majority of these studies have only validated the AMC for humeral elevation in various planes. In a systematic review of these studies, however, Lempereur does note that during extreme elevation (above 90°), the largest errors do tend to occur around the Y axis [23]. Additionally, AMC underestimation of internal rotation has previously been reported in pediatric populations [26], [27]. Those results and the results of this study demonstrate an important limitation of the AMC. While ST upward rotation errors that occur in extreme levels of humeral elevation can be mitigated using a double AMC calibration strategy, large errors still persist across the internal/external rotation axis. Abnormal motion of the scapula about this axis, most notably the presence of scapular winging, is an important indicator of scapular dysfunction [40]. Accurate measurement of this motion is essential for diagnosis of dyskinesia and evaluation of intervention efficacy, and thus the limitations of the AMC in capturing ST internal rotation may prohibit its utility in populations where this motion is prominent. Even in this study, which utilized a healthy adolescent population, underestimation errors were greater than 10° for almost a quarter of the measurements. Researchers could try to address these errors with a double calibration approach that incorporates a position of extreme ST internal rotation, however that approach may sacrifice accuracy on the upward rotation axis. Furthermore, it is unclear which parameter would be used to drive the interpolation, as extreme ST internal rotation (scapular winging) is not limited to one type of HT motion.

The relationship of the ST measurement errors to the amount of HT displacement was consistent with our expectations. No correlations between regression ST errors and HT displacements demonstrated more than a weak relationship. In contrast, for the AMC, moderate correlations existed between HT internal rotation and ST internal rotation and posterior tilt errors. All positions tested required some amount of ST internal rotation, so the positive correlation of these errors with HT internal rotation indicated that the AMC tended to overestimate ST internal rotation with large amounts of HT internal rotation and underestimate with HT external rotation. HT external rotation was most commonly present in positions where the humerus was elevated, and thus these findings could exemplify the failure of the AMC to capture ST winging in humeral elevation. Additionally, AMC posterior tilt errors increased with increased HT external rotation. The positions studied required a mix of ST posterior and anterior tilt, so in this case, the negative correlation simply indicated an error bias toward anterior tilt with HT internal rotation, and a bias toward posterior tilt with HT external rotation. The relationship between AMC errors and HT displacement are a possible consequence of that method's reliance on the three markers affixed to the acromion. Substantial HT displacement produces more muscle and soft tissue movement around the acromion, potentially resulting in a skewed orientation of the AMC and an erroneous estimation of ST angles. In contrast, the regression approach only relies on one acromial marker, making it less susceptible to errors from soft tissue motion with large amounts of humeral motion.

The regression approach, similarly to the double AMC calibration, builds on the concept of using multiple positions to refine estimation of ST orientation. In contrast to the AMC, however, the regression approach does not produce any systematic error about any axis. In this particular study, the only position that produced significant errors was a position that required an HT orientation outside the range of motion established by the regression input positions. This issue could be addressed in future applications of the regression approach by ensuring that the static input positions encompass the entire range of motion that will be evaluated during testing. Since this study limited validation to static positions, the only fair comparison between the regression and AMC involved test positions that were different from those used in the regression input set. For future application, however, researchers may develop a set of input positions that directly correspond to the static position or dynamic motion of interest. This approach would likely further improve the accuracy of the regression method. Moreover, it should be noted that even in the hand to contralateral shoulder position, the regression approach still resulted in a lower RMS error than the AMC.

Conclusion

In static validation, the regression approach outperformed the AMC when compared to palpation. This study did not evaluate dynamic accuracy of the two methods, as the available reference methods for dynamic ST measurement are too invasive for the adolescent population. Nevertheless, we believe the results of static validation provide insight into the performance of these two approaches that can be extended to dynamic conditions. The AMC consistently underestimated ST internal rotation, in contrast to the regression method, which offered an individualized approach devoid of systematic error about any axis of ST motion. Furthermore, analysis of RMS errors revealed that errors from the regression approach were smaller than AMC errors for every axis in every position tested. Accordingly, we recommend the use of the regression approach for measuring scapular kinematics in the adolescent population.

Chapter 3

3D SCAPULAR KINEMATICS DURING FUNCTIONAL MOTION: STATIC VERSUS DYNAMIC MEASUREMENT BY THE ACROMION MARKER CLUSTER

Introduction

Accurate measurement of scapular kinematics is an enduring challenge of upper extremity biomechanics. Non-invasive measurement techniques are the preferred approach for research, especially in younger or injured populations. Numerous studies have evaluated these techniques with varying reports of accuracy [23]. The most widely utilized of these methods—the acromion marker cluster (AMC)—has been evaluated for accuracy under various conditions and in several populations [18], [25]–[27], [37].

Aside from a few studies [19], [41] that have evaluated the AMC against a dynamic standard (bone pins), most of the validation has been performed in static positions [23], [37]. The device is intended, however, for dynamic use, raising the question of whether the static accuracy results translate to clinical application. Several studies have evaluated the effect of static versus dynamic measurement or influence of motion speed on scapular kinematics [42]–[44]. However, most have performed these analyses for less common scapular tracking methods, except for MacLean et al. [45], who specifically investigated static versus dynamic differences for the AMC. These studies found that certain scapulothoracic (ST) parameters differ between static and dynamic measurements, however to our knowledge, these differences have only been examined during humerothoracic (HT) elevation. Furthermore, the only study to specifically investigate the AMC did not compare the dynamic measures to directly-measured static measures and did not incorporate the double calibration [45], which has been shown to greatly improve the accuracy of the AMC at higher levels of humeral elevation [35].

This study examined static versus dynamic accuracy of the AMC using fourteen upper extremity reference positions that can be used as a clinical measure of global shoulder function. An analysis of the AMC in these positions, incorporating the current best practice (the double calibration), provides a clinically relevant context for its performance in measuring ST motion. We hypothesized that testing would reveal differences between static and dynamic measures along specific axes of ST motion that would have implications for clinical interpretation of data collected with the AMC.

Methods

Subjects

Eighteen healthy adolescents (average age: 14.9 ± 1.8 years, 6 males, 12 females) were recruited for this study. Parental consent was obtained in accordance with the requirements of the University of Delaware institutional review board. Subjects were excluded if they had any history of shoulder pathology.

Motion Capture

Subjects sat on a backless chair in a comfortable position. A 12 camera Motion Analysis (Santa Monica, CA) system operating at 60 Hz was used for motion capture. Throughout the trials, the subjects wore three-dimensional (3D) retro-reflective markers at the following locations:

Thorax: sternal notch, T1 spinous process, T8 spinous process

Humerus: medial epicondyle, lateral epicondyle, posterolateral humerus

An AMC was placed on the acromion process in accordance with the recommendations of Warner et al [25]. The subjects proceeded to hold each arm in a series of 15 positions (Figure 5): a neutral resting position (Position 1) and 14 additional positions encompassing a wide range of upper extremity motion (Positions 2-14).

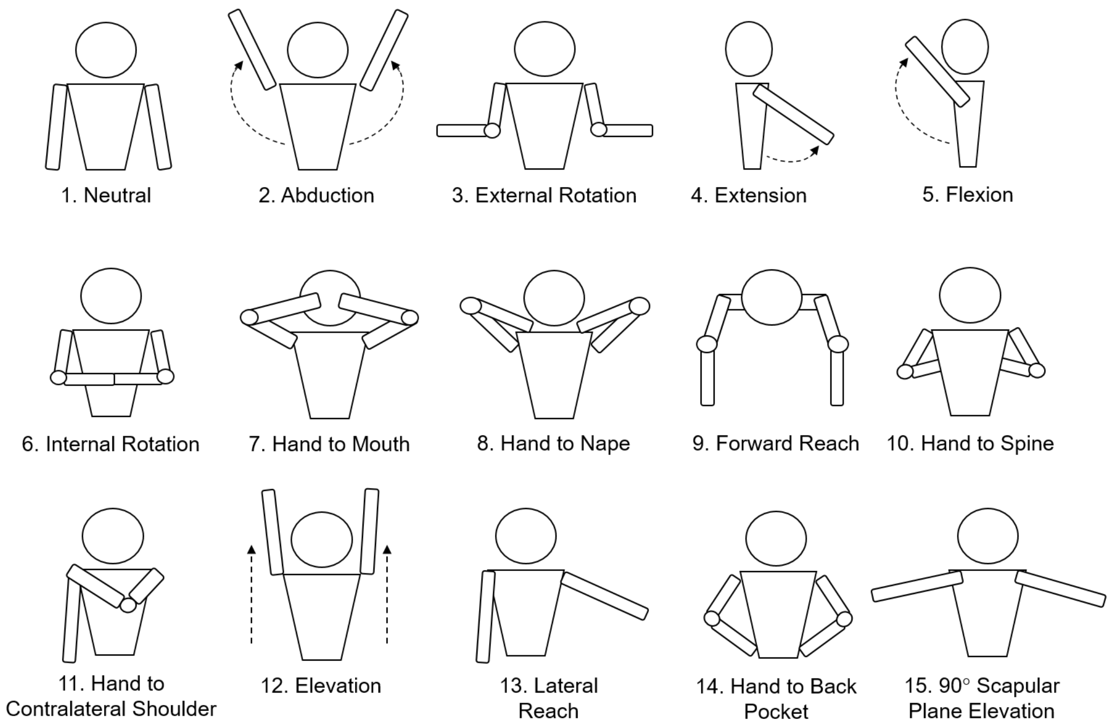

Figure 5 Positions/motions for testing across static and dynamic conditions

At each position, the following anatomical landmarks on the scapula were palpated: trigonum spinae and inferior angle of the scapula. Two-dimensional (2D) retro-reflective markers were placed on the palpated locations (Figure 6) and removed once the position was captured for a duration of one second.

Figure 6 Example marker placement on a subject in the hand to spine position

Following the static captures, the subjects repeated each position, this time not stopping for palpation. Motion capture was recorded as the subject moved from the neutral resting position to each terminal position and then back to neutral. Speed was dictated by the instruction of the researcher, guiding each subject to achieve the terminal position in two seconds and return to neutral in two seconds.

Calculation of Joint Angles

Coordinate systems for the humerus and trunk were created using recommendations from the International Society of Biomechanics (ISB) [32]. The scapular coordinate system was constructed as a slight modification of ISB recommendations. The center marker of the AMC (which was placed directly on the acromion process) was used in place of the acromial angle. ST angles were calculated as per the ISB-recommended YXZ Euler sequence [32]. Rotation about the X axis corresponded to scapular upward and downward rotation, rotation about the Y axis corresponded to internal and external rotation, and rotation about the Z axis corresponded to anterior and posterior tilt. All coordinate system calculations and subsequent calculation of joint angles were performed using custom LabVIEW software (National Instruments, Austin, TX).

AMC Calibration

A non-anatomical coordinate system was constructed from the three markers of the AMC. The transformation matrix between the AMC coordinate system and the scapular coordinate system was calculated in both the neutral position and the abduction position. For each of the test positions, the transformation matrix was interpolated from the neutral and abduction matrices based on the humeral elevation angle, as calculated by a YXY Euler sequence. This approach is modeled after to methods described in the AMC double calibration study proposed by Brochard, et al. [35] and has been implemented in several other studies [36], [37]. The interpolated transformation matrix was subsequently used to determine scapular orientation from the orientation of the AMC during the other static positions and during motion.

Matching of Static and Dynamic Positions

For each position, the 3D helical angle [34] between the HT orientation in the static pose and the HT orientation in each frame of the corresponding dynamic trial was calculated. For every position, the minimum value of this angle across all frames of the dynamic trial was identified. This was considered the frame in the dynamic trial at which the subject was "closest" to that particular static position. Additionally, the absolute difference was calculated between the HT elevation angle (as calculated by the YXY Euler sequence) in the static pose and the afore-mentioned matched frame of the corresponding dynamic trial.

If, at this frame, the HT elevation difference between the dynamic and static orientations was within 10° and the 3D helical angle between dynamic and static orientations was within 20°, the subject was determined to have sufficiently replicated the static position in motion, and the trial was accepted. For each accepted trial, the dynamic ST angles at the matched frame were compared to the static ST angles.

Evaluation of Accuracy

Both the left and right sides of each subject were considered, for a starting total of 36 scapulae. For all 14 positions, the ST angles estimated by the AMC were compared across condition (static and dynamic). For each subject, differences between the static ST angles and the corresponding frame of dynamic ST angles were calculated for each position and along each axis. These differences were ultimately averaged across all subjects who achieved a successful match in that position.

A statistical comparison of the static and dynamic conditions using the acromion marker cluster was evaluated using a within-subjects analysis of variance (ANOVA). Angles were evaluated on two factors: condition (static versus dynamic) and axis of ST motion (X, Y, and Z). Position data was combined for all subjects. General static versus dynamic differences were evaluated by the main effect of condition, and the influence of axis was examined with post hoc t-tests, pending a significant interaction. Significance level for post hoc testing was adjusted with Bonferroni corrections to account for multiple pairwise comparisons. All statistical analyses were performed in SPSS (SPSS v24, IBM, Armonk, NY) and significance level was set at $\alpha = 0.05$.

Results

Means and standard deviations of the AMC estimated ST angle for each position are displayed for both static and dynamic conditions, along with the number of accepted dynamic trials. (Table 3).

Table 3 Means and standard deviations for static and dynamic angles along with the number of accepted matches for each position. Mean differences for each axis along with p values. Significant interaction effects between condition and axis are highlighted by shading the columns of that axis. Blue indicates dynamic angles were on average lower while yellow indicates dynamic angles were on average higher.

	Upward Rotation Mean diff: 0.3° (*p* = .502)		**Internal Rotation** Mean diff: -1.8° (*p* < .001)		**Posterior Tilt** Mean diff: 2.0° (*p* < .001)		# Matches
	Stat	Dyn	Stat	Dyn	Stat	Dyn	
ABD	45.8 (8.1)	52.0 (9.2)	35.7 (11.4)	30.6 (18.8)	-0.2 (7.8)	6.2 (16.2)	25
ER	4.7 (8.6)	4.9 (9.1)	16.1 (7.7)	14.9 (10.6)	0.3 (4.9)	1.7 (6.0)	34
EXT	5.4 (9.0)	6.4 (10.9)	15.4 (8.2)	13.8 (12.1)	0.5 (5.0)	1.4 (6.1)	26
FLEX	48.1 (9.4)	50.7 (10.3)	32.7 (16.3)	30.4 (18.9)	2.1 (12.3)	5.2 (14.3)	32
IR	9.2 (9.0)	6.9 (10.0)	43.8 (13.7)	39.8 (11.5)	-6.9 (8.0)	-4.6 (8.6)	22
MOUTH	24.6 (9.3)	23.9 (10.2)	29.8 (11.2)	29.6 (11.3)	-2.9 (9.3)	-1.1 (9.0)	28
NAPE	34.6 (8.3)	35.5 (9.6)	15.0 (20.9)	15.9 (21.3)	15.0 (15.3)	14.3 (16.4)	26
REACH	27.7 (10.8)	27.5 (9.2)	59.9 (7.5)	57.0 (9.7)	-14.1 (9.2)	-12.2 (9.9)	34
SPINE	27.8 (10.8)	27.2 (9.4)	59.8 (7.4)	57.4 (9.4)	-14.0 (9.1)	-12.6 (9.8)	16
CONTRA	24.4 (12.0)	23.5 (10.7)	56.2 (10.6)	54.8 (13.1)	-10.8 (9.9)	-9.5 (8.1)	29
ELEV	48.4 (8.4)	50.5 (8.7)	36.0 (15.0)	31.1 (19.1)	0.2 (10.5)	6.3 (15.8)	31
LATERAL REACH	18.5 (12.1)	19.6 (9.7)	17.7 (14.4)	17.9 (12.4)	6.8 (10.8)	6.4 (9.0)	31
POCKET	1.8 (8.1)	-0.5 (8.7)	24.6 (7.3)	22.1 (7.7)	-9.6 (6.0)	-8.0 (6.5)	33
SCAPTION	28.8 (10.1)	30.0 (11.1)	33.0 (10.6)	29.6 (12.1)	1.9 (10.0)	2.9 (10.1)	29

Figure 7 displays the means and standard deviations of differences between static and dynamic ST measurements (dynamic minus static) for each position and for each axis of ST motion.

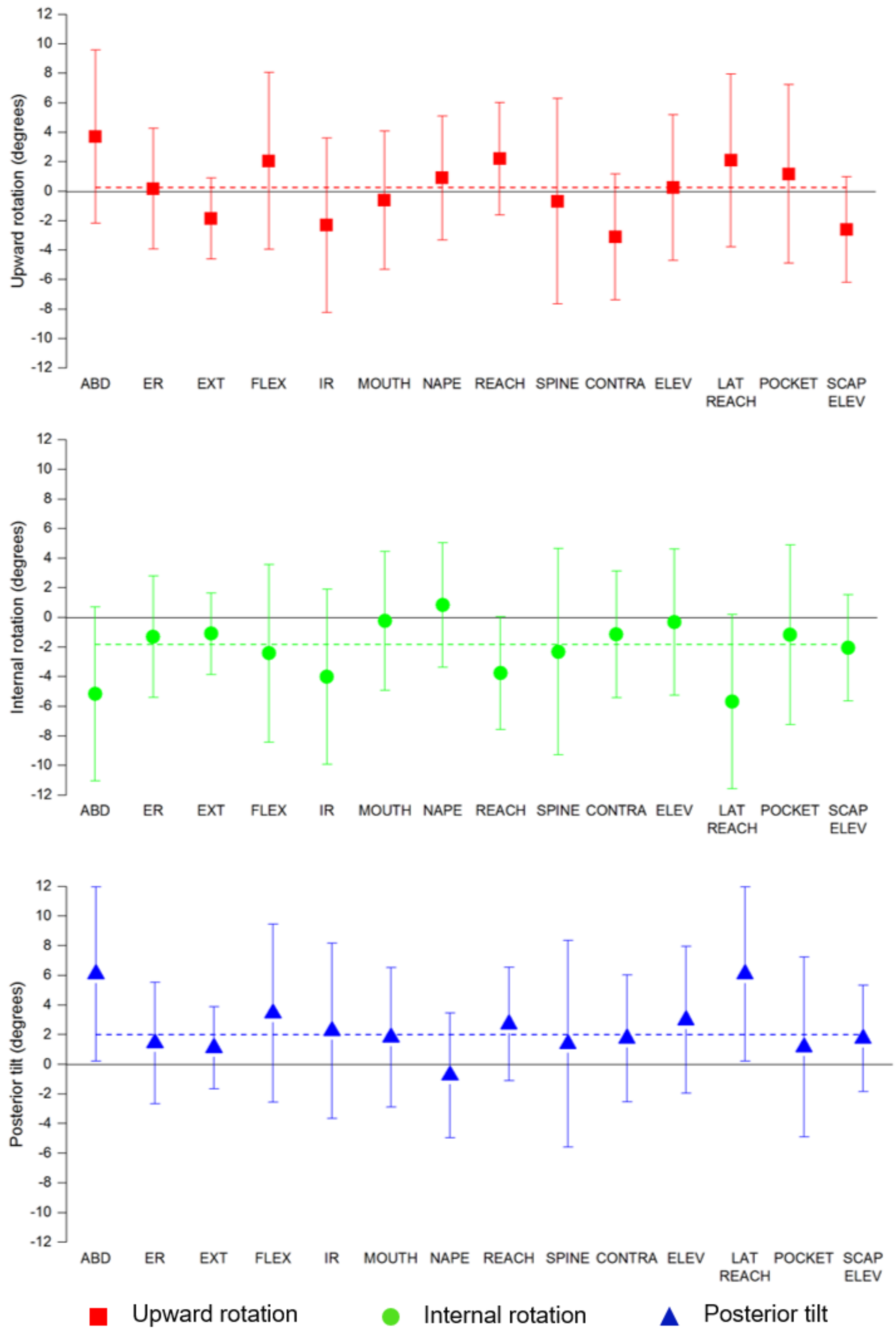

Figure 7 Mean and standard deviation of differences in ST angles (dynamic minus static). Dotted lines represent means across all positions.

Statistical testing did not reveal any significant main effect of condition (static versus dynamic) however a significant interaction effect between condition and axis was present. Along the internal rotation axis, ST angles were significantly lower in the dynamic condition (mean difference -1.8°, $p < .001$). Along the posterior tilt axis, ST angles were significantly higher in the dynamic condition (mean difference 2.0°, $p < .001$).

Discussion

The results of the ANOVA did not demonstrate a significant main effect of condition (static versus dynamic), however an interaction effect was present for two out of three axes. ST posterior tilt was significantly higher in dynamic AMC measurement than in static. Furthermore, average differences (dynamic minus static) were positive for 13 out of 14 positions. These results indicate that the dynamic measurement of the AMC exhibits a bias toward the posterior tilt direction. These results contradict previous conclusions by MacLean et al., who found that dynamic measurement yielded lower ST angles along the posterior tilt axis [45]. There are several dissimilarities between that study and the current study which we believe could provide potential explanations for the differences in findings. First, the MacLean study only examined planar humeral elevation whereas this study evaluated AMC static versus dynamic measurement across a wide range of functional motion. While planar humeral elevation requires ST posterior tilt, many of the other motions required ST anterior tilt. In these motions, the apparent dynamic bias toward posterior tilt is actually an underestimation of anterior tilt. As the MacLean study did not evaluate any motion that exhibited substantial anterior tilt, those findings are not directly comparable with the current study. Additionally, the MacLean study did not incorporate the double calibration of the AMC. With a single calibration, errors along the posterior tilt axis increase significantly above 90° [24], [46]. Indeed, the greatest reduction in RMSE error for the double calibration was along the posterior tilt axis [35]. The MacLean study examined static and dynamic AMC measures from 10° to 120° elevation. As almost a third of this range of motion results in substantial posterior tilt errors, it is difficult to compare those static versus dynamic differences to those obtained in this study which used the more accurate double calibration.

Another significant interaction effect occurred along the internal rotation axis. ST internal rotation was significantly lower in the dynamic condition. Moreover, average differences (dynamic minus static) were negative for 13 out of 14 positions. These results are consistent with those of MacLean et al. [45], who found that the dynamic measures from the AMC produced lower ST internal rotation angles regardless of humeral elevation angle. While the design of this study does not allow for determination of which measurements (static or dynamic) were more accurate, previous studies indicate that, during static validation, the AMC significantly underestimates ST internal rotation [26], [47]. Given that dynamic measurement consistently yields even lower ST angles about this axis, the simplest explanation may be that dynamic AMC measurement of ST internal rotation is less accurate, as opposed to a theory that the scapula actually attains a very different internal rotation orientation when a position is achieved through fluid motion.

One limitation of the study lies in the matching (and thus comparison) of the static and dynamic positions. Any angular difference between static and dynamic measurements contains the difference in AMC measurement between conditions but also error in the match between the static position and that same position achieved during the dynamic trial. Previous static versus dynamic studies have either matched solely on humeral elevation angle [44] or interpolated the static angles [43], [45]. This study incorporated all three axes of HT motion to match a position across static and dynamic conditions and then directly compared these measures. Average HT elevation angle differences for static and dynamic matches were less than 5° and average 3D helical angle differences were less than 8°. Figure 8 displays a skeletal rendering of a representative subject's match for the hand to mouth position.

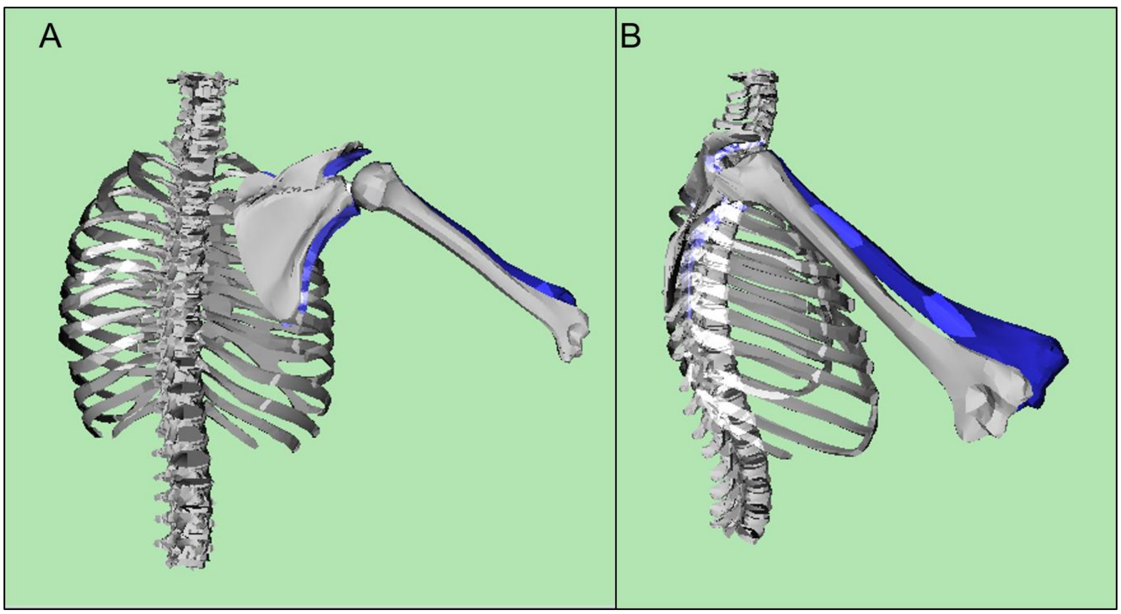

Figure 8 Skeletal rendering from a representative subject in the hand to mouth position from a posterior (A) and lateral (B) view. The grey humerus and scapula represent the static position, while the blue humerus and scapula represent the dynamic match. This image represents an HT helical difference of 6.7° and an ST helical difference of 3.4°.

Given the large range of motion of the humerus and the geometric and anatomical constraints of the ST joint, these small differences in HT angles (average helical differences less than 8°) would suggest a correspondingly close true match of scapular position. As such, we believe this matching approach provides a meaningful comparison of static and dynamic measurement using the AMC.

Conclusion

In this study, statistical analysis did reveal significant differences between AMC static and dynamic measures along certain axes of ST motion. The AMC consistently yielded significantly lower ST internal rotation angles and higher ST posterior tilt angles in the dynamic conditions. Given previous assessments of AMC accuracy about these axes, particularly ST internal rotation, we propose that the AMC is less accurate for dynamic measurement about these axes. The results of this study should be considered when interpreting results of the AMC approach for dynamic measurement of ST motion, particularly in cases where ST internal rotation or posterior tilt is of clinical interest.

Chapter 4

DYNAMIC MEASUREMENT OF SCAPULOTHORACIC ANGLES: DIFFERENCS BETWEEN A REGRESSION APPROACH AND THE ACROMION MARKER CLUSTER

Introduction

Shoulder dysfunction is a key consideration in the adolescent population. The increased sports participation, sports injury, and age-specific orthopedic disorders that occur in adolescence all have implications for shoulder health [16], [31], [48]. While a clinical exam can provide a gross assessment of upper extremity function, a biomechanical analysis evaluates contributions of the underlying scapulothoracic (ST) and glenohumeral (GH) joints and may reveal mechanics associated with risk for shoulder pathology. Capturing these mechanics requires accurate measurement of ST and GH joint motion. Consequently, a suitable technique must be accurate and also easy to implement and non-invasive for use in the adolescent population.

The first component of this thesis used a series of functional positions to evaluate the static accuracy of two non-invasive methods of measurement: the acromion marker cluster (AMC) [24], [25], [41] and an individualized linear regression [28]. The results of the static analysis indicated that both methods possessed limitations in certain conditions. The regression approach was susceptible to error in a position that required a humeral orientation outside of the range of the positions used to build the predicative equations, while the AMC significantly underestimated ST internal rotation across all positions. In general, however, the root mean square (RMS) errors from the regression method were consistently lower than those from the AMC.

The next component of this thesis investigated how measurements by the AMC changed from static to dynamic conditions. AMC angles produced in motion were significantly different than angles measured from the corresponding static position along the internal rotation and posterior tilt axes. A similar static/dynamic analysis was not necessary for the linear regression due to the assumptions required by its design. The regression method assumes that a given humeral orientation and acromion process (AP) position correspond to the same ST orientation, regardless of the path of motion taken to achieve that position. Accordingly, the regression equations predict consistent measures for the same position across static and dynamic conditions.

While these prior analyses were necessary to establish fundamental results in basic science, clinical application of these results would obligate a dynamic evaluation of both methods. Both assessments and interventions for shoulder dysfunction are primarily performed in motion. For a biomechanical analysis to provide relevant supplementary information to a clinical exam, it must also involve dynamic results.

The AMC and regression are both intended for dynamic use. However, validation in motion is difficult to perform, as the available reference methods for dynamic ST measurement have significant limitations. Bone pins [20], [41], [49] and fluoroscopy [21], [50] have been most commonly utilized, but involve either surgical insertion or radiation. Neither is suitable for use outside of healthy adults—certainly not for a younger population such as children or adolescents. Consequently, in the adolescent population, there is no appropriate reference standard for determining the accuracy of the two noninvasive approaches during motion. Given this limitation, we elected to only evaluate differences between the two methods in motion for the final component of this project. This approach allowed us to directly compare the two approaches to each other, as well as determine whether the angles produced from each method were physiologically feasible, based on published values for ST kinematics. Additionally, we incorporated the results from the static accuracy and the static/dynamic differences analyses to provide further context for interpreting trends observed in the dynamic investigation.

The purpose of this study was to directly compare the AMC and regression approaches during a series of functional tasks and utilize the results from the previous work to extract a meaningful interpretation of any differences. We hypothesized that the differences between methods would be related to the errors in corresponding static validation, and the differences would also be related to the amount of humerothoracic (HT) motion during that task.

Methods

Subjects

Eighteen healthy adolescents (average age: 14.9 ± 1.8 years, 6 males, 12 females) were recruited for this study, and assent as well as parental permission was obtained in accordance with the procedures established by the University of Delaware institutional review board. Subjects were excluded if they had history of shoulder pathology or surgery.

Motion Capture

Subjects sat on a backless chair in a comfortable position. A 12 camera Motion Analysis (Santa Monica, CA) system operating at 60 Hz was used for motion capture. Throughout the trials, the subjects wore three-dimensional (3D) retro-reflective markers at the following locations:

Thorax: sternal notch, T1 spinous process, T8 spinous process

Humerus: medial epicondyle, lateral epicondyle, posterolateral humerus

An AMC was placed on the AP in accordance with the recommendations of Warner et al [25]. The subjects proceeded to hold each arm in a series of 15 positions (Figure 1).

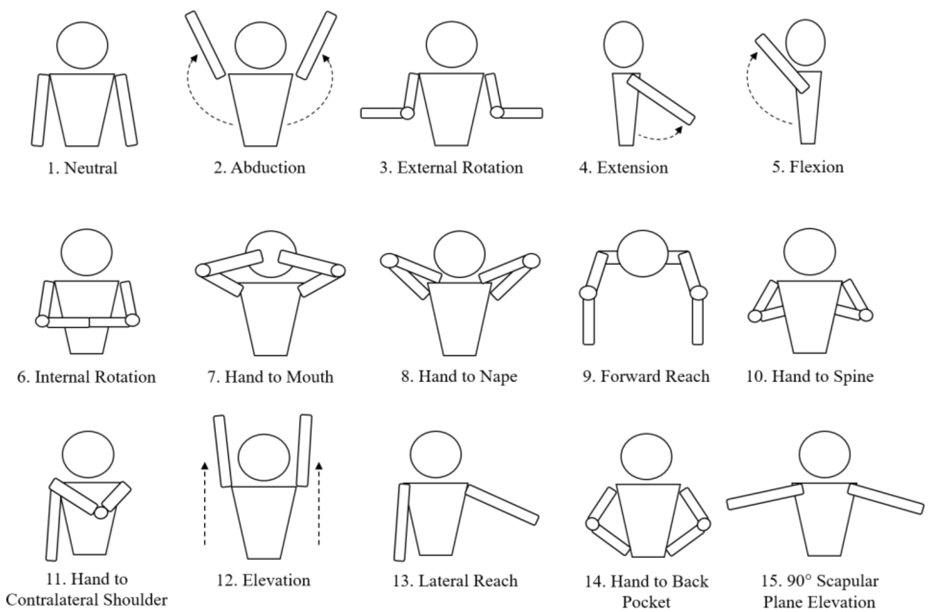

Figure 9 Positions for regression input (1-10) and dynamic testing of the regression and AMC.

At each position, the following anatomical landmarks on the scapula were palpated: trigonum spinae and inferior angle of the scapula. Two-dimensional (2D) retro-reflective markers were placed on the palpated locations and removed once the position was captured for a duration of one second. Following the capture of all of the static positions, the subjects repeated positions 11-15 without stopping for palpation. Speed of motion was guided by the count of the researcher, so that the subject achieved the terminal position in two seconds and then returned to neutral in two seconds.

Calculation of Joint Angles and AP Position

Coordinate systems for the humerus and trunk were created using recommendations from the International Society of Biomechanics (ISB) [32]. The scapular coordinate system was constructed as a slight modification of ISB recommendations. The center marker of the AMC (which was placed directly on the AP) was used in place of the acromial angle. ST angles were calculated as per the ISB-recommended YXZ Euler sequence [32]. Rotation about the X axis corresponded to scapular upward and downward rotation, rotation about the Y axis corresponded to internal and external rotation, and rotation about the Z axis corresponded to anterior and posterior tilt. HT angles were calculated by the helical method to avoid dependence on order of motion and any resulting singularities [34]. Helical angles were then resolved onto the anatomical axes. Resolved helical HT displacements from a neutral resting position were also calculated for each position and in each corresponding dynamic trial. The position of the AP was calculated as the X (anterior/posterior) and Y (superior/inferior) position of the central AMC marker within the trunk coordinate system. All coordinate system calculations and subsequent calculation of joint angles and AP positions were performed using custom LabVIEW software (National Instruments, Austin, TX).

AMC Calibration

A non-anatomical coordinate system was constructed from the three markers of the AMC. The transformation matrix between this coordinate system and the scapular coordinate system was calculated in both the neutral position and the abduction position. For each of the test positions, a transformation matrix was interpolated from the neutral and abduction matrices based on the humeral elevation angle, as calculated by a YXY Euler sequence. This approach is similar to methods described in the AMC double calibration study proposed by Brochard, et al. [35] and has been implemented in several other studies [36], [37]. The interpolated AMC to anatomical scapula transformation matrix was subsequently used to estimate scapular orientation from the orientation of the AMC during the dynamic trials.

Calculation of Regression Equations

Predictive equations for ST angles were developed through a standard multiple linear regression, based on ST, HT, and AP data from positions 1-10, as per Nicholson et. al [28]. One equation was generated for each axis of ST motion, and each equation incorporated the same five predictor variables: the HT angles along each axis of motion (X, Y and Z) and the AP position along the X and Y axes. The input data set contained only 10 different positions, however the capture of each position yielded 60 frames of data, incorporating camera noise and any breathing motion from the subject. Ten positions each with 60 frames produced a total of 600 input data points, which was more than sufficient for the recommended ratio of data points to predictor variables [38]. Coefficients for the regression equations were calculated using the LabVIEW General Linear Fit function (National Instruments, Austin, TX). These equations were applied to all dynamic trials, generating ST angles from the measured HT angles and AP positions.

Evaluation of Differences

Both the left and right sides of each subject were considered, for a total of 36 scapulae. For each dynamic trial, peak absolute differences were calculated. The direction of the difference (AMC minus regression) was also noted. Peak differences were then averaged across all subjects for each axis of motion within each position. RMS differences were also calculated for the entirety of each dynamic trial.

Relationship to Static Errors

Dynamic differences between the AMC and regression measures were evaluated in the context of errors from the static analysis. For each axis of each position (motion), dynamic RMS ST angle differences and static absolute ST angle errors were aggregated across subjects, and Pearson product-moment correlations were calculated for corresponding axes of ST motion. Correlations for each axis were subsequently averaged across all positions using a Fisher Z transformation [51]. Correlation strength was assessed according to the recommendations of Dancey and Reidy, where coefficients greater than or equal to 0.7 indicated a strong relationship, coefficients between 0.4 and 0.7 indicated a moderate relationship, coefficients between 0.1 and 0.39 indicated a weak relationship and coefficients less than 0.1 were considered to have zero relationship [39]. Separate analyses were performed for dynamic differences versus AMC static errors and for dynamic differences versus regression static errors, for a total of six correlational analyses.

Relationship to HT Motion

Differences between the AMC and regression measures were also evaluated in the context of HT motion. For every subject, ST angle differences (AMC minus regression) and HT displacements were aggregated across all motions, and Pearson product-moment correlations were calculated between the differences along each axis of ST motion and displacements along each axis of HT motion. Correlations for each axis were subsequently averaged across all positions using a Fisher Z transformation [51]. Strength of these correlations was also evaluated according to the recommendations of Dancey and Reidy [39].

Results

Average peak differences were less than 16° for all axes and all positions. Individual subject peak differences, however, ranged from 47.9° (AMC over) to -39.4° (regression over) for the upward rotation axis, 30.9° (AMC over) to -43.5° (regression over) for the internal rotation axis, and 41.5° (AMC over) to -30.1° (regression over) for the posterior tilt axis. The most extreme differences occurred in different positions for each axis of ST motion. For upward rotation, the maximum peak difference (AMC over) occurred in the hand to contralateral shoulder position, while the minimum peak difference (regression over) occurred in the lateral reach position. For internal rotation, the maximum peak difference occurred in the hand to contralateral shoulder position, while the minimum peak difference (regression over) occurred in the lateral reach position. For the posterior tilt axis, both the maximum and minimum peak differences occurred in the elevation position.

Figure 10 illustrates the mean peak differences ± one standard deviation for all five motions, separately for each axis of ST motion. Figures 11 to 15 illustrate example dynamic ST angles for each motion. For each axis within each motion, the trial (and subject) exhibiting the highest absolute peak difference (i.e. greatest divergence) between approaches was chosen for display. Figures 11 to 15 also contain the mean and standard deviation palpated ST angles from the corresponding position during the static validation. For 12 out of the 15 trials with the most extreme peak differences (five motions each with three axes), the regression angles were closer than the AMC to the mean palpated ST angle from the corresponding static position.

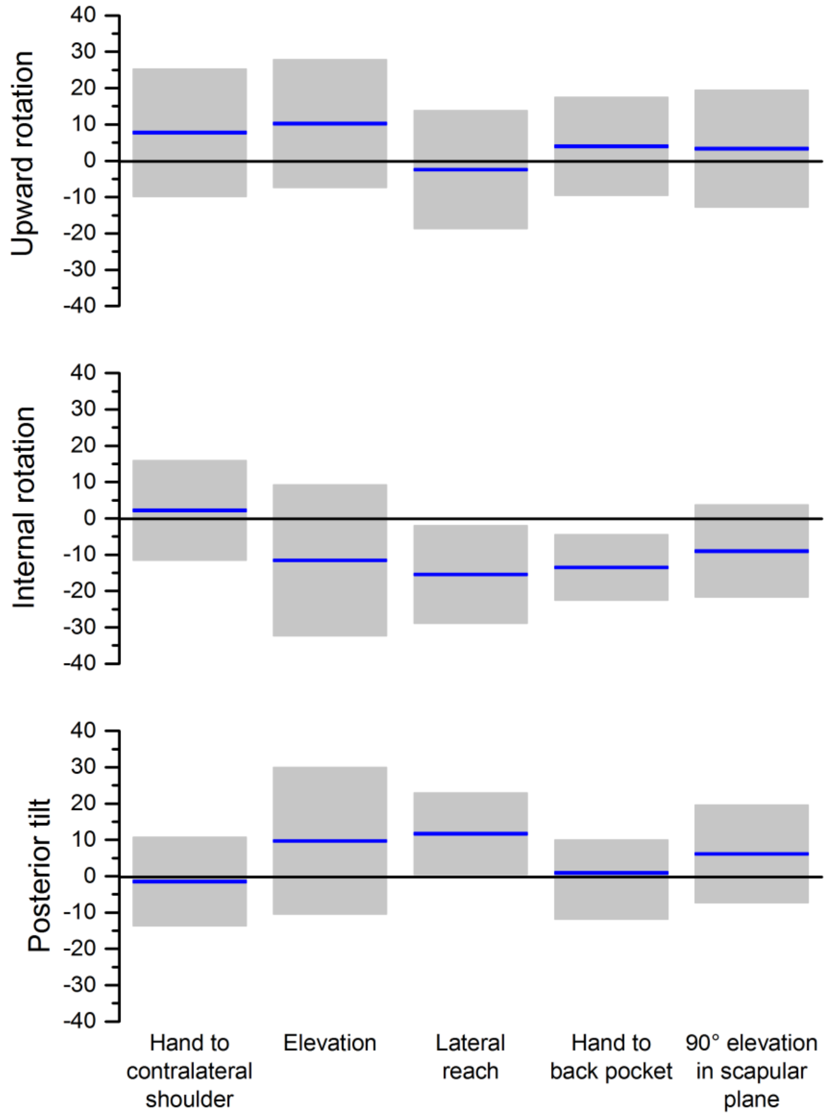

Figure 10 Peak differences between the AMC and regression approaches for each motion and each ST axis. The blue lines indicate average peak differences for a given motion and axis. The grey shaded bars represent ± one standard deviation. A positive value indicates that AMC angles were *greater* than regression angles.

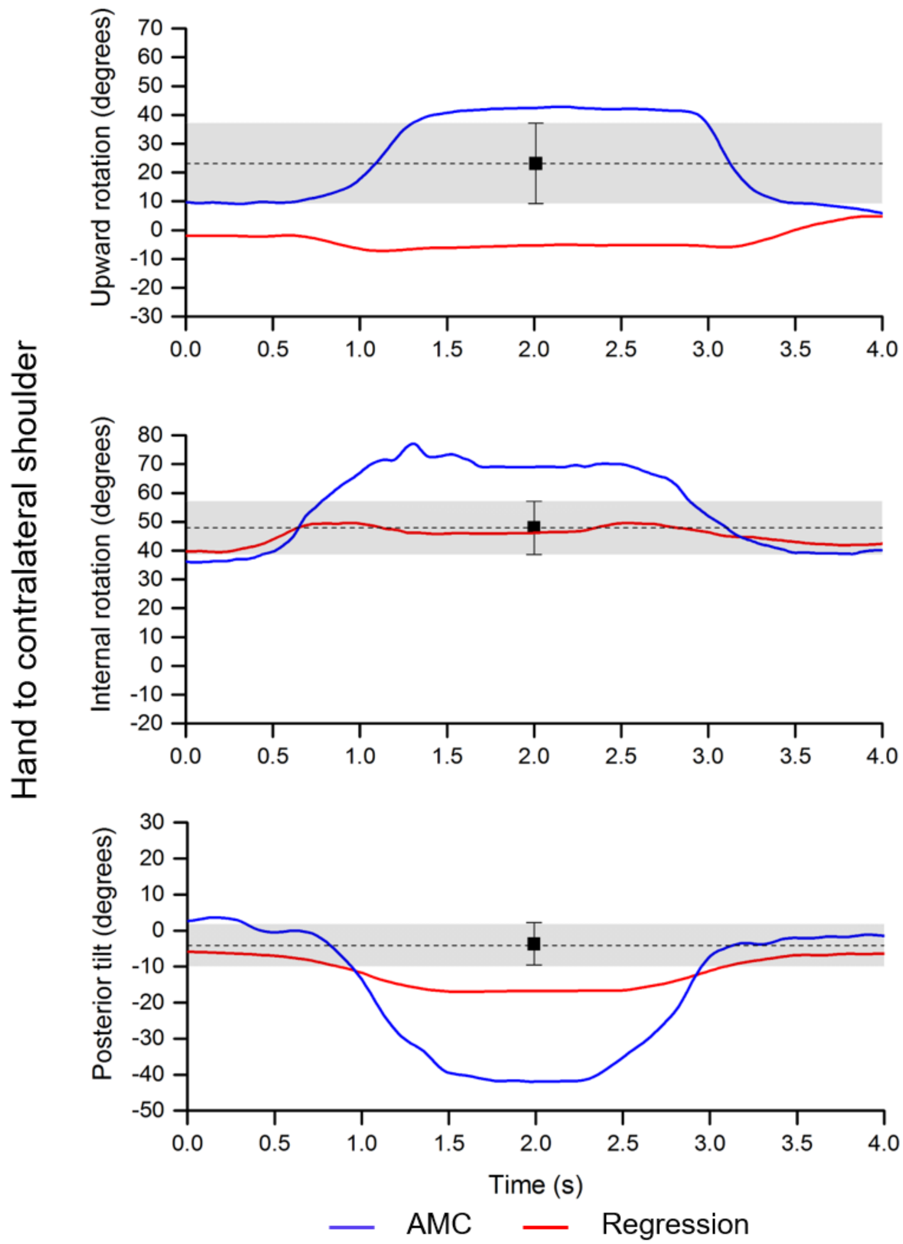

Figure 11 Dynamic ST angles along each axis from the subject who displayed the greatest absolute difference between approaches in the hand to contralateral shoulder position. The grey shaded bar and black dot with error bars display the mean palpated angle from the corresponding static position, ± one standard deviation.

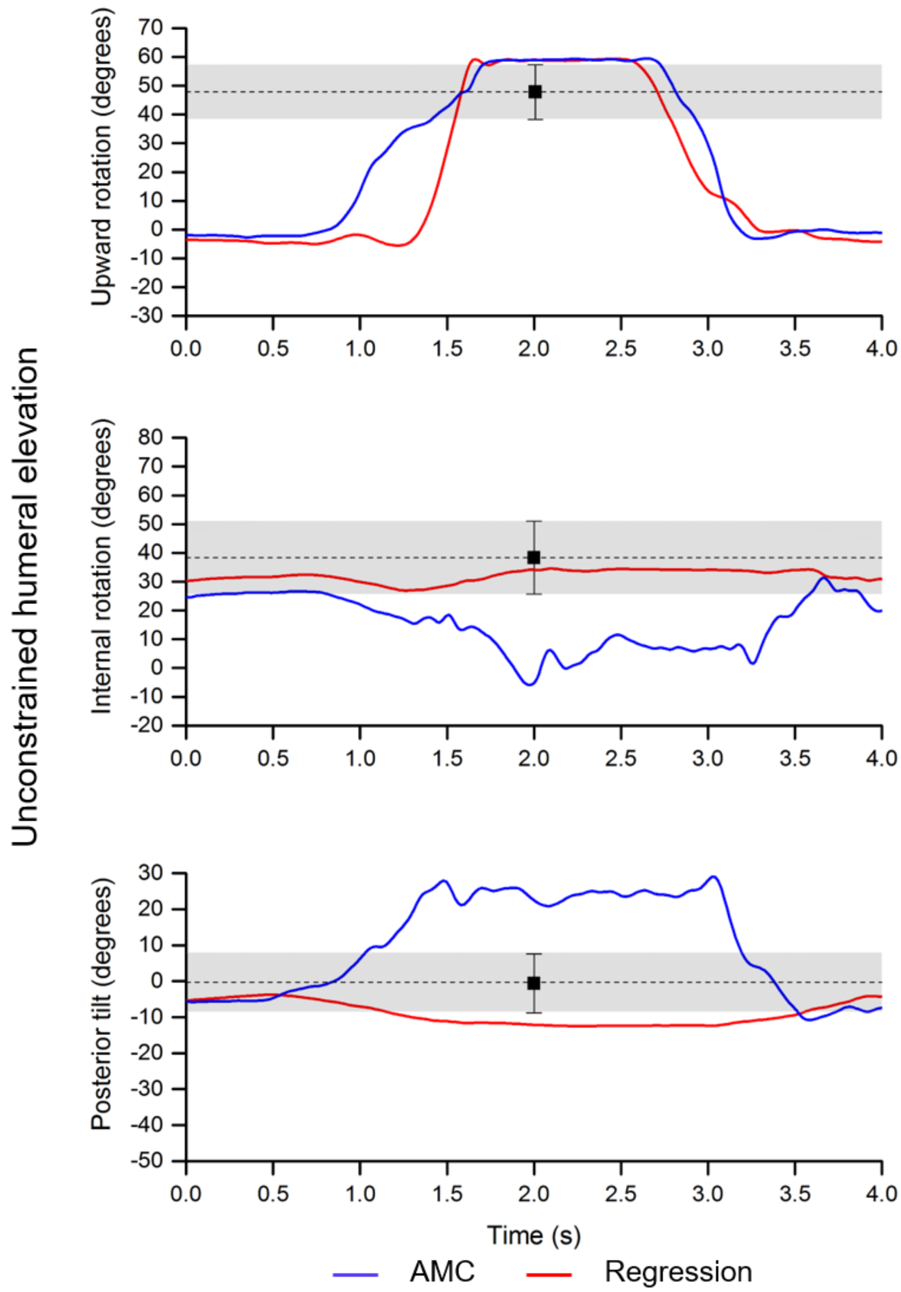

Figure 12 Dynamic ST angles along each axis from the subject who displayed the greatest absolute difference between approaches in the unconstrained humeral elevation position. The grey shaded bar and black dot with error bars display the mean palpated angle from the corresponding static position, ± one standard deviation.

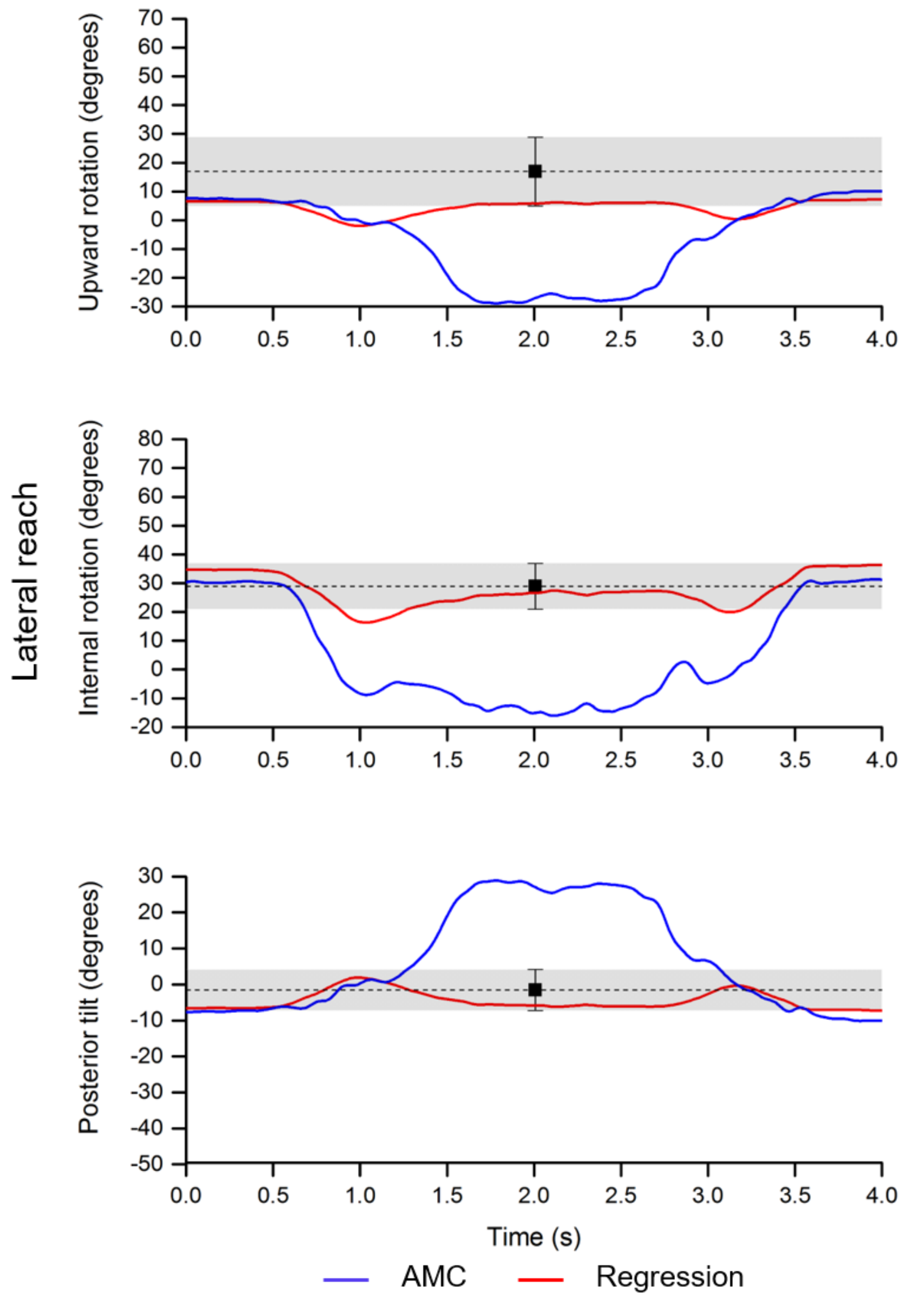

Figure 13 Dynamic ST angles along each axis from the subject who displayed the greatest absolute difference between approaches in the lateral reach position. The grey shaded bar and black dot with error bars display the mean palpated angle from the corresponding static position, ± one standard deviation.

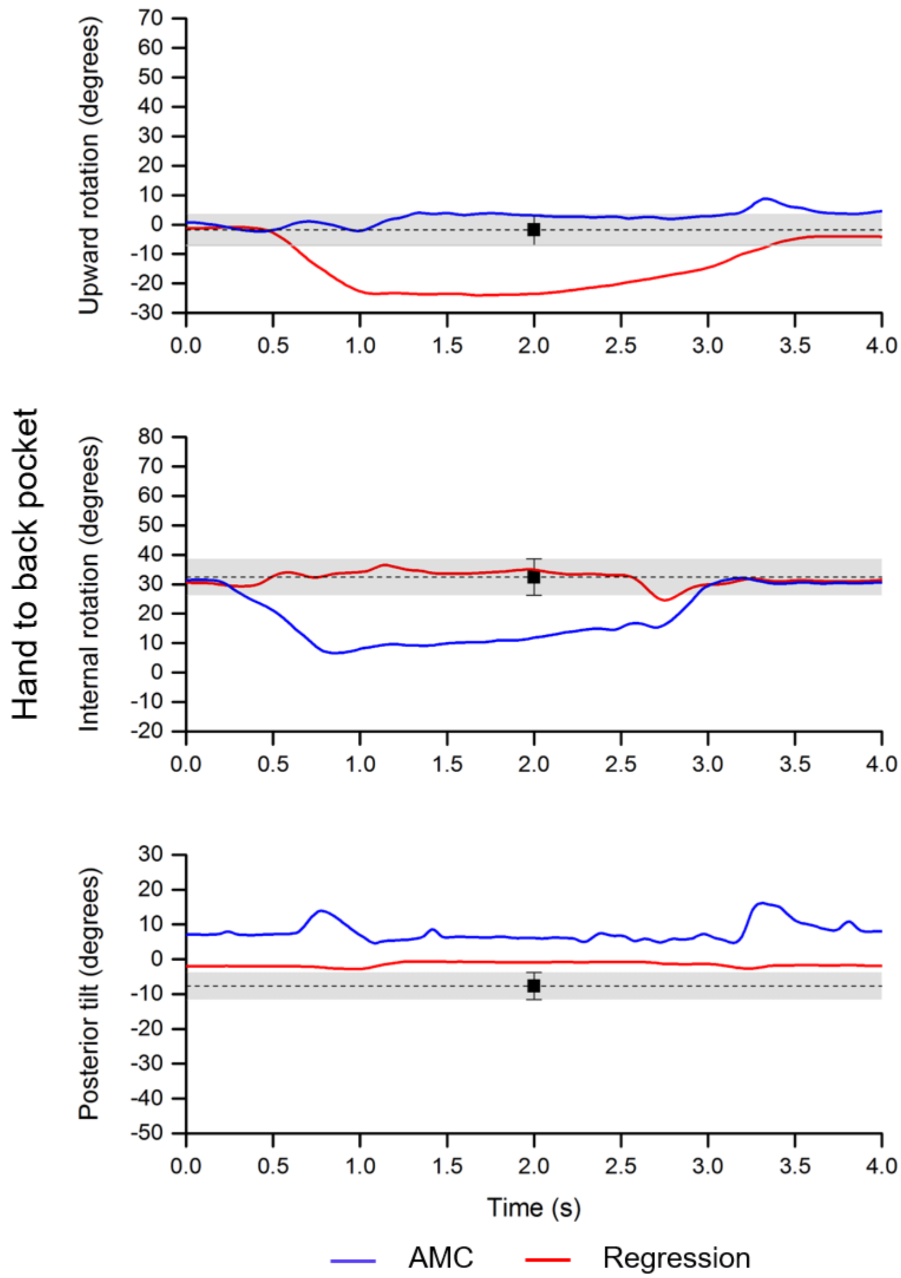

Figure 14 Dynamic ST angles along each axis from the subject who displayed the greatest absolute difference between approaches in the hand to back pocket position. The grey shaded bar and black dot with error bars display the mean palpated angle from the corresponding static position, ± one standard deviation.

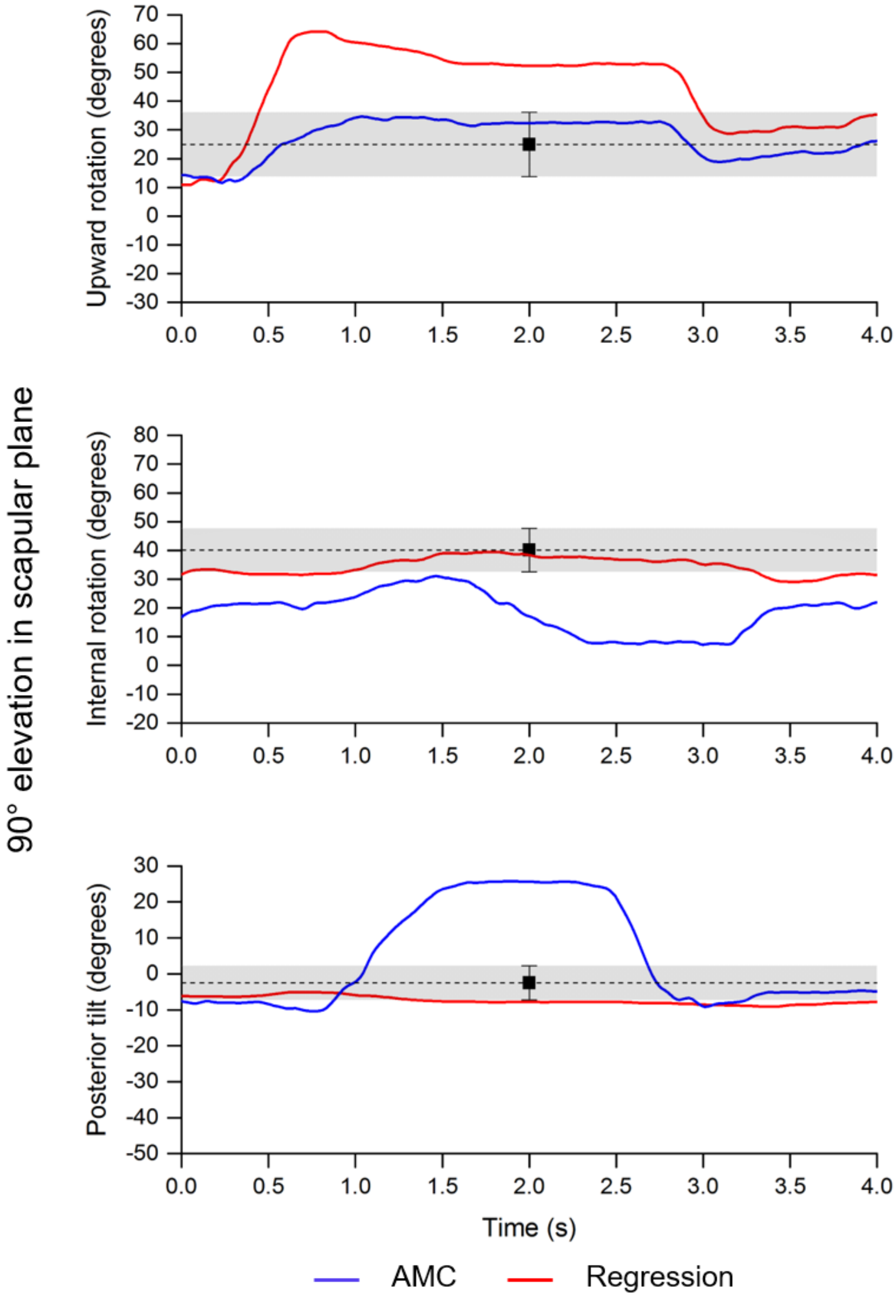

Figure 15 Dynamic ST angles along each axis from the subject who displayed the greatest absolute difference between approaches in the 90° elevation in the scapular plane position. The grey shaded bar and black dot with error bars display the mean palpated angle from the corresponding static position, ± one standard deviation.

Table 4 displays the average correlations between differences along each axis of ST motion and static errors along the corresponding axis. Weak positive correlations were evident between the AMC/regression differences and static AMC errors along the upward rotation and posterior tilt axes. A moderate positive correlation was present between the AMC/regression differences and static AMC errors along the internal rotation axis. A weak negative correlation was present between the AMC/regression differences and static regression errors along the internal rotation axis.

Table 4 Correlations between dynamic RMS differences between the AMC and regression angles and the absolute errors in each approach in the corresponding axis and position during the static validation.

	ST upward rotation	ST internal rotation	ST posterior tilt
AMC errors	0.19	0.46	0.21
Regression errors	0.02	-0.13	0.04

Table 5 displays the average correlations between differences along each axis of ST motion and amount of HT displacement along all three axes. Weak relationships were present between ST upward rotation differences and HT flexion displacement, ST internal rotation differences and all three axes of HT displacement, and ST posterior tilt differences and HT internal rotation and flexion displacements.

Table 5 Correlations between dynamic angle differences (AMC minus regression) along each axis of ST and HT displacement angles along each axis of motion

	HT abduction displacement	HT internal rotation displacement	HT flexion displacement
ST upward rotation differences	0.04	0.07	-0.15
ST internal rotation differences	-0.31	0.30	0.10
ST posterior tilt differences	-0.05	-0.11	0.33

Discussion

Peak Differences

Average peak differences between the regression and AMC approaches in motion were relatively small, ranging from 0.9° to 15.4°. Between subject variability, however, was large, resulting in standard deviations that exceeded 20 degrees in some cases. Given that both approaches utilize an individualized calibration, it is not surprising that one or both methods performed differently for some subjects than they did for others.

Differences Along Axes of ST Motion

Despite the large variability, trends in the differences were still evident. For ST upward rotation, the AMC tended to produce greater ST angles (positive differences) than the regression. Still, while this was true on average for four out of five motions, there was a substantial portion of the distribution that yielded negative differences, indicating that the performance of each approach (and thus the difference between them) varied considerably from subject to subject. In the static accuracy analysis, there was no strongly evident bias in either method. Furthermore, neither method was significantly different from palpation along the upward rotation axis, with the exception of the hand to back pocket position where the AMC overestimated angles and the regression underestimated angles. For the most part, it appeared that the double AMC calibration mitigated errors in ST upward rotation (as validated in static postures) and dynamically, produced similar results to the regression. Correlations between static errors and dynamic differences show a weak relationship along this axis for the AMC, indicating that the two approaches diverged more in positions that yielded larger AMC errors.

In contrast, dynamic differences for ST internal rotation were heavily distributed in the negative region (i.e. the AMC tended to produce lower ST angles than the regression). Four out of five motions yielded negative differences, and for two out of the five motions—lateral reach and hand to back pocket—all differences within one standard deviation of the mean difference were still negative. In static validation studies, including the one performed for these positions in this thesis, the AMC tended to underestimate ST internal rotation [26], [47], while the regression approach exhibited no significant differences from palpation. Furthermore, in the comparison between AMC static and dynamic measures, AMC tended to estimate dynamic internal rotation even lower than the corresponding static measure. While the dynamic analysis from this study can only reveal differences between the two approaches, one might use the previous results to reasonably interpret the negative differences as poor performance of the AMC compared to the regression along the internal rotation axis.

Additionally, along the internal rotation axis, correlations between dynamic differences and static errors revealed a moderate correlation between AMC absolute errors and dynamic RMS differences. As all errors and differences were positive, the positive correlation suggests that higher AMC errors in a static position were associated with higher divergence between AMC and regression measurements during motion. In contrast, the negative correlation between regression errors and dynamic RMS differences indicated as regression errors increased in a static position, angles generated by each approach actually converged during the corresponding dynamic performance of the task.

Average peak differences along the posterior tilt axis were positive for three out of five motions, and the remaining two motions yielded average peak differences of less than 2°. Furthermore, a substantial fraction of the errors was distributed in the positive region, especially for elevation, lateral reach and 90° elevation in the scapular plane. In the static validation, the AMC overestimated posterior tilt in these positions, and specifically, for lateral reach and 90° elevation in the scapular plane, statistical analysis revealed AMC posterior tilt measures were significantly higher than palpation. Furthermore, dynamic measurement by the AMC tended to produce even larger posterior tilt angles than corresponding static measures. Thus, the trend toward higher angles than regression in this analysis is not surprising.

In the hand to contralateral shoulder position, mean internal rotation and posterior tilt differences between AMC and regression estimated ST angles were the opposite direction of the other positions. The AMC on average produced higher ST internal rotation angles (mean difference = 2.2°) and lower posterior tilt angles (-1.4°) than regression. Upon examination of several trials with the largest differences in this direction (including the trials displayed for this position in Figure 11), it appeared that in these cases, the AMC produced values along these axes that were two standard deviations outside of the mean ST angles attained in the static validation of this posture. Additionally, AMC estimated angles in these trials were more than two standard deviations outside of the mean angles (Mean: 48°, SD: 8° for internal rotation and Mean: 11° SD: 5° for posterior tilt) reported in a previous study that measured the hand to contralateral shoulder motion [3]. Figure 16 demonstrates a side by side skeletal representation of the regression and AMC terminal position angles for a representative subject in the hand to contralateral shoulder position. In this representation, the AMC angles appear to be outside of a sensible physiological range.

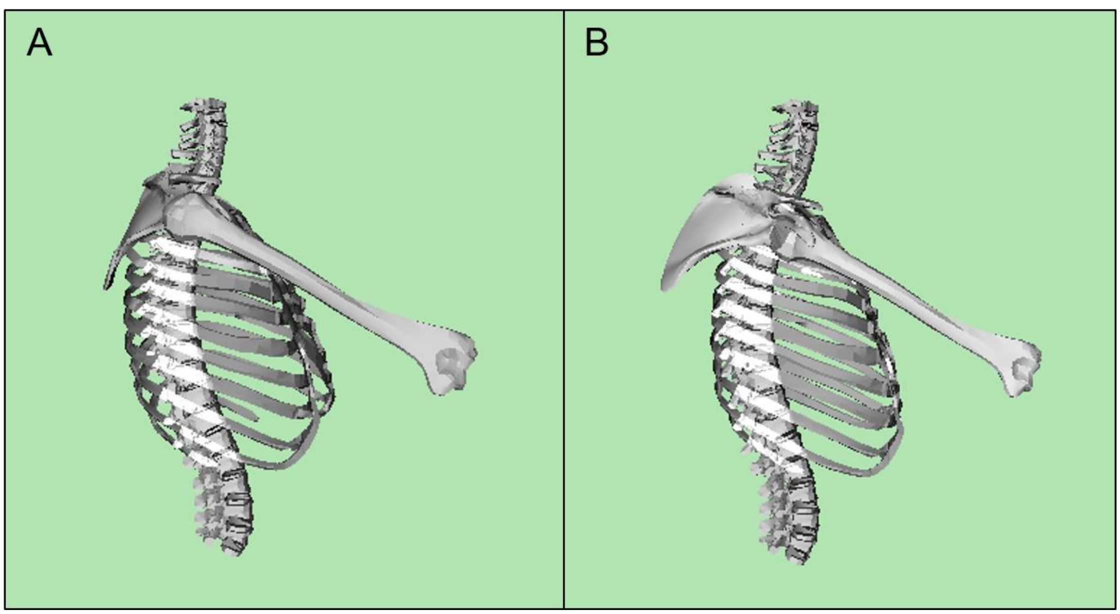

Figure 16 Skeletal representation for the regression (A) and AMC (B) generated ST orientations in the hand to contralateral shoulder position.

Again, in the absence of a gold standard, the dynamic analysis performed in this study can only provide evidence of differences between the two approaches, not their respective accuracy. Still, given the context of previous studies, the previous static validation in this study, and the analysis of AMC static versus dynamic measures, one might again reasonably interpret these results as poor performance in the hand to contralateral shoulder position. The reason for this result is unclear; however, we theorize that the scapular movement pattern that occurs in this position (essentially isolated protraction) is difficult to accurately capture with a device affixed only to the acromion. We suspect that for this motion, the AMC may be overestimating internal rotation and anterior tilt due to soft tissue displacement around the acromion.

Relation to HT Motion

ST upward rotation differences were weakly related to HT flexion displacement. The negative correlation (-0.15) indicated that when HT flexion displacement increased, the AMC tended to produce smaller ST upward rotation angles compared to regression. As the static validation revealed no clear ST upward rotation bias for either method, it is unclear which, if any approach becomes less accurate with increased HT flexion.

ST internal rotation differences were weakly related to both HT abduction and HT internal rotation displacements, albeit stronger than the relationship between ST upward rotation and HT flexion. The direction of the correlation coefficients (-0.31 and 0.30 for HT abduction and internal rotation respectively) indicated that the AMC produced lower angles ST internal rotation angles than the regression approach as HT abduction displacement increased and as HT external rotation displacement increased. Motions with substantial HT abduction and external displacement included the full humeral elevation, lateral reach and 90° scapular plane elevation tasks. While the humerus externally rotated from neutral to achieve these positions, these motions sometimes occurred in conjunction with scapular winging. The lower AMC angles as compared to regression in those instances could be interpreted as evidence of failure to capture scapular winging, as the AMC tended to underestimate this motion during static elevation.

Furthermore, large HT abduction displacement requires deltoid contraction, often causing “bunching” of the soft tissue around the AP. This could compromise the position and orientation of skin fixed markers. The AMC’s reliance on three markers rooted at the AP makes it susceptible to marker error (and thus scapular orientation error). In contrast, the regression approach only relies on one marker at the acromion and thus its accuracy may be less affected by humeral elevation. While the dynamic analysis only reveals divergence between the two methods, anatomical context and results from the static validation can provide reasonable justification for drawing conclusions regarding accuracy in the dynamic experiment.

Conclusion

The dynamic analysis revealed differences between the AMC and regression approaches which were quite substantial for some subjects. Differences along the ST upward rotation axis were slightly biased toward higher angles from the AMC, however variability was high. Differences along the ST internal rotation axis revealed lower angles from the AMC, with much of the distribution skewed in this direction. Similarly, differences along the ST posterior tilt axis revealed higher angles from the AMC, again consistent across most subjects.

These results indicate that the two methods are not interchangeable for measuring dynamic scapular orientation. Differences were particularly evident in motions involving humeral abduction and external rotation, which also happened to be the motions with the greatest overall humeral displacement. The directional biases during dynamic motion were also consistent with performance under static validation and AMC dynamic versus static assessment. In this context, the dynamic results may be interpreted as a worse performance by the AMC along the ST internal rotation and posterior tilt axes. At a minimum, researchers should acknowledge the differences between the two approaches in motion and use caution when comparing across studies that utilize different methods.

Chapter 5

CONCLUSION

This thesis examined two non-invasive methods of measuring scapular kinematics across functional motions in typically developing adolescents. We evaluated the acromion marker cluster (AMC) [41] and the individualized regression approach [28] in five functional positions to determine the accuracy of each method when compared to palpation. We also determined whether the errors from each method were related to the amount of humerothoracic (HT) displacement. Next, we compared AMC measurements of scapulothoracic (ST) angles in static positions to the corresponding position achieved through fluid motion. Finally, we examined differences between the regression and AMC during dynamic performance of the five functional tasks. We explored how these differences related to the errors that occurred in the corresponding static positions and also analyzed how differences between the methods related to the amount of HT displacement. Finally, we used the results of the static accuracy evaluation and static versus dynamic comparison to interpret the results of the dynamic experiment and theorize implications for future applications of these methods

Summary of Results

Static Accuracy and Relation to HT Displacement

A static accuracy analysis was the first step to evaluating performance in measuring scapular kinematics in the adolescent population. ST angles calculated by the AMC and regression approaches were compared to palpated ST angles for five functional positions: hand to contralateral shoulder, unconstrained humeral elevation, lateral reach, hand to back pocket, and 90° elevation in the scapular plane.

Regression angles were significantly different from palpation in the hand to contralateral shoulder position. For many subjects, this position involved a humeral orientation that was notably different from humeral orientations in the set of positions used to build the regression equations, i.e. a humeral orientation outside of the bounds of the set of input angles, requiring the regression equations to extrapolate in order to estimate ST orientation. Accordingly, the regression approach was less accurate under these conditions. For future application, this could be mitigated by insuring the set of input positions encompass the entire desired range of motion for testing.

Additionally, angles estimated by the AMC were significantly lower than palpation along the ST internal rotation axis. This finding is consistent with previous results [26], [27] and represents a failure of the AMC to adequately capture scapular winging. To evaluate the AMC on its most ideal performance, this study used the double calibration approach [35], which did mitigate the error that typically occurs with the AMC in extreme humeral elevation. Nevertheless, errors about the internal rotation axis still persisted, even with implementation of the updated calibration method.

Root mean square (RMS) errors were lower for the regression approach than for the AMC across all axes and positions. This supported the first hypothesis of Aim 1:

> "Absolute differences between the palpated ST orientations and the regression-predicted ST orientations will be smaller than differences between the palpated ST orientations and the AMC-estimated ST orientations."

The correlational analysis revealed several associations between HT displacement and ST angle errors for each method. AMC errors in ST internal rotation and ST posterior tilt were moderately correlated with HT internal rotation displacement. All other correlations were either weak or zero. The moderate correlations, however, led us to conclude that the second hypothesis of Aim 1:

> "For each axis of motion, errors in angles estimated by the AMC will be related to the amount of HT angular displacement from a neutral resting position."

was supported. Additionally, the absence of any moderate or strong correlations between regression errors and HT displacement supported the third hypothesis of Aim 1:

> "For each axis of motion, errors in angles estimated by the regression approach will be independent of the amount of HT angular displacement from a neutral resting position."

Overall, the static accuracy analysis indicated that the regression approach outperformed the AMC. Both methods exhibited limitations in certain conditions, however the consistent underperformance of the AMC along the internal rotation axis, along with the consistently higher RMS errors suggest that the regression approach is a more suitable choice for the adolescent population.

AMC: Static versus Dynamic Analysis

The next step toward ultimately evaluating dynamic performance was to determine how the measurement approaches changed from static to dynamic conditions. This analysis was not necessary for the regression approach; the equations are designed to produce the same ST angles for a given humeral orientation and AP position, regardless of whether that position is held or passed through in motion. Accordingly, only the AMC was compared across static and dynamic conditions. Fourteen functional positions were held by each subject and then repeated without stopping at the terminal position. HT orientations were matched across static and dynamic conditions for each position and ST angles were compared.

Dynamic measurements were overall significantly different from corresponding static measurements in three out of fourteen positions. Additionally, dynamic measurements were significantly different from static on specific axes of ST motion for four out of fourteen positions. These differences, along with trends present along each axis of ST motion, led us to conclude that the first hypothesis of Aim 2:

> "The AMC will produce ST angle estimates that are consistent across both static and dynamic conditions."

was not supported.

Dynamic measurement by the AMC yielded higher angles than static on the posterior tilt axis and lower angles than static along the internal rotation axis. Posterior tilt results contradicted previous work by MacLean et. al. [45]. Nevertheless, the studies are not directly comparable, and we also believe this may be a result of implementing the AMC double calibration in the current study. Internal rotation results were consistent with previous studies investigating static versus dynamic measurement of scapular kinematics [43]–[45]. While this analysis did not ascertain which measures (static or dynamic) were more accurate, the directional bias of the dynamic measurements suggested an exacerbation of errors present in the static validation. When compared to palpation, AMC underestimated internal rotation and overestimated (albeit not significantly) posterior tilt. AMC dynamic measurements were even lower along the internal rotation axis and even higher along the posterior tilt axis than the corresponding static measures. This suggests that dynamic conditions may worsen the AMC's performance along axes where systematic error is already present. Researchers should consider this effect when using the AMC for dynamic measurement of ST kinematics along the internal rotation and posterior tilt axes.

Dynamic Differences Between Methods

The final experiment examined the performance of both the AMC and the regression approach during motion. While the static validation yielded valuable conclusions regarding the accuracy of each method, ultimately both approaches are intended for use in motion and should be evaluated in dynamic conditions. Dynamic gold standards for measuring scapular kinematics are not practical for use in pediatric or adolescent populations, so we elected to directly compare the AMC and regression measures and use the previous analyses to interpret the differences. The five positions evaluated for static accuracy were performed in motion and ST angles measured by each approach were compared in each position and along each axis. Differences between methods were also analyzed in the context of HT displacement.

Peak differences between methods were extremely variable across subjects. On average, the AMC produced higher ST upward rotation angles, lower ST internal rotation angles, and higher ST posterior tilt angles than the regression approach. While upward rotation results were quite varied, the internal rotation and posterior tilt trends persisted for a substantial number of subjects. Additionally, for many subjects who experienced large differences between the two methods, it was noted that the regression angles were typically within one standard deviation of the mean palpated ST angles for the corresponding positions. The AMC, in contrast, often exceeded two standard deviations from the mean. These results were somewhat expected, given the designed consistency of the regression approach from static to dynamic conditions, and the directional bias of the AMC that exacerbated errors along certain axes in motion. Additionally, correlational analyses between static errors and dynamic differences revealed that as AMC static errors worsened, the two methods tended to diverge in the corresponding dynamic expression of the task. In contrast, as regression errors worsened, the two methods tended to converge in motion. This indicated that the second hypothesis of Aim 2:

> "RMS differences between the two methods across the motion trials will be related to the errors observed in the static validation of the corresponding position."

was supported.

The analysis of the differences between methods in the context of HT motion revealed several weak relationships between dynamic differences in HT displacement. The strongest of these relationships demonstrated that the AMC tended to produce lower ST internal rotation angles than regression with increased HT abduction and external rotation displacement. Given the motions analyzed for this study, this can be interpreted as the AMC estimating less ST winging than the regression approach for positions involving humeral elevation (which typically occurred in conjunction with HT external rotation). Additionally, the AMC produced higher posterior tilt estimates than the regression with increasing HT flexion displacement. The third hypothesis of Aim 2:

> "For each axis of motion, differences between the two methods will be correlated with the amount of HT displacement from a neutral resting position."

was only partially supported, as only the differences along the internal rotation and posterior tilt axis appeared to be related to HT displacement, and relationships were weak at best.

Ultimately the results of the dynamic differences experiment were consistent with trends observed in the static validation and the static versus dynamic analysis for the AMC. Investigators should be cautious when comparing angles across methods. The two approaches diverged considerably during motion, particularly along the internal rotation and posterior tilt axis. Extra scrutiny should be given to AMC results along these axes, as dynamic results exacerbated a directional bias that yielded erroneous results in the corresponding static validation.

Future Work

These results from this study can be applied to any other group of interest. Static validation by palpation is a non-invasive approach that can be implemented in sensitive subjects to yield meaningful conclusions. While this study focused on typically-developing adolescents, the same approach could be applied to adolescents with shoulder injury, orthopedic disorders, throwing athletes, or any other population where scapular motion is relevant. Furthermore, the limitations of each method that were revealed in this study provide valuable information for choosing a scapular kinematic measurement method. In particular, this study offered a direct comparison of the less familiar regression approach to the more widely utilized AMC. This study provided evidence of the regression's suitability for measuring scapular motion in functional tasks and demonstrated advantages in selecting that approach over the AMC. Other investigators may examine the conditions under which each method fails and choose the technique that best fits their research questions and conditions.

Conclusions

In this study, the regression approach outperformed the AMC for functional tasks performed by typically-developing adolescents. Both methods exhibited limitations under certain conditions. However, the errors in the regression approach can theoretically be mitigated by modifying the set of input positions to adequately capture the range of motion required for testing. In contrast, the errors with AMC appeared to be systematic. The AMC underestimated internal rotation and overestimated posterior tilt, and this trend was exacerbated from static to dynamic conditions. For planar motions these errors may be minor, but for multiplanar tasks such as those considered in this study, the inaccuracy can be substantial. Furthermore, patients with scapular dyskinesis may exhibit even more motion around these secondary axes. The failure of the AMC to capturing motion such as scapular winging or excessive anterior tilt may critically affect the interpretation of kinematics in these populations.

A non-invasive measurement technique must be capable of accurately capturing scapular range of motion in order to provide meaningful results. The regression approach demonstrated smaller errors than the AMC along each axis of ST motion and provided dynamic measures of ST kinematics that were consistent with available literature. For future application in the adolescent population, both healthy and pathological, we recommend the use of the regression approach for the most accurate results.

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Appendix

IRB APPROVAL DOCUMENTATION

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE:	June 27, 2016
TO:	Elizabeth Rapp, BS
FROM:	University of Delaware IRB
STUDY TITLE:	[767133-6] Scapular Kinematics in Adolescents with Idiopathic Scoliosis
SUBMISSION TYPE:	Amendment/Modification
ACTION:	APPROVED
APPROVAL DATE:	June 27, 2016
EXPIRATION DATE:	June 16, 2017
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	*Expedited 45 CFR 46.110 (b) (2)*

Thank you for your submission of Amendment/Modification materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.

HUMAN SUBJECTS PROTOCOL
University of Delaware

Protocol Title: Scapular Kinematics in Adolescents with Idiopathic Scoliosis

Principal Investigator
Name: Elizabeth A. Rapp
Department/Center: Kinesiology and Applied Physiology
Contact Phone Number: 302-831-8212
Email Address: lizrapp@udel.edu

Advisor (if student PI)
Name: James G. Richards
Contact Phone Number: 302-831-2054
Email Address: jimr@udel.edu

Other Investigators: Amer Samdani, R. Tyler Richardson, Kristen Nicholson

Investigator Assurance:

By submitting this protocol, I acknowledge that this project will be conducted in strict accordance with the procedures described. I will not make any modifications to this protocol without prior approval by the IRB. Should any unanticipated problems involving risk to subjects occur during this project, including breaches of guaranteed confidentiality or departures from any procedures specified in approved study documents, I will report such events to the Chair, Institutional Review Board immediately.

1. **Is this project externally funded?** ☐ YES **X** NO

If so, please list the funding source:

2. Research Site(s)

X University of Delaware

X Other (please list external study sites)

Shriners Hospital for Children—Philadelphia
Nemours/A.I. DuPont Hospital for Children

Is UD the study lead? **X** YES ☐ NO *(If no, list the institution that is serving as the study lead)*

3. **Project Staff**
Please list all personnel, including students, who will be working with human subjects on this protocol (insert additional rows as needed):

NAME	ROLE	HS TRAINING COMPLETE?

Elizabeth Rapp, BS	PI	Yes
Amer Samdani, MD	Co-Investigator	Yes
James Richards, PhD	Co-Investigator	Yes
Kristen Nicholson, MS	Co-Investigator	Yes
R. Tyler Richardson, MS	Co-Investigator	Yes
Ross Chafetz, PT	Research Assistant	Yes
Tiffany Ross	Research Assistant	Yes

4. **Special Populations**
Does this project involve any of the following:

Research on Children? Yes

Research with Prisoners? No

If yes, complete the Prisoners in Research Form and upload to IRBNet as supporting documentation

Research with Pregnant Women? No

Research with any other vulnerable population (e.g. cognitively impaired, economically disadvantaged, etc.)? Please describe

No

5. **RESEARCH ABSTRACT**

Adolescent idiopathic scoliosis occurs in up to 5% of children between the ages of 11 and 18 [1]. By definition, "idiopathic" scoliosis (IS) is scoliosis from an unknown cause. Research exists regarding the measurement and treatment of the resulting spinal curvature. In contrast, little has been done to investigate the motion of the entire shoulder complex despite the fact that shoulder mechanics can be a cause of pain and dysfunction in this population [2]–[4]. Abnormal spinal curvature typically creates a rib hump, creating a bulging surface for the shoulder blade to track across. Studies have shown that posture and trunk shape are associated with changes in shoulder motion and in some cases, shoulder disorders [5]–[9]. Accordingly, the shoulder blade joint mechanics are likely altered and possibly at a disadvantage in the IS population. Previous research compared adolescents with IS to healthy adolescents and found shoulder dysfunction and some abnormalities in shoulder blade motion [10]. The study, however, was limited to motion in only one plane and neglected shoulder blade internal/external rotation (winging). As shoulder blade winging has been shown to cause functional and stability problems [11]–[13], this motion is an important consideration in adolescents with IS. Furthermore, the previous study's measurement technique used for scapular motion is known to have limitations in populations with movement disorders [14], so for adolescents with IS, additional investigation is needed.

Similarly, the effects of surgery to correct the spinal curve on shoulder mechanics have not been analyzed. Investigations of upper arm function after different scoliosis surgical approaches have found that almost all patients returned to their previous range of motion after six months [15]–[17]. The motion considered, however, was only upper arm movement measured by hand, and neglected the motion of the shoulder blade. The spinal surgeries in question involve deep cuts through several layers of shoulder blade muscles. Additionally, the spinal curve is reduced on average by 62%[18]. As a result, the shape of the rib cage changes, which would change the surface on which the shoulder blade moves. As abnormal shoulder blade motion is linked to shoulder joint disorders, the effect of surgery on shoulder joint mechanics is important to IS surgical patients. Understanding the specific effects of these common surgeries on shoulder joint function is expected to improve therapy as well as long-term treatment of idiopathic scoliosis.

The expected outcomes of this study include 1) establishment of a shoulder motion profile for adolescents with IS 2) evaluation of the effect of surgeries on the shoulder joint and 3) a better understanding of the relationship between curvature and rib cage shape change and change in shoulder motion.

6. **PROCEDURES**

Describe all procedures involving human subjects for this protocol. Include copies of all surveys and research measures.

The component of the following protocol occurring at the University of Delaware will be performed on ONLY the typically-developing subjects (recruited through and tested at the University of Delaware). All recruitment and data collection involving the scoliosis subjects will occur at Shriners Hospital for Children in Philadelphia. Temple will be the IRB of record for scoliosis subjects at Shriners, and Nemours will be the IRB of record for scoliosis subjects at Nemours. Notification of approval from these IRBs has been submitted to the University of Delaware IRB. Information regarding the scoliosis subjects has been included in this protocol so as to clarify the entire direction of the study, however those procedures have been approved by the Temple IRB to be performed at Shriners and the Nemours IRB to be performed at Nemours.

Data collection will take place either in the Kinesiology and Applied Physiology Biomechanics (KAAP) Lab at the University of Delaware (non-scoliosis subjects) or the Biomechanics Lab at Shriners Hospital for Children – Philadelphia or Nemours/A.I. DuPont Hospital for Children (scoliosis subjects). Each data collection will take approximately 45 minutes and will consist of motion capture data, self-reported function via the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire, and minimal personal information including name, gender, age, height and weight and relevant medical history including previous upper extremity surgery and measures of curvature (Cobb Angle, vertebral rotation). Typically-developing subjects will participate in one data collection (total of 45 minutes) while scoliosis subjects will participate in one data collection before surgery and one data collection 6 months after surgery for a total of 1.5 hours.

Prior to the motion capture, all subjects will complete the DASH questionnaire. Measures of height and weight will be obtained in a curtained area of the lab so as to insure privacy. For the motion capture, male subjects will remove their shirts, and female subjects will wear a top that leaves the scapular region and the majority of the spine exposed. Subjects will sit on a stool in a comfortable position. A seven camera Motion Analysis (Santa Monica, CA) system will be used for motion capture. Throughout the trials, the subjects will wear three-dimensional retroreflective markers at the following locations:

Thorax Markers	**Humerus Markers**	**Scapula Markers**
C7 spinous process	Medial epicondyle	Acromion process
Thoracic Spinous process above scoliotic curve (or T3 in healthy subjects)	Lateral epicondyle	
Thoracic Spinous process at apex of scoliotic curve (or T8 in healthy subjects	Posterolateral humerus	
Thoracic Spinous process below scoliotic curve (or L1 in healthy subjects)		
Lower Lumbar spinous process		
Left lateral rib (to be removed after position 2)		
Right lateral rib (to be removed after		

position 2)		

The subjects will be asked to briefly hold their arm in each of the following positions, first the right side, then the left.

Position	Description	Position	Description
1	Neutral position (arm at side)	7	Hand to nape of neck
2	Forward trunk bend (arm at side)	8	Hand to mouth
3	Full abduction in frontal plane	9	Hand to spine
4	Full flexion in sagittal plane	10	Full external rotation at 0º abduction
5	Full extension	11	Full internal rotation at 0º abduction
6	Full elevation	12	Forward reach

At each position, the following anatomical landmarks on the scapula will be palpated: trigonum spinae, inferior angle. Retroreflective markers will be placed on the palpated locations and removed once the position is captured. After the static positions are captured, the subjects will move through the above positions without stopping for the final dynamic capture. Once this capture is complete, the markers will be removed and the data collection will be finished. Scoliosis subjects will return six months after surgery to repeat this process.
,

7. **STUDY POPULATION AND RECRUITMENT**

Describe who and how many subjects will be invited to participate. Include age, gender and other pertinent information.

84 children between the ages of 11 and 18 will be recruited for this study – 48 healthy, 36 with idiopathic scoliosis. Healthy children will be recruited from local high schools and middle schools in the Newark community. Children with scoliosis will be recruited from the IS patient population at Shriners Hospital for Children – Philadelphia and Nemours/A.I. DuPont Hospital for Children. The invitation to participate will be offered during orthopedic clinics or routine visits, under the direction of Dr. Amer Samdani and Kim Hayes and Melissa Morrison (Shriners) or Dr. Suken Shah and Dr. Peter Gabos (Nemours). Of the scoliosis subjects, all subjects must have an imminent spine fusion surgery at Shriners Hospital for Children – Philadelphia or Nemours/A.I. DuPont Hospital for Children. No distinction regarding gender or ethnicity will be necessary, as these factors do not affect the measurement or analysis process.

Attach all recruitment fliers, letters, or other recruitment materials to be used. If verbal recruitment will be used, please attach a script.

Recruitment letters are attached

Describe what exclusionary criteria, if any will be applied.

- Subjects who have been diagnosed with a congenital pathology resulting in scoliotic curvature (non-idiopathic scoliosis) will be excluded
- Subjects with excessive soft tissue overlying the scapula will be excluded
- Subjects who have an adhesive allergy will be excluded
- Subjects who are not cognitively able (as determined by referring physician) to follow instructions will be excluded

Describe what (if any) conditions will result in PI termination of subject participation

Permission in this study is voluntary, and subjects may withdraw at any time.

8. **RISKS AND BENEFITS**
List all potential physical, psychological, social, financial or legal risks to subjects (risks listed here should be included on the consent form).

There is a slight risk of having an allergic reaction to the adhesive

In your opinion, are risks listed above minimal or more than minimal? If more than minimal, please justify why risks are reasonable in relation to anticipated direct or future benefits.*

The above risks are minimal

*(*Minimal risk means the probability and magnitude of harm or discomfort anticipated in the research are not greater than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests)*

What steps will be taken to minimize risks?

Subjects will be asked if they have any allergies to adhesive.

Describe any potential direct benefits to participants.

There will be no direct benefits to participants.

Describe any potential future benefits to this class of participants, others, or society.

Shoulder motion trends in adolescents with idiopathic scoliosis will be identified, as will the effect of a common surgical intervention on these mechanics. Should these trends prove pathological, therapy and treatment can be directed toward correction and injury prevention. The spinal fusion surgery can be assessed with regard to effect on the upper extremity and surgeons and patients can be made aware of potential complications.

If there is a Data Monitoring Committee (DMC) in place for this project, please describe when and how often it meets.

There is no DMC in place for this study.

9. **COMPENSATION**
Will participants be compensated for participation?

There is no compensation for participating in this study

10. **DATA**
Will subjects be anonymous to the researcher?

Subjects' identities will be known to the researchers

If subjects are identifiable, will their identities be kept confidential? (If yes, please specify how)

Participation will be kept confidential and data will only be referred to by number (i.e. Subj_01) and no personal information will be stored with the data files.

How will data be stored and kept secure (specify data storage plans for both paper and electronic *files. For guidance see http://www.udel.edu/research/preparing/datastorage.html)*

The information collected will be stored on password protected computers in the KAAP Biomechanics Laboratory at the University of Delaware. Only members of the research team will have access to the computer and the data files. Consent, assent forms, and paper questionnaires will be stored in a locked file cabinet in the PI's office at the University of Delaware.

How long will data be stored?

Paper consent and assent forms and questionnaires will be stored for three years after closure of the project.

Will data be destroyed? **X** YES NO *(if yes, please specify how the data will be destroyed)*

Paper data (i.e. consent forms and questionnaires) will be stored for three years after closure of the project in a locked file cabinet in the PI's office. It will be destroyed with a paper shredder. Electronic data will be stored without any identifying information and thus will not be destroyed.

Will the data be shared with anyone outside of the research team? **X** YES ☐ NO *(if yes, please list the person(s), organization(s) and/or institution(s) and specify plans for secure data transfer)*

Dr. Amer Samdani, Shriners Hospital for Children - Philadelphia
Ross Chafetz, Shriners Hospital for Children – Philadelphia
Dr. Suken Shah, Nemours/A.I. DuPont Hospital for Children
Dr. Peter Gabos, Nemours/A.I. DuPont Hospital for Children

De-identified data will be exchanged on a password-protected USB drive with read-only privileges and will only be viewed (and not stored) on the above persons' computer at Shriners or Nemours.

How will data be analyzed and reported?

3D marker positions will be used to define rigid bodies for the trunk, scapula, humerus, forearm, and hand. Coordinate systems for each segment will be created so that the axes match the International Society of Biomechanics recommendations. 3D scapulothoracic, glenohumeral and humerothoracic joint angles will be calculated using a helical method. Due to limitations with accurately measuring scapular orientation during dynamic movement, the orientation of the scapula beneath the skin will be estimated using two unique novel approaches.

11. **CONFIDENTIALITY**
Will participants be audiotaped, photographed or videotaped during this study?

If the subject gives consent, the scapular region of participants' backs will be photographed. The subjects' faces will not be in the photograph.

How will subject identity be protected?

Data will only be identified by number (i.e. Subj_01) and no personal information will be stored with the data. Consent and assent forms will be stored in a locked file cabinet in the PI's office at the University of Delaware.

Is there a Certificate of Confidentiality in place for this project? (If so, please provide a copy).

There is no certificate of confidentiality in place for this study

If during this study our research team was to observe or suspect, in good faith, child abuse or neglect, we are required by Delaware state law to file a report to the appropriate officials and will do so.

12. **CONFLICT OF INTEREST**
(For information on disclosure reporting see: http://www.udel.edu/research/preparing/conflict.html)

Do you have a current conflict of interest disclosure form on file through UD Web forms?

Faculty advisor PI (Dr. Richards) has the relevant form on file.

Does this project involve a potential conflict of interest?*

No
If yes, please describe the nature of the interest:

13. **CONSENT and ASSENT**

__X__ Consent forms will be used and are attached for review (see Consent Template under Forms and Templates in IRBNet)

__X__ Additionally, child assent forms will be used and are attached.

____ Waiver of Documentation of Consent (attach a consent script/information sheet with the signature block removed).

____ Waiver of Consent (Justify request for waiver)

14. **Other IRB Approval**
Has this protocol been submitted to any other IRBs?
This protocol has been approved by:

Temple University IRB, which governs research done at Shriners Hospital for Children in Philadelphia. Temple will be the IRB of record for the scoliosis subjects who are patients at Shriners.
Protocol Number: 23198
Approval Date: 3/3/2016
Expiration Date: 3/2/2017

Nemours/A.I. DuPont Hospital for Children IRB. Nemours will be the IRB of record for the scoliosis subjects who are patients at Nemours.

Protocol Number: 833806
Approval Date: 12/16/2015
Expiration Date: 12/15/2016

Both approval letters along with the corresponding consent and assent documents have been uploaded to IRBnet for this application and have been acknowledged by the University of Delaware IRB.

15. **Supporting Documentation**
Please list all additional documents uploaded to IRBNet in support of this application.

Informed Consent (For subjects 18 years of age and parents of subjects younger than 18)
Assent Document (For subjects younger than 18)
DASH Questionnaire (Used in the data collection)
Recruitment letter for typically developing subjects
Recruitment letter for scoliosis subjects

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Rev. 10/2012

INFORMED CONSENT TO PARTICIPATE IN RESEARCH

Typically-Developing Subjects

Title of Project: Scapular Kinematics in Adolescents with Idiopathic Scoliosis

Principal Investigator(s): Elizabeth Rapp, Jim Richards, PhD.

You (or your child) are being invited to participate in a research study. This consent form tells you about the study including its purpose, what you (or your child) will be asked to do if you decide to take part, and the risks and benefits of being in the study. Please read the information below and ask us any questions you may have before you decide whether or not you want to participate.

WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this study is to learn more about how the shoulder moves in adolescents with idiopathic scoliosis. Since scoliosis typically changes the shape of the rib cage, we would like to find out if the shoulder blade moves differently in scoliosis children than in adolescents without scoliosis and if this is affecting daily activities. We would like to see if potential differences relate to the amount of curvature. We also would like to learn more about what happens after surgery corrects the spine curve and changes the rib cage shape. To do this, we will compare shoulder motion between adolescents with and without scoliosis and also shoulder motion before and after surgery in adolescents with scoliosis. This study will be used as part of a master's thesis as well as a doctoral dissertation at the University of Delaware. We will perform part of this study—the part involving adolescents with scoliosis—at Shriners hospital for children in Philadelphia. The portion of the study occurring at the University of Delaware for which we are asking your permission is only looking at adolescents without scoliosis. You (or your child) will be one of approximately 18 participants in this study who do not have scoliosis.

WHY ARE YOU BEING ASKED TO PARTICIPATE?

You are being asked to participate because…

- You are an 18 year old adolescent without scoliosis or a parent of an adolescent without scoliosis between the ages of 11 and 17.
- You (or your child) would be excluded if
    - You have a lot of skin or soft tissue around your shoulder blade and we can't feel the bone
    - You are allergic to adhesives, such as Band-Aids
    - You are not able to follow directions for putting your arm in different positions

WHAT WILL YOU BE ASKED TO DO?

As part of this study you (or your child) will be asked to…….

- The study will take place in University of Delaware KAAP Biomechanics Lab.

Participant's Initials _________

- Data collection will take approximately 45 minutes.
- Your height and weight will be recorded.
- Your parent or caretaker (or you) will be present if both of you choose.
- You (or your child) will be asked to complete the Disabilities of the Arm, Shoulder and Hand questionnaire (DASH).
- You (or your child) will change for the data collection: boys will remove their shirts and girls will wear a sports bra or a bathing suit top so we can see the back and shoulders.
- 15 reflective markers will be placed on your (or your child's) trunk and arms and attached with small Velcro adhesive dots.
- You (or your child) will be asked to hold 12 different trunk and arm positions. At each of these positions, one of the researchers will place 3 more markers on your shoulder blade.
- While you (or your child) are holding each position, motion capture cameras will record the position of all the markers.
- After all 12 positions, you (or your child) will be asked to move through the positions without stopping while we record with motion capture.
- After recording the motion, the markers will be removed and your (or your child's) participation in this study will be complete.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

Possible risks of participating in this research study include ………

- There is a slight risk of having an allergic reaction to the adhesive. We will ask if you (or your child) are allergic to adhesive or Band-Aids, to minimize this risk.

WHAT ARE THE POTENTIAL BENEFITS?

- There will be no direct benefits to you (or your child) from this study.
- There are potential future benefits to patients with scoliosis as we learn more about shoulder motion in scoliosis. We will also learn more about how surgery affects this motion. Our findings could be used to influence treatment and therapy decisions for scoliosis patients.

NEW INFORMATION THAT COULD AFFECT YOUR PARTICIPATION:

During the course of this study, we may learn new information that could be important to you (or your child). This may include information that could cause you to change your mind about participating in the study. We will notify you as soon as possible if any new information becomes available.

HOW WILL CONFIDENTIALITY BE MAINTAINED? WHO MAY KNOW THAT YOU PARTICIPATED IN THIS RESEARCH?

- Your (or your child's) information will be kept confidential
- Data will be identified and reported by number only (for example: subj01).

Participant's Initials _________

- The electronic information collected will be de-identified and stored on password protected computers in the Biomechanics Laboratory at the University of Delaware and only members of the research team will have access to this information. Your consent forms will be stored for three years after closure of the project in a locked file cabinet in Dr. Richards' office. After three years they will be destroyed by a paper shredder.
- No personal information such as name or age will be stored with the data files.
- General results only (not your name or anything identifying you or your child personally) will be shared with Dr. Samdani at Shriners Hospital for Children - Philadelphia.
- If you consent, we would potentially use a photograph of you (or your child) in a future publication or presentation. The photograph would be of the shoulder region of your (or your child's) back and your face would not be shown.

The confidentiality of your (or your child's) records will be protected to the extent permitted by law. Your (or your child's) research records may be viewed by the University of Delaware Institutional Review Board, which is a committee formally designated to approve, monitor, and review biomedical and behavioral research involving humans. Records relating to this research will be kept for at least three years after the research study has been completed.

- We also must let you know that if during your (or your child's) participation in this study our research team was to observe or suspect, in good faith, child abuse or neglect, we are required by Delaware state law to file a report to the appropriate officials.

WILL THERE BE ANY COSTS TO YOU FOR PARTICIPATING IN THIS RESEARCH?

- There will be no costs to you (or your child) associated with participating in the study.

WILL YOU RECEIVE ANY COMPENSATION FOR PARTICIPATION?

- There is no compensation for participating in this study.

DO YOU HAVE TO TAKE PART IN THIS STUDY?

Taking part in this research study is entirely voluntary. You (or your child) do not have to participate in this research. If you choose to take part, you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled.

Your decision to stop participation, or not to participate, will not influence current or future relationships with the University of Delaware or Shriners Hospital for Children – Philadelphia.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?

Participant's Initials _________

If you have any questions about this study, please contact the Principal Investigator, Liz Rapp at (717) 468-5160 or lizrapp@udel.edu, or her advisor, James Richards at (302) 831-2054.

If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at hsrb-research@udel.edu or (302) 831-2137.

Your signature on this form means that: 1) you are at least 18 years old; 2) you have read and understand the information given in this form; 3) you have asked any questions you have about the research and those questions have been answered to your satisfaction; 4) you accept the terms in the form and volunteer to participate in the study. You will be given a copy of this form to keep.

______________________________	_________________________	_________
Printed Name of Participant	Signature of Participant	Date
______________________________	_________________________	_________
Person Obtaining Consent (PRINTED NAME)	Person Obtaining Consent (SIGNATURE)	Date

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You are making a decision whether or not to have your child participate in this study. Your signature indicates that you have read the information provided above and decided to allow your child to participate.

_____________________________	_____________________________	________
(Printed Name of Parent/Guardian)	(Signature of Parent/Guardian)	(Date)
__________________________	_________________________	__________
Person Obtaining Consent (PRINTED NAME)	Person Obtaining Consent (SIGNATURE)	Date

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Participant's Initials _________

<u>OPTIONAL</u> CONSENT FOR ADDITIONAL USES OF VIDEO RECORDINGS/PHOTOGRAPHS

I voluntarily give my permission for the researchers in this study to use photographs of me (and/or my child) collected as part of this research study to be used in publications, presentations, and/or for educational purposes. I understand that no identifying information beyond that contained in the photographs will be provided to educational/scientific audiences and my facial features (and/or those of child) will not be seen.

____ _______________

(Signature of Participant OR Parent/Guardian) (Date)

____

(Printed Name of Participant OR Parent/Guardian)

<u>OPTIONAL</u> CONSENT TO BE CONTACTED FOR FUTURE STUDIES:

Do we have your permission to contact you regarding participation in future studies? Please write your initials next to your preferred choice.

________ YES ________ NO

Participant's Initials _________

ASSENT TO PARTICIPATE IN RESEARCH – Typically Developing Subjects

Title of Project: Scapular Kinematics in Adolescents with Idiopathic Scoliosis

Investigator(s): Elizabeth Rapp, Jim Richards, PhD.

I am asking if you want to be part of a research study. This form tells you what the study is about, what you will be asked to do if you want to be in the study, and the possible bad and good things about this study. Please read this paper and ask us any questions you have.

WHAT IS THE PURPOSE OF THIS STUDY?

This research study is to learn more about how the shoulder moves in adolescents with scoliosis (a curved spine). Since scoliosis typically changes the shape of the rib cage, we would like to find out if the shoulder blade moves differently in scoliosis children than in children without scoliosis and if this is affecting daily activities. We would like to see if potential differences relate to the amount of spinal curve. We also would like to learn more about what happens after surgery corrects the spine curve and changes the rib cage shape. To do this, we will compare shoulder motion between adolescents with and without scoliosis and also shoulder motion before and after surgery in adolescents with scoliosis. This will help us make decisions about therapy and treatment for scoliosis.

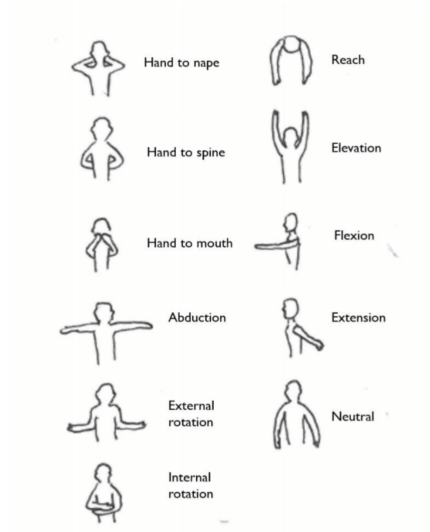
We are asking you if you want to be in it because you are between the ages of 11 and 18 and you do not have scoliosis.

WHAT WILL YOU BE ASKED TO DO?

If you want to participate we will ask you to…….

- You will come to the University of Delaware KAAP Biomechanics Lab.
- The study will take approximately 45 minutes. Your parent will be present if you choose.
- First you will complete a questionnaire about your shoulder.
- Your height and weight will be recorded
- You will change into data collection clothes – boys will take their shirts off and girls will wear a sports bra or a bathing suit top so that we can see your shoulders and back.
- We will place small shiny marker cubes (Picture 1) on your arm and back and attached them with Velcro stickers. This allows our special cameras to record the position of your arm when you move.
- You will be asked to hold your arm in several different positions (up in the air, behind your back, etc – Picture 2) while we take special pictures.
- After all the positions, we will ask you to do the same positions but this time without stopping. You can go at your own pace. We will again record with the special cameras.
- After this movement, we will take off the markers and you will be finished with the collection.

Participant's Initials ______________



Picture 1: Shiny markers for taking a special picture of your arms

Picture 2: Positions to hold your arms in while we take a picture

WHAT ARE THE POSSIBLE BAD THINGS ABOUT THIS RESEARCH?

A few things about this study that could make you uncomfortable or hurt you……

- We do not think that participating in this research will make you uncomfortable or hurt you, but if your arm gets tired at any point, let us know and you can rest.
- You will be asked if you are allergic to adhesive or Band-Aids before we start. This will help avoid the possibility of an allergic reaction to the sticky Velcro dots. After we take them off, there may be a little bit of redness, but this should go away after a short time.

WHAT ARE THE POTENTIAL GOOD THINGS ABOUT IT?

- You will not benefit directly from being in the study. We hope to learn new things during this study that would help to better understand how the shoulder moves during scoliosis and how surgeries affect this movement. This may help treat children with scoliosis in the future.

Participant's Initials ______________

WHO MAY KNOW THAT YOU PARTICIPATED IN THIS RESEARCH?

- No one other than the investigators will know that you were in this study. If we tell other people about the research we will not use your name.
- If you allow us to, we might take a picture of your back and shoulder and use it for a presentation. We would only show your back and not your face.
- We also must let you know that if you tell us that someone has done or is doing bad things to you or other children, we will tell people who can help.

WILL YOU RECEIVE ANY COMPENSATION FOR PARTICIPATION?

- There won't be any compensation for participating, but if you like, we can give you a picture of yourself with the markers on.

CAN YOU CHANGE YOUR MIND ABOUT BEING IN THE STUDY?

You do not have to say yes. Even if your parent says yes, you can still say no. Taking part in this research study is up to you. If you choose to take part, you can change your mind and stop at any time. If you decide not to participate or if you decide to stop taking part in the research later, nothing bad will happen to you and no one will be upset with you. If, at any time, you decide to stop please let us know by telling one of the researchers.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?

If you have any questions about this study, please tell Liz Rapp at 717-468-5160 or lizrapp@udel.edu. You may also tell Dr. James Richards at 302-831-2054 or jimr@udel.edu

*If you have any questions or concerns about your rights as a research participant, you may contact the University of Delawa*re Institutional Review Board at hsrb-research@udel.edu or (302) 831-2137.

If you want to participate, and we have answered all of your questions about it, please sign below.

____________________________	________________________	_________
Printed Name of Participant	Signature of Participant	Date

Participant's Initials ______________

______________________________	________________________	_________
Person Obtaining Consent (PRINTED NAME)	Person Obtaining Consent (SIGNATURE)	Date

Participant's Initials ______________