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MEASURING SCAPULAR MOVEMENT USING THREE-DIMENSIONAL ACROMIAL PROJECTION

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Keywords

Shoulder; Scapula; Torso; Biomechanics; Motion Capture

Introduction

Abnormal scapular kinematics are associated with a number of shoulder pathologies, including, but not limited to, shoulder impingement syndrome [1, 2], rotator cuff tendinopathy [3], rotator cuff tears [4], shoulder instability [5], and adhesive capsulitis [6, 7].

A variety of methods have been proposed to quantify scapular movement. These have progressed from initial attempts utilizing two-dimensional radiographs to modern experimental designs creating digital maps from high-speed computerized imaging [8]. In 1944, Inman et al utilized two-dimensional analysis of radiographs to report a 2:1 relationship between glenohumeral elevation and upward rotation of the scapula [9]. This relationship was termed the *scapulohumeral rhythm*, and recent studies have reported similar rhythm ratios [10–12]. Despite being able to capture broad motions, these initial methodologies fail to account for “out of plane” movements and provide inaccurate definitions for scapular motions [13]. To address these issues, three-dimensional techniques including three-dimensional radiographic analysis [14], three-dimensional digitization techniques [15–17], and three-dimensional electromagnetic-based measurements [18, 19] were developed. However, none thus far has been clinically accepted as a model for shoulder biomechanics.

Existing noninvasive approaches to tracking scapular motion have limitations. Because of the scapula's complex 3-dimensional kinematics and its mobility relative to the overlying skin, tracking the scapula using surface markers can be difficult and can produce systematic error [20]. Karduna et al present two noninvasive methods for measuring scapular orientation using surface cutaneous markers [21]. The first is a custom adjustable jig that attaches to the scapular spine [21–23]. The second method consists of applying an electromagnetic sensor to the skin over the acromion to track scapular motion [21]. While both methods offer reasonable validity in measuring scapular motion, with less than ten-degree error measuring between 30 and 120-degrees of humerothoracic elevation, the acromial projections were found to more accurately measure upward rotation of the scapula [21]. Although it is difficult to track the scapula using cutaneous methods, the advantages of this technique over other previous methodologies are ease of use and the noninvasive approach [24]. The use of an electromagnetic sensor on an acromion cluster has been found to be an effective method of tracking the scapula as validated by a recent study using bone pins [25]. Unfortunately, electromagnetic systems are limited both by the number of channels that can be simultaneously recorded, by requiring close proximity of the participant to the system's receiver, and by requiring that the participant be "wired" to the device. Video motion capture systems, in contrast, allow for simultaneous collection of additional segmental data (e.g., simultaneous capture of the humerus, thorax and neck), while reducing the proximity requirements. These factors ultimately led to the use of video motion capture in measuring shoulder kinematics.

The purpose of this investigation was to assess the accuracy of a method for measuring the three-dimensional dynamics of the shoulder complex utilizing video motion capture and reflective cutaneous markers affixed to the skin over the acromion process. This would provide an easy-to-use, noninvasive model for assessing shoulder biomechanics for use in studies of shoulder injury.

Methods

Participants

The protocol for data collection and participant interaction was approved by the Human Research Protection Office (HRPO). A convenience sample of nine healthy adults, consisting of four men and five women, was recruited by word of mouth. Participants were between 24 and 32 years of age (Table 1). Eight participants were right-handed; one left-handed.

Inclusion criteria included age 18 years or older and able to perform active humeral elevation of 135 degrees or more. Additionally, participants had to understand and follow verbal commands. Exclusion criteria included any history of upper extremity surgeries; injury to the upper extremity within the past 6 months; current upper extremity pain or movement restrictions; or an inability to hold the arm in static positions at 0, 30, 60, 90, and 120 degrees, and end-range, for up to one minute while being measured by an examiner.

Equipment

A six-camera video motion capture system recorded three-dimensional movements as each participant sat comfortably on a stool in the center of a room. An optical infrared motion capture system (Eagle-4 Digital RealTime System; Motion Analysis Corporation; Santa Rosa, CA) detected thirty-six 6mm diameter reflective markers attached to each participant, recording at 60 Hz. Positional data were later tracked and corrected offline (Cortex; Motion Analysis Corporation; Santa Rosa, CA).

A scapular jig (Figure 1a) was used to digitize scapula position during static trials [26]. The scapular jig consisted of two arms attached at an adjustable axis. Three apex markers were positioned on dull plastic digitizing pins corresponding to three vertices of the scapula: the acromion process, the root of the spine, and the inferior angle of the scapula. Custom-formed acromion triads (Figure 1b) were made from thermoplastic splint material (Rolyan 1/8" Polyform) for both the right and left acromion of each participant. These were created for each participant by palpating the acromial angle, acromioclavicular joint, and an arbitrary third bony acromion prominence – at the medial-posterior aspect of the acromion process, near its junction with the spine of the scapula. Markers were placed on each of the three corners of the triad to represent the location of each of these palpated landmarks. (Figure 1c)

Data Collection

Surface markers were placed on each participant at anatomically meaningful locations where subcutaneous tissues were thin to reduce marker movement artifacts. The inter- and intra-tester reliability of placing surface-based landmarks for video motion capture is high ($r=0.953$ and 0.957 , respectively) [27]. Markers were applied to the torso, arms and forearms in accordance with recommendations of the International Shoulder Group (ISG) of the International Society for Biomechanics (ISB) [28] (Figure 2). Additional markers were placed along the acromion triad (Figure 1b), scapula (Figure 1c), and the vertex and zygomatic processes of the head, to measure movement of the scapula and head with respect to the thorax, as described previously [29]. The use of an acromion triad has been demonstrated to have acceptable between-trial (within-session) reliability [30]. Prior to motion capture, the scapular marker sets were attached when the participant was in an anatomically neutral position to ensure consistent placement. Anatomic neutral was defined as having participants' arms relaxed at their sides, with forearms supine, with their backs comfortably straightened while seated on a stool with feet at shoulder width apart and knees bent at 90 degrees. After marker placement, the participants were seated in the center of the room, facing an investigator, and instructed to mirror the investigator in a series of planar upper extremity movements.

Participants began with a series of dynamic planar shoulder movements. Each participant performed the following three movements for three consecutive trials, first on one side then on the other: (1) humeral elevation in the coronal plane (humeral abduction), (2) humeral elevation in the sagittal plane (humeral flexion), and (3) humeral elevation in the scapular plane (humeral scaption). Humeral scaption was visually determined as 30 degrees anterior to the coronal plane of the thorax. Data were collected as the participant moved in concert

with the investigator at a consistent speed (1Hz) guided by an electronic metronome. Beginning from the anatomic neutral position, participants moved one arm at a time through the arc of the particular planar movement to end range to a count of three seconds, returning to anatomic neutral position along the same path at the same rate. The data were collected continuously at the rate of 60 Hz. A second investigator modeled the movements and timing which the subject would mirror, and provided verbal feedback to the participant and first investigator.

Following dynamic trials, static movements were collected for humeral abduction, flexion, and scapulation of the non-dominant upper extremity. Digitization with the jig was first performed by skin palpation of the three previously described bony landmarks of the scapula. Participants then elevated their arms to each of the following angles: anatomic neutral, 30°, 60°, 90°, 120°, and end-range, with angles confirmed by goniometer. Recording began once the jig was re-digitized in the new position. Elevation and digitization of the scapula took less than 60 seconds per trial, with 73% of trials being completed in under 30 seconds. On average, approximately one second of digitized data from each trial were used for the analyses. An overview of the testing process is available in Figure 3.

Kinematics Processing

All kinematics processing was performed using custom MATLAB scripts [29] derived from Chadwick [31] as described by the ISB [28]. A local coordinate system (LCS) was generated for the thorax, each scapula and each humerus in accordance with ISB guidelines [28]. The scapula LCS (Figure 1c) was defined as follows:

Origin _{scapula} :	Acromial angle.
Z _{scapula} :	The line connecting the root of the spine and the acromial angle, pointing toward the acromial angle.
X _{scapula} :	The line perpendicular to the plane formed by the inferior angle, acromial angle, and root of the spine, pointing forward.
Y _{scapula} :	The line perpendicular to X _{scapula} and Z _{scapula} , pointing upward.

The position of the inferior angle and spinal root of each scapula was defined relative to its respective acromion triad in the neutral trial. Virtual markers for the inferior angle and spinal root were generated based on these relationships and substituted for the surface markers.

To determine scapula position based on the digitized jig, markers on the jig corresponding to inferior angle, spinal root, and acromial angle were substituted for the surface markers.

Per Wu [28], glenohumeral variables included plane of elevation ($e1$), internal rotation ($e3$), and elevation ($e2$) (Table 2). Scapulothoracic variables included internal rotation ($e1$), anterior tilt ($e3$), and upward rotation ($e2$) relative to the LCS. All scripts were executed in MATLAB R2007b (The MathWorks Inc., 2007). Glenohumeral and scapulothoracic variables were analyzed at 30, 60, 90 and 120-degrees of humerothoracic elevation). For the sake of consistency, data from the non-dominant upper extremity only were considered in the current analysis.

Visual estimation of the scaption plane was confirmed by averaging the humerothoracic plane of elevation at 90° of humerothoracic elevation in the static scaption trials. Plane of elevation during scaption was 34(7) degrees (*mean(SD)*).

Statistical Analysis

A generalized linear model analysis of variance with repeated measures (ANOVA) was performed to detect differences between virtual scapular projections and the jig digitization. For all movement patterns, angular parameters were compared between static virtual projections and jig landmarks. Mean error between the two measurements was determined, and intraclass correlation coefficients (ICC) were calculated to assess consistency between the jig and projected values. The ICC determines the likelihood of the two data sets being from the same sample, as a measure of the consistency between the jig and projected angles. Measured angles included: glenohumeral plane (per Wu, “plane of elevation”), angle (“elevation”), and external rotation (“internal rotation”), as well as scapulothoracic external rotation, upward rotation, and anterior-posterior tilt (Table 2).

Data obtained from dynamic trials were not included in the statistical analysis due to the variability inherent in the unconstrained dynamic trials. Dynamic data were compared visually to static projected and jig values.

A post-hoc power analysis was performed to determine the potential for type II error in the presence of negative findings. The power analysis was performed in G*Power 3.1.2 software (Faul, Erdfelder, and Buchner, 2007). Assumptions included $\alpha = .01$, nine participants, and an effect size estimated at .2 based on the prior findings of van Andel et al [25].

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Results

For both humeral abduction and scaption movements, the acromial projection technique overestimated scapulothoracic upward rotation, while underestimating scapulothoracic anterior-posterior tilt (Figure 4). Glenohumeral plane was also overestimated, projecting the humerus further anterior as compared to jig projections. The degree of error amounted to less than ten degrees for each variable. Flexion trials were rendered unusable by missing data.

Linear analysis of variance (ANOVA) showed no statistically significant differences between static measurement techniques for glenohumeral plane and external rotation, and scapulothoracic external rotation, upward rotation and anterior-posterior tilt, for either

movement pattern at the 0.01 significance level (Table 3). ICC between the two models was greater than 0.5 for glenohumeral plane and angle, and scapulothoracic external rotation, across both movement patterns (Table 3). However, both the ICC and corresponding p-values decreased for scapulothoracic upward rotation and AP tilt for scaption patterns.

Dynamic projections of scapulothoracic upward rotation, anterior-posterior tilt, and external rotation, were within five-degrees of static projections for both abduction and scaption movements. Visual comparison revealed similar correlation patterns between dynamic and jig projections as to those between static and jig projections, as well. However, there was a lack of correlation between dynamic and static projections of glenohumeral plane, angle, and external rotation (Figure 4). Direct statistical comparison of the dynamic and static projections is precluded by the variability inherent in multiple trials of unconstrained movement [25].

The post-hoc power analysis revealed a β value of .95, suggesting high probability of type II error.

Discussion

The purpose of this study was to assess the utility of measuring the three-dimensional dynamics of the shoulder complex utilizing a video motion capture system and reflective cutaneous markers affixed to the skin over the acromion process. Limitations of this study include lack of power to confidently accept the null hypothesis, the physical homogeneity of the sample (Table 1), variability resulting from unconstrained movements by study participants, and differences between dynamic and static trials. Due to the subjectivity inherent in determining bony landmark locations, and because of the small size of the acromial triad, a small error in marker placement can magnify error in the projected virtual scapula. Consequently, the method requires a skilled professional experienced in palpating fine bony anatomy in order to be used in clinical practice. Additionally, a large proportion of flexion movement data were missing, possibly due to camera setup location. This has since been addressed by the acquisition of two additional cameras, improving line of sight on surface markers.

Previous investigations suggested the possibility of using digitized scapular projections in assessing strict planar shoulder movements via electromagnetic and optical tracking techniques [21, 25, 26]. The current work suggests the usefulness of video motion capture in assessing natural dynamic shoulder movements, unencumbered by forcing participants through restricted arcs typically seen in previous work.

Unlike previous studies, allowing participants to move naturally through the study movements resulted in increased intra- and inter-participant variability in humerus and scapular rotations when compared to results that might be obtained by forcing participants into unnatural positions to achieve more consistent planar movements. The greatest variability typically occurred at 30-degrees of humerothoracic elevation, for both abduction and scaption movements. These factors resulted in increased variability in both glenohumeral and scapulothoracic positioning.

Variation exists between the dynamic glenohumeral values as compared to the static projection and jig values (Figure 4). This results from the dynamic trials being completed separately from the static trials, and participants' individual variation in humeral movement during unrestrained dynamic movement patterns. Van Andel previously found even physically restricted planar shoulder movements can result in variable humeral positions, due to differences in wrist and elbow flexion, and thoracic rotation [25]. Scapular kinematics were consistent for jig, static projected, and dynamic projected values when achieving a set level of humerothoracic elevation.

Previous literature has shown the potential of using three-dimensional digitization techniques for measuring the motion of the scapula to analyze shoulder mechanics. Analogous methodology allows our results to be compared to Meskers' study using magnetic sensors [26], as well as to van Andel's [25] and Karduna's [21] studies using acromial sensors. Similar to previous findings [21, 25, 26], acromial projection was shown to be a validated technique for measuring internal-external rotation of the scapula during planar movements. Our results have similar error to van Andel's static acromial projections for humeral abduction, with deviations between the static projections and jig values averaging less than ten degrees (Figure 4). Similarly, there is increased variability and standard deviation in error toward the extremes of humerothoracic elevation (30-degrees and 120-degrees) for scapulothoracic upward rotation, external rotation, and anterior-posterior tilt. This contrasts somewhat with Meskers' findings, which show increasing error from 70 to 110-degrees of humeral elevation before lowering at higher degrees of humeral elevation. While the dynamic trials cannot be directly compared statistically to the static projections since they were recorded separately, the static and dynamic trials are empirically similar for the scapulothoracic variables.

The current work suggests that scapular projection from a reflective cluster affixed closely to the skin over the acromion produces a reasonable estimate of dynamic scapular movement during natural, unencumbered planar movements. The results are consistent with our previous work [28, 30, 32], which suggests the acromion projection method allows for greater ranges of scapulothoracic anterior-posterior tilt, internal-external rotation, and upward rotation, as compared to using surface markers alone. Humeral positioning as well as scapulothoracic external rotation are accurately assessed using this technique, while upward rotation of the scapulae tend to be overestimated for planar movement patterns.

One drawback of this technique is the relative overestimation of the contribution of the scapula to total shoulder movement during abduction and scaption movements. However, importantly, our results show similar error in humeral and scapular positioning for humeral scaption and abduction movements, indicating consistency during complex shoulder movements involving simultaneous rotations in all three planes of scapular movement. We believe the systematic overestimation of the upward rotation of the scapula relative to the humerus could be corrected for with a linear correction factor. A larger sample study may allow for a more accurate definition of this systematic error, and allow future recordings to simply be adjusted to the identified normal values based on the other virtual outputs.

The findings of this study suggest the usefulness of the acromial projection of the scapulae in video motion capture analysis of shoulder dynamics. The study confirms that, similar to results obtained from electromagnetic methodology, acromial projections via video motion capture closely approximate shoulder positioning data obtained using goniometry. The statistical correlation between the virtual scapular projections and digitized markers serves to validate this technique as a useful, reproducible method for quickly assessing dynamic shoulder kinematics, although the study was underpowered to confidently accept this result. This technique could prove useful for analyzing shoulder dynamics and movement patterns for a wide variety of shoulder pathology, from injury to movement abnormalities caused by diseases and shoulder impingements. Future research could include additional fixed structures, such as the anterior border of the clavicle, in the model to increase clinical utility and decrease the possibility of error produced by individual marker misplacement.

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Bibliography

1. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Phys Ther.* 2000 Mar; 80(3):276–291. [PubMed: 10696154]
2. McClure PH, Michener LA, Karduna AR. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. *Phys Ther.* 2006 Aug; 86(8):1075–1090. [PubMed: 16879042]
3. Michener LA, McClure PW, Karduna AR. Anatomical and biomechanical mechanisms of subacromial impingement syndrome. *Clin Biomech (Bristol, Avon).* 2003 Jun; 18(5):369–379.
4. Mell AG, LaScalza S, Guffey P, Ray J, Maciejewski M, Carpenter JE, et al. Effect of rotator cuff pathology on shoulder rhythm. *J Shoulder Elbow Surg.* 2005 Jan-Feb; 14 Suppl S(1):58S–64S. [PubMed: 15726088]
5. Illyes A, Kiss RM. Kinematic and muscle activity characteristics of multidirectional shoulder joint instability during elevation. *Knee Surg Sports Traumatol Arthrosc.* 2006 Jul; 14(7):673–685. [PubMed: 16362361]
6. Rundquist PJ. Alterations in scapular kinematics in subjects with idiopathic loss of shoulder range of motion. *J Orthop Sports Phys Ther.* 2007 Jan; 37(1):19–25. [PubMed: 17286095]
7. Vermeulen HM, Stokdijk M, Eilers PHC, Meskers CGM, Rozing PM, Vliet Vlieland TPM. Measurement of three dimensional shoulder movement patterns with an electromagnetic tracking device in patients with a frozen shoulder. *Ann Rheum Dis.* 2002 Feb; 61(2):115–120. [PubMed: 11796396]
8. Gomes PF, Sesselmann M, Faria C, Araujo PA, Teixeira-Salmela LF. Measurement of scapular kinematics with the moire fringe projection technique. *J Biomech.* 2010 Apr; 43(6):1215–1219. [PubMed: 20097346]

9. Inman VT, Saunders JB, Abbot LC. Observations of the function of the shoulder joint. 1944. Clin Orthop Relat Res. 1996 Sep;(330):3–12. [PubMed: 8804269]
10. Freedman L, Munro RR. Abduction of the arm in the scapular plane: scapular and glenohumeral movements. A roentgenographic study. J Bone Joint Surg Am. 1966 Dec; 48(8):1503–1510. [PubMed: 5955639]
11. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am. 1976 Mar; 58(2):195–201. [PubMed: 1254624]
12. de Groot JH, Valstar ER, Arwert HJ. Velocity effects on the scapulo-humeral rhythm. Clin Biomech (Bristol, Avon). 1998 Dec; 13(8):593–602.
13. de Groot JH. The scapulo-humeral rhythm: effects of 2-D roentgen projection. Clin Biomech (Bristol, Avon). 1999 Jan; 14(1):63–68.
14. Hogfers C, Peterson B, Sigholm G, Herberts P. Biomechanical model of the human shoulder joint--II. The shoulder rhythm. J Biomech. 1991; 24(8):699–709. [PubMed: 1918093]
15. Ludewig PM, Cook TM, Nawoczenski DA. Three-dimensional scapular orientation and muscle activity at selected positions of humeral elevation. J Orthop Sports Phys Ther. 1996 Aug; 24(2): 57–65. [PubMed: 8832468]
16. van der Helm FC, Pronk GM. Three-dimensional recording and description of motions of the shoulder mechanism. J Biomech Eng. 1995 Feb; 117(1):27–40. [PubMed: 7609482]
17. Pearl ML, Jackins S, Lippitt SB, Sidles JA, Matsen FAI. Humeroscapular positions in a shoulder range of motion examination. J Shoulder Elbow Surg. 1992 Feb; 1(6):296–305. [PubMed: 22959252]
18. McQuade KJ, Smidt GL. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. J Orthop Sports Phys Ther. 1998 Feb; 27(2): 125–133. [PubMed: 9475136]
19. Finley MA, Lee RY. Effect of sitting posture on 3-dimensional scapular kinematics measured by skin-mounted electromagnetic tracking sensors. Arch Phys Med Rehabil. 2003 Apr; 84(4):563–568. [PubMed: 12690596]
20. Matsui K, Shimada K, Andrew PD. Deviation of skin marker from bone target during movement of the scapula. J Orthop Sci. 2006 Mar; 11(2):180–184. [PubMed: 16568391]
21. Karduna AR, McClure PW, Michener LA, Sennett B. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J Biomech Eng. 2001 Apr; 123(2):184–190. [PubMed: 11340880]
22. Ebaugh DD, McClure PW, Karduna AR. Scapulothoracic and glenohumeral kinematics following an external rotation fatigue protocol. J Orthop Sports Phys Ther. 2006 Aug; 36(8):557–571. [PubMed: 16915977]
23. Suprak DN, Osternig LR, van Donkelaar P, Karduna AR. Shoulder joint position sense improves with external load. J Mot Behav. 2007 Nov; 39(6):517–525. [PubMed: 18055357]
24. Rab G, Petuskey K, Bagley A. A method for determination of upper extremity kinematics. Gait Posture. 2002 Apr; 15(2):113–119. [PubMed: 11869904]
25. van Andel C, van Hutten K, Eversdijk M, Veeger D, Harlaar J. Recording scapular motion using an acromion marker cluster. Gait Posture. 2009 Jan; 29(1):123–128. [PubMed: 18815043]
26. Meskers CGM, van de Sande M, de Groot J. Comparison between tripod and skin-fixed recording of scapular motion. J Biomech. 2007; 40(4):941–946. [PubMed: 16584738]
27. Engsberg J, Lenke LG, Reitenbach AK, Hollander KW, H BK, Blanke K. Prospective Evaluation of Trunk Range of Motion in Adolescents with Idiopathic Scoliosis Undergoing Spinal Fusion Surgery. Spine. 2002; 27(12):1346–1354. [PubMed: 12065985]
28. Wu G, van der Helm F, Veeger HEJ, Makhssous M, Van Roy P, Anglin C, et al. ISB recommendations on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. J Biomech. 2005; (38):981–992. [PubMed: 15844264]
29. Janes WE, Brown JM, Essenberg JM, Engsberg JR. Development of a method for analyzing three-dimensional scapula kinematics. 2011

30. Barnett ND, Duncan RD, Johnson GR. The measurement of three dimensional scapulohumeral kinematics - a study of reliability. *Clinical Biomechanics*. 1999 May; 14(4):287–290. [PubMed: 10619117]
31. Chadwick. [cited 2010] ISG Code. [Online]. 2010. Available from: <http://trac.assembla.com/isgcode/browser/kinematics>.
32. Yee, A.; Janes, WE.; Essenberg, JM.; Saheb-Al-Zamani, M.; MacKinnon, SE.; Brown, JM. Objective quantification of scapular kinematics using an infrared motion capture system. Presented at the ASPN Annual Meeting, Boca Raton, FL; Boca Raton, FL. 2010 Jan.

Figure 1.
Photographs of (a) jig and (b) acromial triad and (c) diagram of scapula local coordinate system.

Figure 2.

Posterior view of participant with surface markers affixed to palpated bony landmarks. Markers are accentuated by the use of an led flash for the purpose of this photograph. Note that three markers on each acromion process are affixed via the thermoplastic acromion triad.

Figure 3.
Sequence of testing events.

Abduction *Scaption* **Figure 4.**

Comparison of static and dynamic acromial projections to jig standard during abduction and scaption. Vertical axes are measured values in degrees. Horizontal axes are in degrees humerothoracic elevation.

Table 1

Participant information

Variable	Mean	Standard Deviation
Weight	72kg	10kg
Height	180cm	12cm
BMI	21.2	7
Age	24 – 32 years	

Table 2

Descriptions of measured angles

Kinematic Variable	Rotation Order	Rotation Axis	Description
Humerothoracic			
Elevation	Y-X-Y	<i>e2</i>	Rotation about the anterior-posterior axis of the humerus
Scapulothoracic			
Internal Rotation	Y-X-Z	<i>e1</i>	Rotation about the vertical axis of the thorax
Anterior Tilt	Y-X-Z	<i>e3</i>	Rotation about the horizontal axis of the scapula
Upward Rotation	Y-X-Z	<i>e2</i>	Rotation about the axis perpendicular to <i>e1</i> and <i>e3</i>
Glenohumeral			
Plane of Elevation	Y-X-Y	<i>e1</i>	Rotation about the vertical axis of the scapula
Internal Rotation	Y-X-Y	<i>e3</i>	Rotation about the longitudinal axis of the humerus
Elevation	Y-X-Y	<i>e2</i>	Rotation about the anterior-posterior axis of the humerus

Table 3

Linear ANOVA Results and Intra-class Correlation Coefficient

Parameter	Abduction			Scaption		
	F	p	ICC	F	p	ICC
GH Plane	0.119	0.073	0.79	0.085	0.037	0.81
GH Angle	0.017	0.045	0.70	0.146	0.008	0.68
GH ExtRot	0.798	0.918	0.00	0.614	0.010	0.38
ST ExtRot	0.322	0.139	0.87	0.451	0.314	0.95
ST UpRot	0.006	0.055	0.49	0.298	0.021	0.33
ST APtilt	0.474	0.015	0.54	0.648	0.015	0.13

Note. GH Plane=Glenohumeral Plane. GH Angle = Glenohumeral Angle. GH ExtRot = Glenohumeral External Rotation. ST ExtRot = Scapulohoracic External Rotation. ST UpRot = Scapulohoracic Upward Rotation. ST APtilt = Scapulohoracic Anterior-Posterior Tilt.