Development of a method for analyzing three-dimensional scapula kinematics

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Abstract

Background Scapula mobility complicates upper extremity kinematics assessment. Existing methods are diverse, providing inconsistent results. The current gold standard (bone pins) is prohibitively invasive. The purposes of the current study are to describe a virtual projection alternative to surface markers for video motion capture (VMC) of the scapula and to compare the results of the projection and surface marker methods to the results of similar existing methods.

Methods Ten participants were evaluated using VMC. Surface markers were applied to the trunk and arm in accordance with existing guidelines. Three markers were affixed to plastic base on the skin over the acromion process. Other scapular landmarks were digitized in a neutral position. These landmarks' locations were defined in reference to the acromion cluster and used to generate the projection. Humerothoracic, glenohumeral, and scapulothoracic kinematics were evaluated

during shoulder abduction, flexion, and scaption. Joint angles produced by the surface markers and the projection were compared by Bonferroni-adjusted *t* tests. The results were compared to prior findings in the literature.

Results The projection resulted in greater scapulothoracic upward rotation, internal rotation, and anterior–posterior tilt and less glenohumeral elevation ($p < .0055$) than did surface markers. The virtual scapula produced greater estimates of scapular mobility than did surface markers, corresponding to pre-existing results from similar methodologies.

Conclusions The result is a noninvasive measurement tool that produces different and superior results than do scapula surface markers. Measuring scapula kinematics via VMC without bone pins will facilitate future investigations into interactions between upper extremity injury, kinematics, and activity performance.

Keywords Biomechanics · Kinematics · Shoulder · Scapula

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Introduction

Altered shoulder biomechanics are both the cause and a potential result of numerous musculoskeletal and neurological injury processes throughout the upper extremity (UE). Great effort has been expended attempting to quantify the biomechanics associated with musculoskeletal disorders including frozen shoulder [24] and rotator cuff injuries [16]. In turn, these kinematic deficits can contribute to further pain and injury. Nerve injuries ranging from brachial plexus [6] to spinal cord injuries [21] and stroke [18] often lead to dramatically altered shoulder kinematics. Kinematic alterations in the axilla and proximal UE have also been implicated in distal neuropathy via thoracic outlet syndrome [19] and multilevel nerve compression [20]. Adequate measurement and assessment of any such conditions demands a noninvasive measurement tool capable of quantifying complete UE, including scapular, kinematics during active movement.

Numerous methods have been proposed for collecting in vivo UE movement data. Early work relied on goniometry, radiography, and cinematography to describe shoulder kinematics [2, 8, 13]. More recently, three-dimensional (3D) motion capture has been employed for the evaluation of shoulder kinematics [9, 17, 23]. Previous work includes evaluations of “normal” shoulder mechanics in cadavers [4] and healthy persons [22] as well as descriptions of movement in persons with orthopedic injuries [12]. The methods employed in these studies have been diverse, with little consensus on marker placements and evaluation methods.

To minimize the heterogeneity of methods, the International Society for Biomechanics (ISB) published the first clear guidelines for the collection and analysis of in vivo UE motion capture data [25]. This attempt to clarify and codify UE motion capture studies has not been consistently implemented, in part due to the difficulty of noninvasively measuring scapula position during dynamic movement. Surface markers are inadequate for tracking scapular movement because the scapula is irregular in shape and moves independently of the skin, particularly in the plane of the thorax. As a result dynamic shoulder position has typically been interpolated from static positions measured throughout the range of motion [1]. Such methods are time-consuming and have not been sufficiently validated against dynamic movement. Additionally, such techniques preclude measurements of scapular dynamics during normal activities or fluid movements.

Dynamic measurement of scapula movement can be most reliably accomplished with the use of bone pins [3, 9]. Bone pins are invasive and uncomfortable, precluding their use in minimal-risk studies of shoulder movement. Since the acromion process is relatively superficial and moves closely with the skin, it provides a site for accurate scapula tracking. Acromion tracking methods to date have utilized electromagnetic [17] and visual (Optotrak) motion capture [23] sensors affixed to the surface of the acromion process. Tracking the scapula via an electromagnetic sensor on the acromion process has been validated against bone pins [15]. Electromagnetic systems are bulky, require participants to remain close to the receiver, and limit the number of segments that can be measured simultaneously.

Video motion capture has the potential to record dynamic scapula kinematics using markers affixed noninvasively to the surface of the acromion process. The scalability of video motion capture allows for simultaneous recording of thorax, head, bilateral scapulae, and bilateral UE kinematics. The ability to simultaneously measure all segments of the kinematic chain, including the scapula, has potential applications in injury evaluation, treatment planning, and outcomes assessment. The purposes of the current study were to describe a virtual projection alternative to surface markers for video motion capture of the scapula and to compare the results of the projection and surface methods to the results of similar existing methods.

Methods

Participants

Ten participants (24 ± 1.4 years, 4 men and 6 women) were evaluated for this investigation. All individuals provided informed consent in accordance with the institutional review board of the university. All reported no history of UE surgery and were free of UE pain or pathology.

Kinematic Data Collection System

Kinematic data were collected using a 3D video motion capture system [Motion Analysis Corporation (MAC), Santa Rosa, CA, USA]. Six “Eagle” digital cameras detected the location of spherical reflective markers attached to the skin of each individual at 60 Hz. Input from each camera was compiled by EVa Real-Time (EVaRT) software, version 5.0.4 (MAC).

Marker Set

Twenty-two 6-mm diameter spherical reflective markers, each with a 7-mm circular base, were utilized. The marker set for the current study (Table 1) was based on ISB guidelines [25]. With few exceptions (explained below), markers were affixed directly to the skin over palpated bony landmarks using a two-sided tape. Markers on the medial and lateral epicondyles and olecranon processes were applied with elbows flexed to 90°. All other markers were applied with participant seated, UEs in anatomical position.

To facilitate tracking of the scapula, acromion bases were formed from 1/8" Polyform splint material (Sammons

Table 1 Bony landmarks for marker placement

Segment	Bony landmark
Thorax	C7 spinous process
	T8 spinous process
	Sternal notch
	Xiphoid process
Scapula	Root of the spine
	Inferior angle
	Acromioclavicular joint ^a
	Acromial angle ^a
	Third acromion ^a
Humerus	Corocoid process
	Lateral epicondyle
	Medial epicondyle
	Olecranon process of the ulna

^a Indicates markers attached via thermoplastic acromion base

Preston, Bolingbrook, IL, USA) (Fig. 1). Investigators palpated three easily identifiable landmarks on the flat superior surface of the acromion process: (1) the acromioclavicular joint, (2) the lateral or acromial angle, and (3) an arbitrary third acromion point approximately 2 cm medial to the acromial angle. These points were marked with an ink pen. The resulting triangle was traced to a paper towel and subsequently to the splint material. The material was heated and cut. Markers were affixed to the triangle vertices. When cooled, the triangle was reapplied to the acromion to ensure that markers lay directly superficial to their respective landmarks. The triangle was reshaped as needed to ensure fit.

Once both acromion triads were formed and all other markers affixed, each participant was instructed to sit with upper extremities in the anatomical position. Both acromia were palpated one final time, and the Polyform triads were affixed to their respective locations by the two-sided tape. The remaining scapula landmarks were palpated and markers affixed. Before the movement battery began, two sets of initial static data were collected. These trials assisted with data processing and were not for evaluation.

Movement Battery

Three shoulder movements were evaluated: flexion, abduction, and scaption. Flexion refers to elevation of the arm in the sagittal plane. Abduction refers to elevation of the arm in the frontal plane. Scaption refers to elevation of the arm in a plane coincident with the broad, flat planar surface of the scapula. Each trial was designed to last approximately 6 s. A metronome set to 1 Hz aided in timing of the movements. A researcher sat facing the participant and performed each movement in time with the metronome as a visual guide. For each trial, participants were instructed to start by sitting comfortably with hands in lap ($\leq$ second 0), move bilateral UE into anatomical position (second 0–1), perform the

movement with the target UE (seconds 1–3), reverse the movement to return the UE to anatomical position (seconds 3–5), and return to the starting position (second 5–6). The contralateral UE remained stationary in the anatomical position during the task. Each movement was performed twice on each side. No external restrictions were placed on the participant to force adherence to a distinct planar movement.

Data Processing

Raw surface marker data were labeled, tracked, and verified using the EVaRT software. Kinematic variables were calculated using MATLAB scripts provided by Chadwick as described by the ISB [5, 25] (Table 2). All scripts were executed in MATLAB R2007b (The MathWorks, 2007). MATLAB processing resulted in one text file for each 6 s (approximately 360 frames) trial.

A local coordinate system (LCS) was generated for the thorax, each scapula, and each humerus in accordance with ISB guidelines [25]. The scapula LCS warrants additional explanation and was defined as shown in (Fig. 2.).

Two methods (surface and virtual) were used to define the scapula LCS (Fig. 2). In the surface method, markers placed directly over the palpated root of the spine and inferior angle were used to generate the LCS definition. In the virtual method, 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 interior angle and spinal root were generated based on these relationships and substituted for the surface markers.

Each trial was trimmed to approximately 2 s of data corresponding to the upward phase of the movement. Trimmed data started at the minimum point of humerothoracic elevation in the first half of the trial (approximately second 1, frame 60) and ended at the maximum point of humerothoracic elevation (approximately second 3, frame 180).

Fig. 1 Sample thermoplastic acromion bases **a** in isolation and **b** affixed to the right shoulder of a participant

Table 2 Kinematic variable definitions, adapted from Wu et al. [25]

Movement	Definition
Humerothoracic	(Y–X–Y rotation order)
Plane of elevation	e 1: Longitudinal axis of the humerus about the vertical axis of the thorax
Internal rotation	e 3: Axial rotation about the longitudinal axis of the humerus
Elevation	e 2: About the anterior–posterior axis of the humerus
Scapulothoracic	(Y–X–Z rotation order)
Internal rotation	e 1: Vertical axis of the scapula about the vertical axis of the thorax
Anterior–posterior (A–P) tilt	e 3: About the medial–lateral axis of the scapula
Upward rotation	e 2: About the axis perpendicular to e 1 and e 3
Glenohumeral	(Y–X–Y rotation order, Euler decomposition)
Plane of elevation	e 1: Longitudinal axis of the humerus about the vertical axis of the scapula
Internal rotation	e 3: Axial rotation about the longitudinal axis of the humerus
Elevation	e 2: About the anterior–posterior axis of the humerus

Analysis 1: Comparison of Virtual Scapula to Surface Markers

Maximal range of each humerothoracic, scapulothoracic, and glenohumeral kinematic variable was defined as the difference between the maximum and minimum values achieved across both trials of each movement for each

individual. Within each movement (abduction, flexion, scaption), Bonferroni-corrected *t* tests were used to detect differences between surface and virtual methods for each kinematic variable.

Analysis 2: Comparison of Kinematic Ranges to Pre-existing Values

Ranges generated by both the surface and virtual methods were compared with previous results generated by diverse methods to provide context for the current findings. Previous methods include 2D radiography [8], 3D radiography [11], optical motion capture [23], electromagnetic motion capture [7, 14, 15], and video motion capture (current investigation). The diversity of methods for recording and reporting kinematic data precluded quantitative comparisons.

Results

Analysis 1: Comparison of Virtual Scapula to Surface Markers

Across all three movements, the virtual scapula method resulted in significantly greater range of scapulothoracic movement in all three directions and less glenohumeral elevation (Table 3). No differences were detected between methods for any humerothoracic variables.

Analysis 2: Comparison of Kinematic Ranges to Pre-existing Values

As expected, the total range achieved by the surface method generally fell at the low end of previously reported ranges, and external rotation was particularly underestimated by the surface method (Table 4). The virtual scapula method achieved a total range that fell at or above the high end of previously reported ranges, particularly in upward rotation and external rotation. The virtual method results closely matched those achieved previously with bone pins [3] for upward rotation and external rotation, but not anterior–posterior tilt. These findings closely match the agreements noted between the bone pins of Bourne et al. and that of McClure et al. [15] electromagnetic motion capture results. Additionally, the virtual method most closely resembled the electromagnetic motion capture results of McClure et al. [15], with agreement between 2° (external rotation during scaption) and 9° (anterior tilt during scaption) of McClure's reported ranges. This agreement is expected, given the similarity of methods described. The lack of agreement regarding scapulothoracic anterior tilt is explored in “Results,” below.

The virtual method agreed least with the results of van Andel et al. [23], with the exception of external rotation during

Fig. 2 Scapula LCS. 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

Table 3 Range of motion in degrees for all kinematic variables across each movement [mean (standard deviation)]

	Abduction		Flexion		Scaption	
	Surface	Virtual	Surface	Virtual	Surface	Virtual
Humerothoracic						
Plane of elevation	98 (37)	93 (34)	112 (36)	111 (36)	102 (40)	96 (37)
Elevation	146 (5)	141 (5)	146 (4)	141 (4)	147 (5)	143 (5)
External rotation	82 (26)	80 (27)	88 (23)	90 (26)	89 (29)	86 (32)
Glenohumeral						
Plane of elevation	105 (30)	101 (31)	110 (55)	115 (57)	124 (46)	107 (64)
Elevation	111 (10)	92 (10)*	117 (7)	92 (10)*	116 (7)	91 (15)*
External rotation	93 (34)	95 (41)	107 (49)	106 (55)	108 (47)	96 (59)
Scapulothoracic						
External rotation	7 (5)	23 (5)*	16 (4)	34 (7)*	11 (3)	26 (12)*
Upward rotation	38 (7)	55 (15)*	33 (7)	54 (15)*	37 (7)	57 (14)*
A–P tilt	8 (4)	21 (7)*	9 (3)	25 (10)*	9 (3)	21 (4)*

* $p < .0055$, significant difference at the Bonferroni-corrected α

abduction, for which there was no disagreement. Otherwise, the virtual method and van Andel et al. [23] agreed from within 11° (external rotation during flexion) to 27° (upward rotation during abduction). This lack of agreement is to be expected given the differences in the motion capture technology used and the limitation of humerothoracic elevation to 120° by van Andel et al.

Discussion

The purposes of this investigation were to describe a method for measuring scapula movement using video motion capture and to compare the results of that method to previously reported results using similar methods.

Table 4 With the exception of Inman's seminal work, the studies below are those that used 3D motion capture methods to measure scapulothoracic kinematics during movement in live, healthy controls and that reported numerical results sufficient to calculate ranges

Movement	Method	HT limit	Anterior tilt	Upward rotation	External rotation
Abduction					
Inman 1944	2D radiograph	30°–150°		40	
Bourne 2007	Optoelectric	Unknown	44	49	27
van Andel 2009	Optotrak	Min–120°	–0.3	28	23
<i>Surface method</i>	<i>VMC</i>	<i>Min–max</i>	8	35	7
<i>Virtual method</i>	<i>VMC</i>	<i>Min–max</i>	21	55	23
Flexion					
Inman 1944	2D radiograph	30°–150°		50	
McClure 2001	Electromagnetic	16°–153°	31	46	26
van Andel 2009	Optotrak	Min–120°	–1.4	28	23
<i>Surface method</i>	<i>VMC</i>	<i>Min–max</i>	9	33	16
<i>Virtual method</i>	<i>VMC</i>	<i>Min–max</i>	25	54	34
Scaption					
Kondo 1984	3D radiograph	0°–max	24	60	8
Ludwig 1996	Electromagnetic	0°–140°	15	34	13
McClure 2001	Electromagnetic	11°–147°	30	50	24
Ebaugh 2005	Electromagnetic	Min–max	3	54	4
<i>Surface method</i>	<i>VMC</i>	<i>Min–max</i>	9	37	11
<i>Virtual method</i>	<i>VMC</i>	<i>Min–max</i>	21	57	26

Also included are the surface and virtual methods of the current work. Not included are those that used non-3D methodology, included cadavers or musculoskeletal injuries, interpolated values from static positioning, or reported results only graphically or in terms of differences between methods. Values indicate total range (in degrees) of excursion in each of three scapulothoracic rotations. Methods in italics refer to the current investigation

Utilizing the existing ISB marker set facilitates replicable placement of surface markers. The use of a thermoplastic acromion triad obviates the need for bone pins or interpolation of static data. The processing stream for data analysis is based on freely available code. The resulting output allows for complex evaluations of shoulder kinematics in clinically relevant terms. The resulting description of shoulder kinematics is remarkably similar to previous findings using similar methods. This appears to be the first system that combines these attributes into a single method for dynamic kinematic analysis using video motion capture. Combined with the advantage of scalability inherent in video motion capture systems relative to other forms of motion capture, this method leverages ISB standards to provide for robust motion capture of the entire UE during unconstrained movement.

A number of limitations can be identified in the present study. Relatively large standard deviations, particularly in the glenohumeral and humerothoracic range variables, suggest a heterogeneous sample with no restrictions placed on their movement. Alternatively, this variability may be attributed in part to an artifact of skin movement independent of the bone itself. Similar methods using bone pins have validated acromial estimation of scapula movement up to 120° of humerothoracic elevation [10]. Most works to date have similarly limited the total humerothoracic range considered to minimize variability. Artificially limiting range of motion may explain the lack of agreement between van Andel et al. [23] and the current work, despite their similar motion capture methodology. It is not surprising that ranges achieved in the current work generally exceed those achieved in more restricted ranges of humerothoracic motion. Of the studies described in Table 4, only McClure et al. [15] and Bourne et al. [3] used bone pins and did not limit range of motion. That their results generally agree with those of the virtual method is encouraging.

Disagreement in anterior tilt as measured by Bourne et al. and the virtual method replicates the disagreement between the measurement of Bourne et al. and that of McClure et al. for the same variable using bone pins. Bourne's group recognized this error and attributed it to differences in movement performed and coordinate system definition. This explanation bolsters the finding of agreement between the virtual method and that of McClure et al., while suggesting that disagreement with that of Bourne et al. should not necessarily be viewed as a limitation. Indeed, much of the variability between previous measurements (Table 4) may be attributable to diversity of methods, as all but van Andel et al. [23] preceded the ISB guidelines.

More rigorous statistical comparisons to previous work are rendered impossible by the tendency to report only means and differences, often without standard deviations or original range values. The authors acknowledge the existence of similar studies of motion capture methods focusing on the use of

the acromion process as a proxy for scapula kinematics (most notably [10] and [17]). Those works report only differences between values obtained via two methods rather than the values themselves, again preventing their inclusion in the current analysis.

The current work adds to the body of knowledge by describing a noninvasive, nonrestrictive method for video motion capture of the scapula, which is more sensitive to in vivo scapulothoracic kinematics than is the use of surface markers. The virtual method presented here appears to be among the more sensitive techniques for measuring scapulothoracic kinematics.

The clinical relevance of this method is the provision of a noninvasive measurement tool for unrestricted dynamic scapula movement. Sensitively measuring scapula kinematics in relation to adjacent body segments via video motion capture is a critical step in quantifying biomechanics in persons with a variety of UE conditions, including musculoskeletal injuries, nerve entrapments, spinal cord injury, and stroke, among others. This system will facilitate future investigations into the interactions among injury (regardless of mechanism), shoulder kinematics, and performance of everyday activities.

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