Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements

Yungchien Chu[a], Jon Akins[a], Mita Lovalekar[a], Scott Tashman[b], Scott Lephart[a], Timothy Sell[a,*]

[a] Neuromuscular Research Laboratory, University of Pittsburgh, 3830 South Water St. Pittsburgh, PA 15203, United States
[b] Orthopaedic Biodynamics Laboratory, University of Pittsburgh, 3820 South Water St. Pittsburgh, PA 15203, United States

ARTICLE INFO

Article history:
Accepted 24 June 2012

Keywords:
Scapular kinematics
Validation
Motion analysis

ABSTRACT

Background: Current non-invasive 3-D scapular kinematic measurement techniques such as electromagnetic tracking are subjected to restrictions of wired sensors and limited capture space. Video-based motion analysis provides greater freedom with relatively less movement restriction. However, video-based motion analysis was rarely used in and not validated for scapular kinematics.
Methods: Scapular kinematics of five subjects performing abduction, scaption, and internal/external rotation was captured simultaneously with video-based motion analysis and dynamic stereo X-ray, a gold standard for tracking scapular movements. The data from video-based motion analysis was correlated with the data from dynamic stereo X-ray for validity evaluation.
Findings: Strong and significant correlations were identified in scapular protraction/retraction and medial/lateral rotation during abduction and scaption, and scapular medial/lateral rotation and anterior/posterior tilt during internal/external rotation.
Interpretation: Video-based motion analysis is valid for evaluating a single subject's scapular movement pattern in protraction/retraction during abduction and scaption, and medial/lateral-rotation during internal/external rotation. Anterior/posterior-tilt during abduction and scaption should be investigated with caution. Video motion analysis is also valid for evaluating group average of scapular kinematics except for protraction/retraction during internal/external rotation. While acknowledging the inherent limitations, video-based motion analysis is an appropriate technique for tracking scapular kinematics.

1. Introduction

Individuals frequently suffer shoulder injuries due to repetitive overhead motion during sports, occupational, and recreational activities. Many of these injuries result in functional impairment and significant healthcare costs (Savoie III et al., 1995; Mckee and Yoo, 2000). Coordinated movement between the scapula and the humerus is essential for normal function and dynamic stability of the glenohumeral joint (Kibler, 1998). Accurate assessment of scapular movements is critical for injury prevention, risk factor identification, and rehabilitation/treatment design for subjects with shoulder injuries. Multiple methods have been used to assess scapular kinematics. However, many of the methods have inherent limitations including 2-D measures (Michiels and Grevenstein, 1995; Mcquade et al., 1998), radiation exposure (Bey et al., 2006; Karduna et al., 2001), limited dynamic measurement capacity (de Groot et al., 1998), and movement restriction (Meyer et al., 2008). Among methods that are non-invasive and capable of 3-D measurements, skin-based electromagnetic tracking is the most prevalent in research settings. Numerous studies have contributed to a better understanding in normal, pathological, adapted, and fatigued scapular kinematics with data collected using electromagnetic systems (Borstad and Ludewig, 2002; Laudner et al., 2006; Ludewig and Cook, 2000; Mcclure et al., 2006; Mcquade et al., 1998; Myers et al., 2005; Tsai et al., 2003). The major limitations of utilizing these systems are that the motion capture volume and the movement of the subject may be restricted due to the wired sensors and the movement of the cables can induce noise in the recorded signals (Meyer et al., 2008). Video-based motion analysis (VMA) has the advantages of being a 3-D, non-invasive, and dynamic measurement with relatively less movement restriction. Despite these strengths, its application in scapular kinematics measurement has not been validated.

Video-based motion analysis, one of the most widely used technologies in general kinematic research, is a wireless technology offering greater freedom of movement. However, attempts to apply VMA in the measurement of scapular kinematics have been limited. In a pilot study, we established the concurrent validity of the technique by demonstrating that scapular kinematics measured with a VMA system were highly correlated ($R > 0.950$) with data from an electromagnetic tracking system. We also determined that compared with electromagnetic tracking, VMA had

---

[*] Corresponding author. Tel.: +1 4122460460.
E-mail address: tcs15@pitt.edu (T. Sell).

0021-9290/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2012.06.025

Please cite this article as: Chu, Y., et al., Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements. Journal of Biomechanics (2012), http://dx.doi.org/10.1016/j.jbiomech.2012.06.025

similar inter-trial reliability (ICC 0.947 vs. 0.937) and significantly better precision (SEM 0.94 vs. 1.23, $p < 0.001$) in scapular kinematic measurements. Despite these findings, this scapular kinematic measurement technique using VMA has not been validated against a gold standard.

With the improvement of hardware capacity, we believe that VMA can now realize its potential in assessing scapular movement. Therefore, the purpose of the current study was to validate the VMA scapular kinematic measurement technique against a gold standard, Dynamic stereo X-ray (DSX), which can provide direct, high-accuracy measurements of bone motion. We hypothesized that high correlations ($R > 0.70$) in the scapular kinematic patterns would exist between the VMA and DSX data. If validated and with the high prevalence of VMA systems in biomechanical laboratories, more researches can be conducted, stimulating research variability and quantity.

2. Methods

2.1. Subjects

Five right handed, healthy, and physically active male subjects (age = 27.8 ± 6.9 yr; Ht = 181.0 ± 4.9 cm; Wt = 77.9 ± 9.5 kg) volunteered to participate in this study. All subjects had no history of musculoskeletal injury to the upper extremity within 3 months before their participation and no history of any upper extremity joint reconstructive surgery. All subjects provided informed consent in accordance with the University's Institutional Review Board.

2.2. Instrumentation

In this study, the DSX model-matching technique, a gold standard for measuring scapular kinematics (Bey et al., 2006), was used to validate the VMA technique. The DSX system (Fig. 1) included two 100 kW pulsed X-ray generators (EMD Technologies, Quebec, Canada), two 40 cm image intensifiers (Thales, Neuilly-sur-Seine, France), and two high-speed video cameras (Vision Research, Wayne, NJ, USA) that were synchronized together. The system was configured with an inter-beam angle of approximately 60°. Both beams were aimed at the dominant shoulder of the subject to capture X-ray images of the scapula and humeral head. The distance between the X-ray sources and the subject was approximately 100 cm and the distance between the subject and the image intensifiers was about 50 cm. In this study, the system was set to capture at 50 Hz using a pulsed protocol (2 ms pulses, 70kVp, up to 160 mA). Total radiation exposure from DSX testing was less than 7 mGy. A Vicon Nexus motion capture system with eight high-speed cameras (Vicon, Oxford, UK) was used for VMA. The VMA system was also set at 50 Hz and synchronized with the DSX system using a trigger allowing for simultaneous data collection.

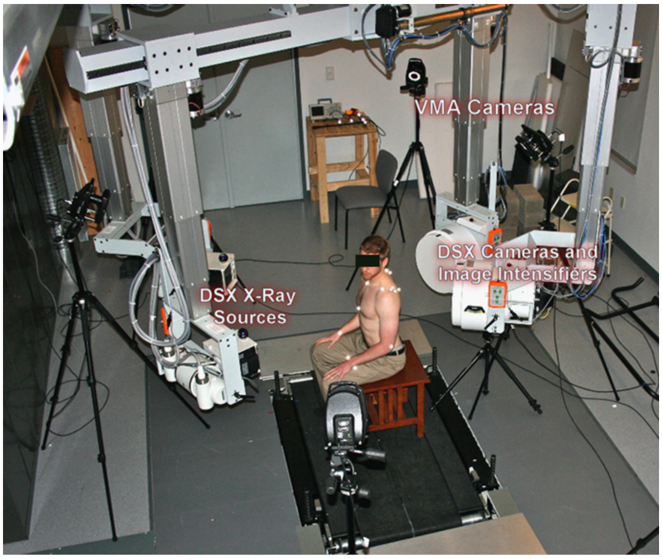

Fig. 1. Equipment setting during data collection.

2.3. Procedures

Subjects underwent a CT scan for the scapula and humerus on their dominant arms. Images were collected with a slice thickness of 1.25 mm using a LightSpeed16 System (GE Healthcare, Waukesha, WI, USA). The CT images were reconstructed into 3-D computer bone models of scapula and humerus using Mimics software (Materialise Medical Software, Leuven, Belgium). Local coordinate systems (LCS) for the humerus and scapula were defined using anatomical landmarks listed in Table 1.

Reflective markers with a diameter of 9 mm were attached to anatomical landmarks on each subject's trunk, humeri, and scapulae (Table 1). Two custom-made triads, each with three reflective markers, were attached to the flat, broad portion of the acromial process, bilaterally. The triads were triangular in shape with a reflective marker on each corner, approximately 3 cm apart. For each subject, a static capture of the markers was made using the VMA system with the subject in the standard anatomical position. After the static capture, the acromial angle, root of the scapular spine, and inferior angle markers were removed.

Subjects performed abduction (arm elevation in the frontal plane), scaption (arm elevation in the scapular plane), and an internal/external rotation task at 90° abduction. Movements were guided by a metronome at a frequency of 0.5 Hz. Once the subjects were on pace with the metronome and the movements were performed smoothly, the researcher would trigger the DSX and VMA systems to capture a one-repetition trial.

2.4. Data reduction

3D kinematics of the scapula and humerus were determined from the DSX image sequences using a previously described and validated model-based tracking technique (Bey et al., 2006). Briefly, a 3-D volumetric bone model was derived from CT. A virtual model of the DSX system geometry was created for generating a pair of digitally reconstructed radiographs (DRR's) via ray-traced projection through the CT bone model. The bone model was automatically repositioned within the virtual model until the best match was achieved between the simulated DRR's and the actual radiographic image pair. Once the positions of the humerus and scapula were determined for each motion frame, the positions of all the anatomical landmarks previously defined in bone LCSs were transformed into the global coordinate system (GCS) of the DSX and exported by custom software. For the VMA data, the 3-D positions of markers were reconstructed in the GCS of the VMA. The position of the humeral head was estimated on the anthropometric data using the Plug-in Gait Model (Vicon, Oxford, UK). The 3-D coordinates of the markers were exported by the Vicon Nexus software.

The VMA and DSX data were loaded into a custom Matlab program (Mathworks, Natick, MA) for further processing. Data were filtered using a fourth order zero-lag low-pass Butterworth filter with a cutoff frequency set at 5 Hz, as determined with power spectrum analysis. For each trial, the local coordinate system (LCS) of the thorax was defined using the VMA data, as it was not modeled with the DSX. The LCSs of the humerus and scapula were defined for both VMA and DSX data. Humeral and scapular movements were calculated as the humerus and scapula LCSs with respect to the thorax LCS. The scapular movement was decomposed into three

Table 1
Anatomical landmarks used in this study and their data source.

Body segment	Anatomical landmarks	Source of data	
		VMA	DSX
Humerus	Humeral head	Virtual positions estimated based on surface markers and anthropometric data	Positions marked in 3-D computer bone model
	Medial epicondyle Lateral epicondyle	Surface marker positions	
Scapula	Acromioclavicular joint	Surface marker positions	Positions marked in 3-D computer bone model
	Acromial angle Root of the spine of scapula Inferior angle	Virtual positions estimated based on surface markers in the static capture and triad markers	
Thorax	C7 T10 Jugular notch Xiphoid process	Surface marker positions	(Use VMA data)

Please cite this article as: Chu, Y., et al., Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements. Journal of Biomechanics (2012), http://dx.doi.org/10.1016/j.jbiomech.2012.06.025

components in Euler sequence: protraction/retraction, medial/lateral-rotation, and anterior/posterior-tilt; the humeral movement was decomposed into elevation plane, elevation, and internal/external rotation. All the LCSs and movement components were defined following the ISB recommendations (Wu et al., 2005).

2.5. Statistical analyses

The validity of the VMA against the DSX was evaluated on both the individual and group level for different application purposes. If validated at the individual level, the VMA can be used to record the scapular movement of a single subject and identify potential pattern abnormality. If validated at the group level, the VMA can be used for group comparisons to identify the potential kinematic differences between a healthy and a pathological group.

At the individual level, Pearson's correlation coefficient was calculated and averaged across subjects. Alpha was set at 0.05 for correlation analysis. The range of motion (ROM) for the humerus (the major component of movement only) and scapula were calculated for both the DSX and VMA data. Paired *t*-tests were used to compare the humeral and scapular ROM measured with the DSX and VMA, with alpha set at 0.05.

To make comparisons possible at the group level, data were extracted for every 10° increment from 30° to 140° of arm elevation for the abduction and scaption tasks, and from 30° arm internal rotation to 40° external rotation for the internal/external rotation task. Pearson's correlation coefficient was calculated between the DSX and VMA scapular data using the group averages at these data points, with alpha set at 0.05. The correlations were calculated for the full movement, and movements of different humeral movement directions. To evaluate the accuracy of the VMA technique, errors were also evaluated for every 10° increment of humeral angle within the stated range of motion of each task. For a given humeral angle, the root mean square of the difference between the scapular orientations measured by the DSX and VMA was calculated, and then averaged across subjects.

3. Results

Results of the individual level analyses are presented in Table 2. For the abduction task, the DSX and VMA data were strongly correlated for all the three components of scapular orientation (all $p < 0.01$). For the scaption task, a weak and insignificant relationship was found in one subject's scapular anterior/posterior-tilt ($R = -0.120$, $p = 0.246$). For the internal/external rotation task, a weak and insignificant relationship was found in two subjects' scapular protraction/retraction ($R = -0.130$, $p = 0.198$ and $R = 0.080$, $p = 0.425$, respectively). Humeral and scapular range of motion is presented in Table 3. The ROM of the DSX measurements were significantly greater in scapular medial/lateral-rotation for both the abduction and scaption task ($p = 0.001$ and 0.002, respectively), and in anterior/posterior-tilt for the internal/external rotation tasks ($p = 0.03$). The root mean square errors are presented in Table 4.

Table 4
Root mean square errors of the scapular kinematic measurements.

Task	Humerus movement	Pro/retraction (deg.)	Med/lat rotation (deg.)	Ant/posterior tilt (deg.)
Abduction	Humerus raising	3.7	4.6	5.3
	Humerus lowering	3.8	9.2	5.3
	Both	3.8	6.9	5.3
Scaption	Humerus raising	6.2	4.5	7.0
	Humerus lowering	4.3	5.9	4.9
	Both	5.2	5.2	6.0
IR/ER	Humerus rotating in	5.9	14.2	6.7
	Humerus rotating out	6.2	10.8	6.4
	Both	6.0	12.5	6.6

Table 2
Pearsons' *R* of scapular orientations.

Task	Analysis level	Variable	Scapular orientation components		
			Pro/retraction	Med/lat rotation	Ant/posterior tilt
Abduction	Individual	Pearson's *R*	0.913(0.093)	0.967(0.032)	0.573(0.698)
	group	Pearson's *R* humerus raising	0.981	0.985	0.997
		Pearson's *R* humerus lowering	0.963	0.999	0.994
		Pearson's *R* both	0.901	0.902	0.986
Scaption	Individual	Pearson's *R*	0.802(0.093)	0.969(0.023)	0.705(0.470)
	group	Pearson's *R* humerus raising	0.833	0.992	0.937
		Pearson's *R* humerus lowering	0.957	0.998	0.965
		Pearson's *R* both	0.885	0.947	0.946
IR/ER	Individual	Pearson's *R*	0.412(0.433)	0.935(0.047)	0.887(0.096)
	group	Pearson's *R* humerus rotating in	−0.157[a]	0.998	0.995
		Pearson's *R* humerus rotating out	−0.967	0.992	0.997
		Pearson's *R* both	−0.141[b]	0.849	0.748

[a] Insignificant correlation ($p = 0.717$).

[b] Insignificant correlation ($p = 0.606$).

Table 3
Range of motion (ROM) of the humerus and scapula during different tasks.

Task	Humeral ROM (of the primary component of movement)	Scapular ROM					
		Pro/retraction		Med/lat rotation		Ant/posterior tilt	
		VMA	DSX	VMA	DSX	VMA	DSX
Abduction (deg.)	128.6(11.2) (elevation)	12.7(7.4)	10.6(1.6)	31.2(3.4)*	45.7(2.1)*	14.1(4.2)	14.7(7.2)
Scaption (deg.)	121.7(7.5) (elevation)	10.9(6.2)	12.0(5.9)	34.4(5.4)*	48.5(5.5)*	13.9(4.6)	14.0(3.9)
IR/ER (deg.)	111.3(23.3) (IR/ER)	9.2(2.5)	7.1(1.5)	12.9(7.7)	14.9(10.5)	11.5(6.5)*	14.8(8.3)*

* Significant difference between the DSX and VMA measurements (paired *t*-test $p < 0.05$).

Please cite this article as: Chu, Y., et al., Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements. Journal of Biomechanics (2012), http://dx.doi.org/10.1016/j.jbiomech.2012.06.025

At the group level, Pearson's correlation coefficients were calculated separately with the different directions of movement taken into consideration (Table 2). For both the abduction and scaption task, strong and significant linear relationships in all three scapular orientation components were detected ($p < 0.001$). For the internal/external rotation task, the linear relationship in protraction/retraction was weak and not significant. The linear relationships were strong and significant for the other two components ($p < 0.001$)

4. Discussion

Video-based motion analysis is widely used in general biomechanical studies but less in scapular kinematic research. The purpose of this study was to validate the application of VMA in scapular kinematics. The hypothesis of high correlation between the VMA and DSX data was supported except for anterior/posterior tilt of the scapula during abduction and for scapular protraction/retraction during internal/external rotation. We concluded that, with some limitations acknowledged, VMA is a valid technique to quantify scapular kinematics for clinical and research purposes. With the prevalence and versatility of VMA, this technique has the potential to expand the field of scapular kinematic research.

For clinical applications, the VMA technique must be capable of capturing the true movement pattern and orientation of the scapula on a single subject, so one can determine whether an observed pattern or scapular angle is pathological. In such cases, a high correlation and comparable range of motion (ROM) between the VMA and DSX data might be expected. For abduction and scaption, the correlation was high for both protraction/retraction and medial/lateral-rotation. The correlation of anterior/posterior-tilt was high for four of the five subjects, but the weak correlation in one subject negatively affected the mean values. This subject was very muscular and the poor agreement was likely due to a greater amount of soft tissue effect. Caution should be used when VMA is utilized to evaluate a single subject's scapular anterior/posterior-tilt pattern during arm elevation when the subject is muscular. For internal/external rotation, the correlation was high for both scapular medial/lateral-rotation and anterior/posterior-tilt. The correlation was only moderate for protraction/retraction, and not significant in two of the five subjects. It may be inappropriate to evaluate a single subject's scapular protraction/retraction pattern during internal/external rotation using VMA.

A high correlation is not enough to guarantee high pattern agreement. Two sets of data can correlate perfectly when the patterns change together, but may have different amplitudes and slopes. The medial/lateral-rotation ROM during abduction and scaption was significantly underestimated by approximately 14°. Similarly, Meskers et al. 2007 found that skin-based electromagnetic tracking underestimated the scapular lateral rotation by 13°. Such underestimation was most likely due to soft tissue effects. Soft tissue effects might increase the difference between DSX and VMA as arm elevation angle increased, as was observed in a previous validation study using an electromagnetic tracking device (Karduna et al., 2001). In Karduna et al. (2001), the underestimation of scapular lateral rotation was 25°, likely due to a greater humeral range of motion (up to 150° humeral elevation, compared to 140° in the current study). Considering the high correlations, VMA is valid for evaluating scapular medial/lateral rotation acknowledging the measurements are underestimated. The high correlation also indicated that soft tissue effects may be corrected with regression (Van Der Helm, 1997).

For group level analysis, correlations were high except for protraction/retraction during internal/external rotation, indicating the inappropriateness of using VMA for this specific assessment. For all other measures, high similarity between VMA and DSX data was observed (Fig. 2). Similar to Karduna et al., (2001), the error steadily increased with arm elevation angle. However, unlike Karduna et al., we did not find dramatically increased error in protraction/retraction and anterior/posterior tilt beyond 120° of arm elevation, suggesting the validity of these two measurements through 140°. The scapular movement patterns appeared more

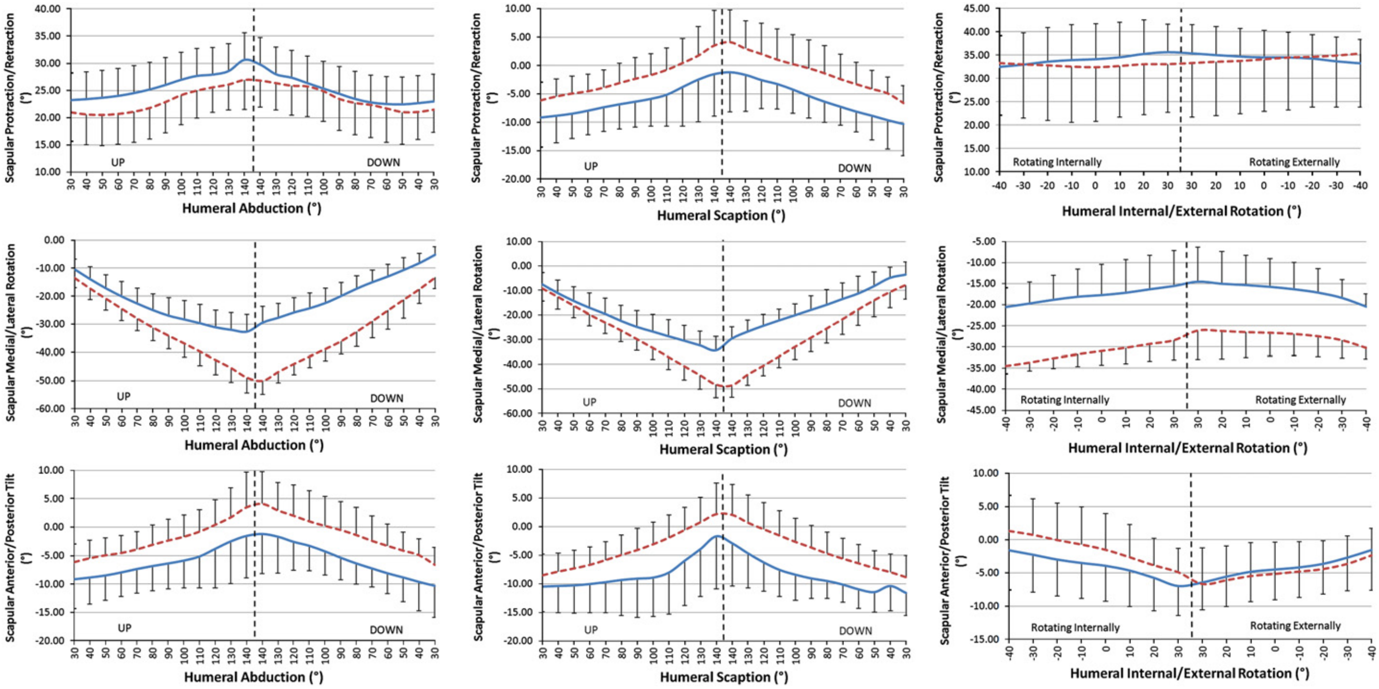

Fig. 2. Group average of scapular kinematics (solid line: VMA; dashed line: DSX; error bars: standard deviations across subjects).

Please cite this article as: Chu, Y., et al., Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements. Journal of Biomechanics (2012), http://dx.doi.org/10.1016/j.jbiomech.2012.06.025

linear when utilizing the group average, consistent to the previous radiography findings: the variability of scapulohumeral rhythm across different phases decreased when calculated based on group average scapular and humeral orientations, compared with calculating the average scapulohumeral rhythm of a group (Freedman and Munro, 1966). Correlations were typically higher when different arm movement directions were evaluated separately. The effects of arm movement direction on scapular kinematics have been studied using bone-pin (Mcclure et al., 2001), palpation and digitizing (Borstad and Ludewig, 2002; de Groot, Brand, 2001), and skin-based electromagnetic tracking (Fayad et al., 2006).

Knowing that the VMA data at the group level replicated the DSX data well enables researchers to use this technique to compare scapular kinematic patterns among groups. Group comparisons have been used to identify the scapular kinematic differences between healthy people and impingement subjects (Mcclure et al., 2006; Ludewig and Cook, 2000) or overhead athletes (Laudner et al., 2006). So far there are no conclusive criteria to classify a subject into a normal or pathological group, as the line separating normal scapular kinematics and scapular dyskinesis is yet to be established (Kibler et al., 2009). The use of the VMA technique may expand the base of knowledge and result in the accumulation of more data to establish the classification criteria.

The accuracy of the VMA technique was evaluated by calculating the root mean square errors over the entire range of motion (Table 4). The calculated errors were within a range comparable to the errors of the electromagnetic tracking technique, as presented by Karduna et al. (2001). The current results showed that the accuracy was higher during humerus raising than lowering in the abduction and scaption tasks, and higher during humerus rotating out than rotating in the IR/ER task. In Karduna et al. (2001), only the data during humeral raising and rotating out were analyzed.

Several limitations of the VMA technique need to be addressed. First, to minimize the radiation exposure to the subjects, only one trial of data for each arm movement was collected. As a result, a comprehensive error evaluation that involves inter-trial analysis could not be conducted. Second, in the current study, data were collected with five healthy and physically active male subjects, which may lead to questioning the generality of the results. Previous validation studies have used similar sample sizes (Karduna et al., 2001; Meskers et al., 2007). We believe that with the high pattern of correlation observed, five subjects are sufficient for the research purpose. Although female subjects were not recruited for this study, previous validation studies have not reported a gender effect (Karduna et al., 2001; Meskers et al., 2007). As we did not expect that the soft tissue effects over the acromion differ in females, recruiting only male subjects was sufficient for our purpose. Finally, muscle and subcutaneous fat thickness were not measured over the acromion. We found that scapular anterior/posterior tilt measurement during arm elevation was not valid for a muscular subject. Increased subcutaneous fat may have similar or different effects. Further research of larger sample size is needed to evaluate the effects of muscle and/or fat and to investigate whether such effects can be corrected.

In summary, VMA can be used for evaluating a single subject's scapular movement pattern in protraction/retraction during abduction and scaption, and medial/lateral-rotation during internal/external rotation. Anterior/posterior-tilt during abduction and scaption should be investigated with caution by confirming whether the movement direction agrees with previous research. Video-based motion analysis is also valid for evaluating group average of scapular kinematics except for protraction/retraction during internal/external rotation. While acknowledging the inherent limitations, VMA is an appropriate technique for tracking scapular kinematics.

Conflict of interest statement

None

Acknowledgment

This study is funded by the Central Research Development Fund, University of Pittsburgh.

References

Bey, M.J., Zauel, R., Brock, S.K., Tashman, S., 2006. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. Journal of Biomechanical Engineering 128, 604–609.

Borstad, J.D., Ludewig, P.M., 2002. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. Clinical Biomechanics 17, 650–659.

De Groot, J.H., Brand, R., 2001. A three-dimensional regression model of the shoulder rhythm. Clinical Biomechanics 16, 735–743.

De Groot, J.H., Valstar, E.R., Arwert, H.J., 1998. Velocity effects on the scapulohumeral rhythm. Clinical Biomechanics 13, 593–602.

Fayad, F., Hoffmann, G., Hanneton, S., Yazbeck, C., Lefevre-Colau, M.M., Poiraudeau, S., et al., 2006. 3-D scapular kinematics during arm elevation: effect of motion velocity. Clinical Biomechanics 21, 932–941.

Freedman, L., Munro, R.R., 1966. Abduction of the arm in the scapular plane: scapular and glenohumeral movement—a roentgenographic study. Journal of Bone and Joint Surgery-A 48, 1503–1510.

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

Kibler, W.B., 1998. The role of the scapula in athletic shoulder function. American Journal of Sports Medicine 26, 325–337.

Kibler, W.B., Ludewig, P.M., Mcclure, P., Uhl, T.L. & Sciascia, A., 2009. Scapular Summit 2009: introduction. Journal of Orthopaedic and Sports Physical Therapy39, A1-A13.

Laudner, K.G., Myers, J.B., Pasquale, M.R., Bradley, J.P., Lephart, S.M., 2006. Scapular dysfunction in throwers with pathologic internal impingement. Journal of Orthopaedic and Sports Physical Therapy 36, 485–494.

Ludewig, P.M., Cook, T.M., 2000. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Physical Therapy 80, 276–291.

Mcclure, P.W., Michener, L.A., Karduna, A.R., 2006. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. Physical Therapy 86, 1075–1090.

Mcclure, P.W., Michener, L.A., Sennett, B.J., Karduna, A.R., 2001. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. Journal of Shoulder and Elbow Surgery 10, 269–277.

Mckee, M.D., Yoo, D.J., 2000. The effect of surgery for rotator cuff disease on general health status. Results of a prospective trial. Journal of Bone and Joint Surgery-A 82, 970–979.

Mcquade, K.J., Dawson, J., SMIDT, G.L., 1998. Scapulaothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. Journal of Orthopaedic and Sports Physical Therapy 28, 74–80.

Meskers, C.G.M., Van De Sande, M.A.J., De Groot, J.H., 2007. Comparison between tripod and skin-fixed recording of scapular motion. Journal of Biomechanics 40, 941–946.

Meyer, K.E., Saether, E.E., Soiney, E.K., Shebeck, M.S., Paddock, K.L., Ludewig, P.M., 2008. Three dimensional scapular kinematics during the throwing motion. Journal of Applied Biomechanics 24, 24–34.

Michiels, I., Grevenstein, J., 1995. Kinematics of shoulder abduction in the scapular plane: on the influence of abduction velocity and external load. Clinical Biomechanics 10, 137–143.

Myers, J.B., Laudner, K.G., Pasquale, M.R., Bradley, J.P., Lephart, S.M., 2005. Scapular position and orientation in throwing athletes. American Journal of Sports Medicine 33, 263–271.

Savoie III, F.H., Field, L.D., Jenkins, R.N., 1995. Costs analysis of successful rotator cuff repair surgery: an outcome study. Comparison of gatekeeper system in surgical patients. Arthroscopy 11, 672–676.

Tsai, N.-T., Mcclure, P.W., Karduna, A.R., 2003. Effects of muscle fatigue on 3-dimensional scapular kinematics. Archives of Physical Medicine and Rehabilitation 84, 1000–1005.

Van Der Helm, F.C.T., 1997. A standardized protocol for motion recordings of the shoulder. In: Veeger, H.E.J., Van Der Helm, F.C.T., Rozing, P.M. (eds.), First Conference of the International Shoulder Group, August 26–27 1997, Delft, The Netherlands. Shaker Publishing B.V.

Wu, G., Van Der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., et al., 2005. ISB recommendation on definitions of joint coordinate system of various joint for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. Journal of Biomechanics 38, 981–992.

Please cite this article as: Chu, Y., et al., Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements. Journal of Biomechanics (2012), http://dx.doi.org/10.1016/j.jbiomech.2012.06.025