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Abstract: The shoulder complex is prone to numerous pathologies and instabilities due to its large range of motion. The extent of injury is assessed through a series of observations and physical examinations. It is hypothesized that objective kinematic analysis of the shoulder could yield useful functional insights to aid clinical practice. Non-invasive motion analysis techniques to monitor shoulder function have been developed using passive markers; however, accurate measurement of scapula kinematics is problematic because of overlying tissue. The scapula locator is the accepted standard by which alternative non-invasive techniques of scapula tracking are validated. In this study, the viability of using skin-mounted markers to measure dynamic scapula movement is determined. Complete kinematic descriptions of ten healthy shoulders were obtained. Elevations of the glenohumeral joint were similar with both techniques, indicating that the skin marker method is suitable for gathering functional glenohumeral data. The main differences of note are seen at the scapulothoracic articulation where the skin marker method underestimated lateral rotation by more than 50° at maximum elevation. However, the correlation between the two approaches is greater than 0.7, suggesting that it may be possible to derive linear regression models to predict dynamic scapulothoracic lateral rotation accurately using skin-mounted scapula markers.

Keywords: shoulder, scapula, skin artefact, passive markers

1 INTRODUCTION

The shoulder complex consists of four articulations: the sternoclavicular (SC) joint; the acromioclavicular (AC) joint; the glenohumeral (GH) joint; and the scapulothoracic (ST) articulation. These four articulations act simultaneously to provide a greater range of motion (ROM) than any of the individual articulations and than any other joint complex in the human body. As a result of this extended ROM, the shoulder complex is inherently unstable and prone to a large variety of pathologies and injuries. Shoulder pathologies are diagnosed and monitored through a series of questionnaires, observations, and physical examinations, which combine to provide an overall score of functionality. There are more than 20 different clinical scores used to assess shoulder functionality [**1**]. These include the Oxford Shoulder Score [**2**, **3**] (and the Oxford Shoulder Instability Score [**4**]), the Constant–Murley Score [**5**], and the American Shoulder and Elbow Surgeons Shoulder Score Index [**6**]. This method of assessment is problematic as there is no globally adopted standard, the correlations between different scores are low to moderate, and the assessments of function between different scores are not equivalent [**1**]. It is hypothesized that objective kinematic analysis of the shoulder complex could yield useful functional insights that may complement clinical practice pre and post-treatment.

The scapulothoracic articulation is responsible for approximately one third of the shoulder complex's full ROM [**7**]. Altered scapula kinematics can also be

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indicative of certain pathology types, e.g. increased lateral rotation, or 'winging' of the scapula in subjects with recurrent GH dislocations and abnormal scapulohumeral rhythm in patients with adhesive capsulities (frozen shoulder) [**8**]. Accurate *in-vivo* non-invasive measurement of the kinematics of the scapula is problematic because of the presence of overlying skin. Pronk [**9**] used a single-point locator attached to a three-dimensional spatial linkage instrument to determine the three-dimensional position of the acromial angle, the root of the scapular spine, and the inferior angle, and thus infer the orientation and position of the scapula. The method was found to be accurate but too time consuming, as the landmarks needed to be identified independently at each static increment of humeral elevation. Johnson *et al.* [**10**] expanded on this method by making the assumption that the scapula is a rigid body. They developed a three pointed palpator to determine the locations of the three landmarks simultaneously. The scapula locator has been applied since to numerous other studies [**8**, **11–13**] and it has now become the 'gold standard' by which other non-invasive methods of scapula tracking are assessed and calibrated [**14**]. One limiting factor of the scapula locator is that it can only be used to take measurements of scapula orientation during static elevations. Dynamic scapulohumeral rhythm must then be inferred through linear regression equations for the arm-reachable workspace [**15**, **16**]. Collecting the data necessary to establish the scapulohumeral rhythm for the arm-reachable workspace can be time consuming and, with patient groups where pain and fatigue are major factors, may not always be practical. The current study uses non-invasive opto-electronic motion analysis techniques to monitor shoulder function [**17**, **18**]. Retro-reflective markers are attached to the bony landmarks of the four articulating segments of the shoulder complex. The trajectories of the markers are tracked by eight Qualisys Pro-Reflex MCU 1000 cameras [**19**] with a sampling frequency of 60 Hz. Anatomical coordinate systems are generated and joint and segment rotations calculated according to the International Society of Biomechanics (ISB) recommendations [**20**]. In this study the viability of using skin-mounted markers to measure the dynamic movement of the scapula directly is assessed.

2 MATERIALS AND METHODS

2.1 Experimental protocols

Ten subjects (six males and four females of mean age 27.5 ± 5.1 years) with no previous history of shoulder pathology or instability were recruited for the study. Ethical approval for the study was granted by the Cardiff University Research Committee Ethics Panel and informed consent was obtained from each subject prior to the study. Retro-reflective markers were attached to the bony landmarks of the thorax, clavicle, scapula, humerus, and forearm of each subject's right arm as recommended by the ISB [**20**] (Fig. 1) (Table 1). The centre of GH rotation was estimated by linear regression [**21**] to provide a third

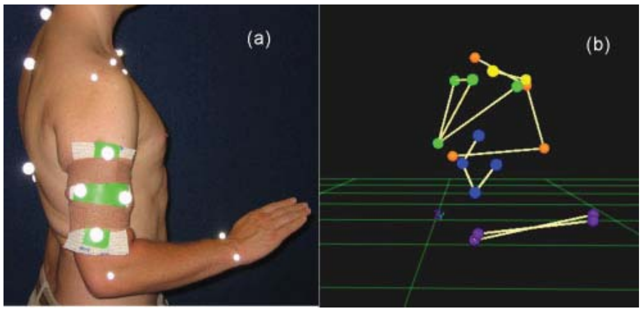

Fig. 1 (a) Subject posing in the neutral position wearing the upper-limb marker set with humerus marker cluster. (b) Qualisys Track Manager (QTM) software view of the subject

Table 1 Anatomical landmarks proposed by the ISB

Thorax	C7	Spinous process of the seventh cervical vertebra
	T8	Spinous process of the eighth thoracic vertebra
	IJ	Deepest point of Incisura Jugularis
	PX	Processus Xiphoideus, most caudal point on the sternum
Clavicle	SC	Most ventral point on the SC joint
	AC	Most dorsal point on the AC joint
Scapula	TS	Trigonium Spinae, the midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine
	AI	Angulus Inferior, most caudal point of the scapula
	AA	Angulus Acromialis, most laterodorsal point of the scapula
	PC	Most ventral point of processus coracoideus
Humerus	GH	GH rotation centre (estimated)
	EL	Most caudal point on the lateral epicondyle
	EM	Most caudal point on the medial epicondyle
Forearm	RS	Most caudal–lateral point on the radial styloid
	US	Most caudal–medial point on the ulnar styloid

landmark to generate the humerus anatomical coordinate system (ACS). The humerus ACS was then related to a technical coordinate system (TCS) consisting of four markers (Fig. 1). Subjects performed incremental arm elevations in the coronal and sagittal planes. All elevations were performed with the arm straight and hand pronated.

A neutral-position anatomical calibration measurement was captured for 1 s at the start of each trial with the elbow flexed to 90° and the hand pronated (Fig. 1). An external reference frame fitted with retro-reflective markers was used to guide arm elevation in the different anatomical planes and to assist in post-experimental data acquisition (Fig. 2). Subjects performed each elevation in increments of 30° of the external frame. Static measurements were taken at each increment using a scapula locator with markers attached to represent each of the three scapula bony landmarks (Fig. 3(a)). Individual skin-mounted markers were then attached to each of the scapula bony landmarks (Fig. 3(b)) with the subject in a neutral-position measurement (Fig. 1(a)). Elevations in the coronal and sagittal planes were then repeated dynamically using skin-mounted markers.

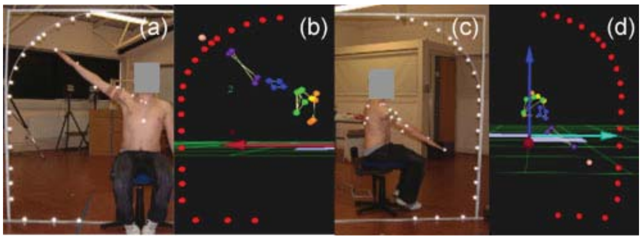

Fig. 2 Elevation of the arm by the subject using the frame for guidance: (a) coronal plane elevation in the real view; (b) coronal plane elevation in the QTM view; (c) sagittal plane elevation in the real view; (d) sagittal plane elevation in the QTM view

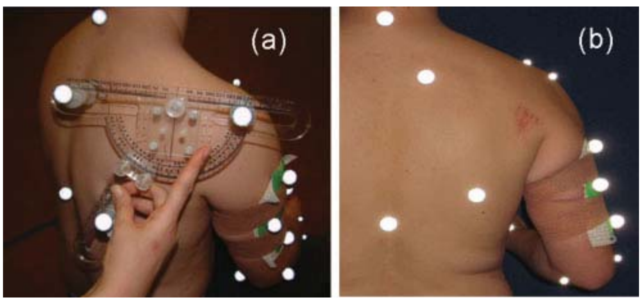

Fig. 3 (a) Scapula locator with markers attached used to measure the spatial orientation of the scapula; (b) skin markers used to identify the bony landmarks of the scapula

2.2 Data Processing

The static data collected with the scapula locator was used in a similar manner to previous studies [**15**, **16**] to generate multiple linear regression models which predict scapula orientation during dynamic movements based on the position of the humerus relative to the thorax. Joint rotations for the AC joint, the GH joint, and the ST articulation were evaluated at each value of humerothoracic elevation, to allow comparison with the data collected dynamically using the skin-mounted scapula markers. Polynomial fits of order two to seven were fitted to the data sets generated by the ten subjects. The order of the polynomial fits were chosen to maximize the coefficient of determination values R^2 in each case, which indicate the proportion of variability in each data set that is accounted for by its associated model. The order of the polynomial fits and the R^2 values can be found in Table 2. Paired sample *t* tests ($p = 0.05$) were used to compare the rotations measured with each method during coronal and sagittal plane elevation, with the exception of plane of elevation and axial rotation of the GH joint, which were compared using the Wilcoxon signed-rank test, as their difference variables were not normally distributed.

3 RESULTS

Complete kinematic descriptions of the shoulder complex were obtained for the ten shoulders during elevations in the coronal and sagittal planes. To maintain consistency, all rotations are plotted against elevation of the humerus relative to the thorax. Polynomials were fitted to the data sets generated by the ten subjects (Table 2), similar to previous studies [**8**, **11**]. A full set of rotations for the thorax relative to the global coordinate system (GCS), the SC joint, the AC joint, the GH joint, and the ST articulation are shown for coronal plane elevation (Fig. 4) and sagittal plane elevation (Fig. 5). Solid curves represent the dynamic rotations measured directly with the skin-mounted markers. Dashed curves represent the predicted rotations using multiple linear regression models based on static measurements with the scapula locator.

For the thorax relative to the GCS and for the SC joint, only the data collected during the skin-mounted marker trial are shown, as these rotations are unaltered by the different methods of measuring scapula orientation. It is not possible to measure axial rotation of the SC joint as only two landmarks

Table 2 R^2 values for the polynomial fits to the angles describing the rotations of the thorax relative to the GCS, the SC joint, the AC joint, the GH joint, and the ST articulation during humeral elevation in the coronal and sagittals plane for ten subjects as measured with the scapula locator and scapula-mounted skin markers. The values in parentheses represent the order of the polynomial used (see also Figs 4 and 5)

System Measurement method	Angle describing the rotation R^2					
	Abduction			Flexion		
Thorax relative to GCS	Flexion–extension	Lateral flexion	Axial rotation	Flexion–extension	Lateral flexion	Axial rotation
Skin markers	0.0671 (4)	0.9515 (5)	0.7271 (4)	0.9672 (2)	0.4372 (4)	0.751 (2)
SC joint	Retraction	Elevation	Axial rotation	Retraction	Elevation	Axial rotation
Skin markers	0.969 (2)	0.9346 (5)	N/A	0.9152 (5)	0.9533 (2)	N/A
AC joint	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Scapula locator	0.8898 (5)	0.9983 (5)	0.9361 (2)	0.9435 (5)	0.9961 (5)	0.9762 (4)
Skin markers	0.9658 (3)	0.9521 (4)	0.9663 (3)	0.7202 (4)	0.9579 (5)	0.9595 (2)
GH joint	Plane of elevation	Elevation	External rotation	Plane of elevation	Elevation	External rotation
Scapula locator	0.8898 (5)	0.9976 (7)	0.9957 (5)	0.9558 (3)	0.9989 (7)	0.8937 (3)
Skin markers	0.2676 (6)	0.9877 (5)	0.7964 (5)	0.1342 (5)	0.9741 (4)	0.6974 (4)
ST articulation	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Scapula locator	0.9467 (5)	0.9967 (5)	N/A*	0.8619 (3)	0.9946 (4)	0.8672 (7)
Skin markers	0.7521 (5)	0.9434 (4)	0.9474 (2)	0.7291 (3)	0.9686 (3)	0.9236 (2)

*N/A, not available.

on the clavicle can be palpated. For anterior tilt of the ST articulation during coronal plane elevation, only the skin marker data are presented, as it was not possible to generate a significant regression model using the scapula locator data.

The coefficient of determination values R^2 for each polynomial fit are shown in Table 2 to indicate the proportion of variability in each data set that is accounted for by its associated polynomial fit. Correlation values for each rotation as measured by the two different methods are given in Table 3. The measured ROMs and kinematic waveforms appeared to be comparable in many cases; however, the paired sample *t* tests and Wilcoxon signed-rank tests found that there was a statistically significant difference between measurements with the scapula locator and the skin-mounted markers for every rotation during both elevations. The salient features to note when comparing the rotations measured, using the scapula locator and the skin-mounted markers, are as follows.

For the AC joint:

1. For coronal plane elevation, an offset of 60° was observed for protraction. For sagittal plane elevation, the kinematic waveforms for protraction as measured with each method were different. The skin marker method measured a ROM of 10°, while the scapula locator measured a ROM of 60°.
2. During coronal and sagittal plane elevations, the measured lateral rotation began to deviate after arm elevation of 20°. The skin markers underestimated the rotation by over 50° as full arm elevation was reached.
3. Anterior–posterior tilt during coronal plane elevation displayed an initial offset of approximately 7°, which increased to 16° at full arm elevation. This resulted in underestimation of the ROM by the skin-marker method. During sagittal plane elevation, anterior–posterior tilt ROM was underestimated by the skin marker method from an arm elevation of 20° upwards, reaching a maximum difference of just over 60° at full arm elevation.

For the GH joint:

1. The main discrepancy when measuring the plane of elevation of the GH joint during elevation in the coronal and sagittal planes was caused by gimbal lock. This caused an offset greater than 40° for coronal plane elevation. During sagittal plane elevation the skin marker method showed an erratic kinematic profile with maximum offsets of approximately 60°.
2. Elevation profiles and ROMs in the coronal plane displayed an offset of approximately 30° throughout the majority of the movement. During sagittal plane elevation the arm elevation had an offset of approximately 10° up to 70°, after which the two waveforms began to diverge. By maximum arm elevation, the skin marker method underestimated elevation by approximately 35°.

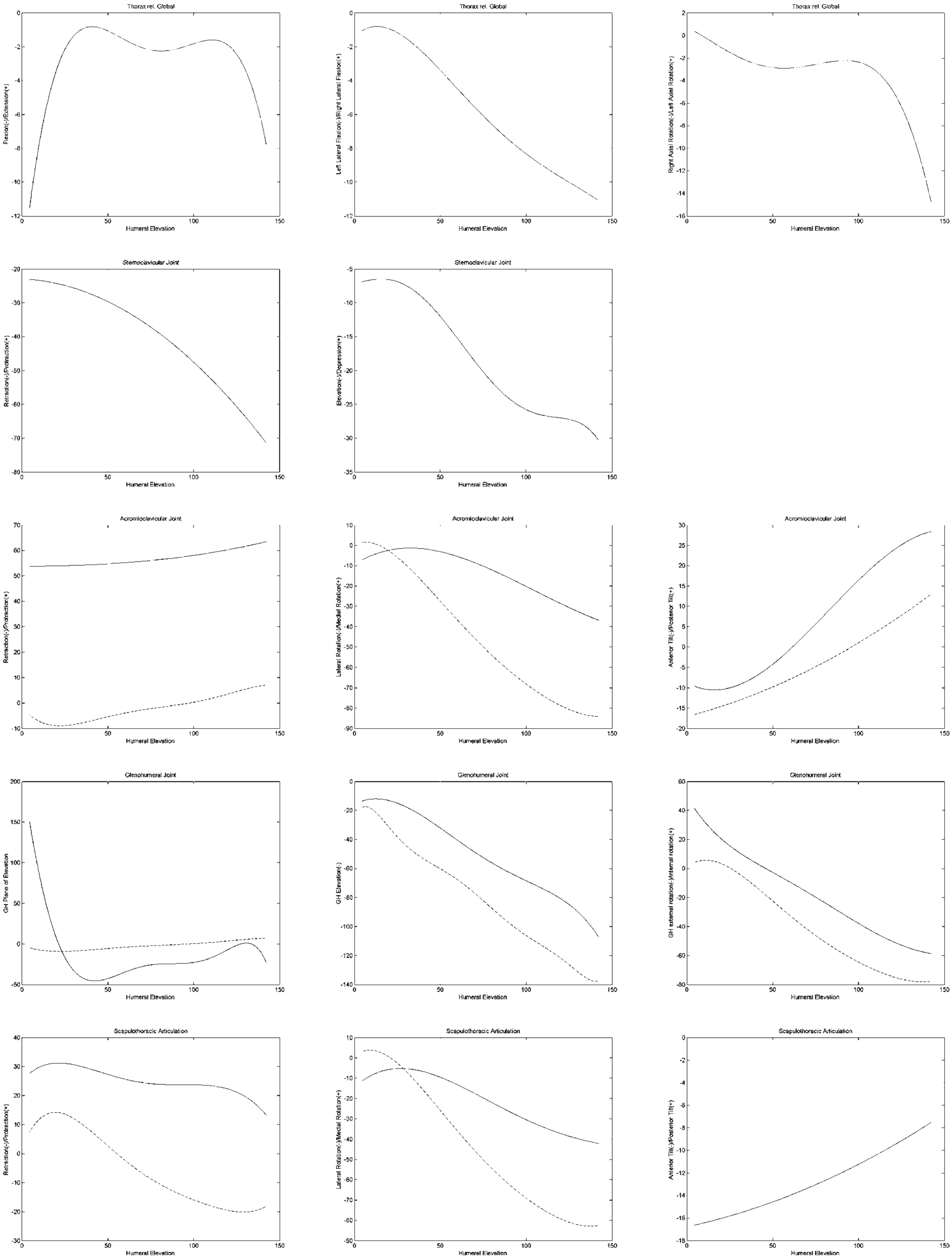

Fig. 4 Polynomial fits to the angles describing the rotations of the thorax relative to the GCS: the SC joint, the AC joint, the GH joint, and the ST articulation from a data set of ten healthy shoulders during sagittal plane elevation. Subjects have the elbow extended and the hand pronated. Solid lines: dynamic measurements with skin-mounted scapula markers. Dashed lines: dynamic motion profiles estimated through multiple linear regression based on static measurements taken with the scapula locator. All rotations measured in degrees

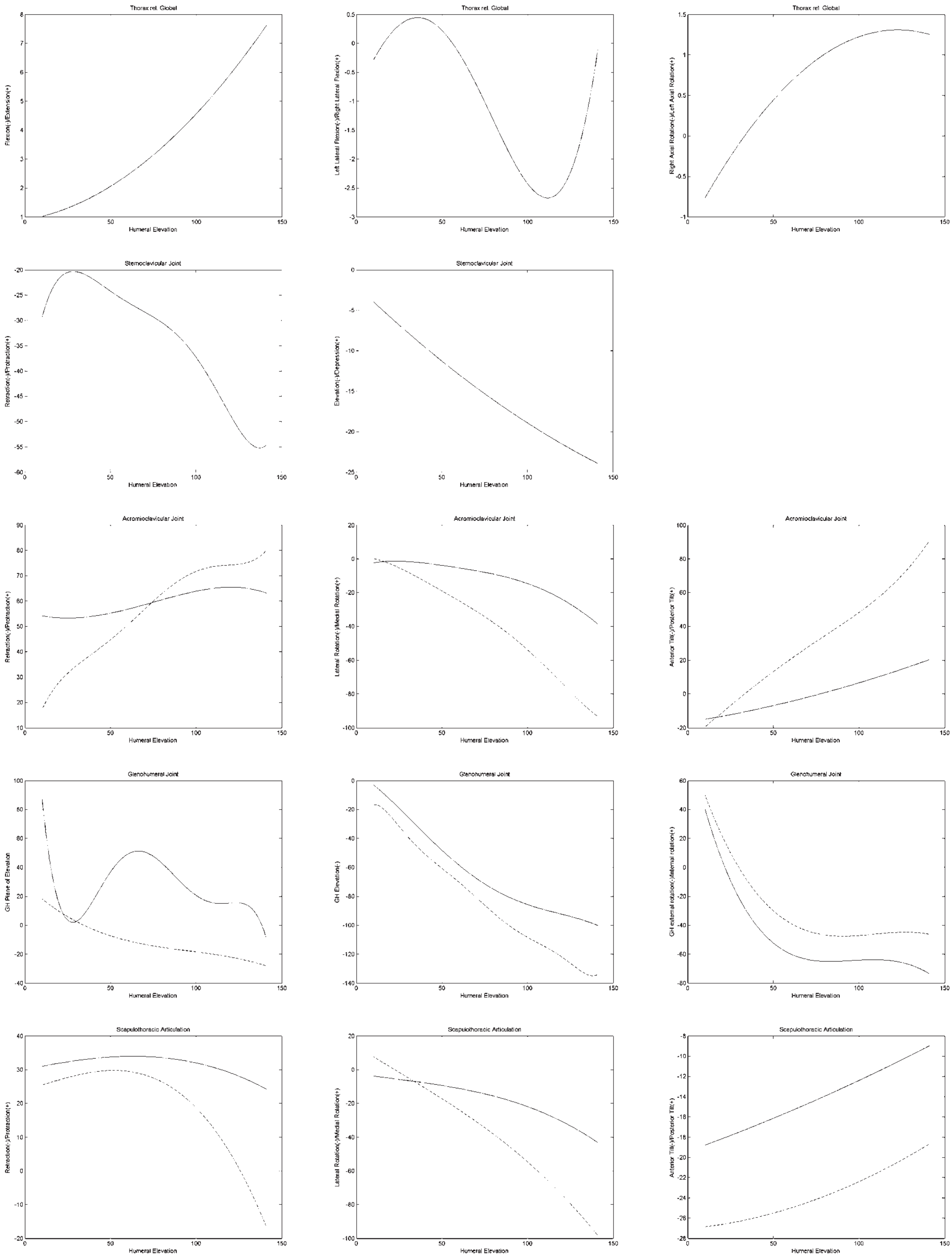

Fig. 5 Polynomial fits to the angles describing the rotations of the thorax relative to the GCS: the SC joint, the AC joint, the GH joint, and the ST articulation from a data set of ten healthy shoulders during coronal plane elevation. Subjects have the elbow extended and the hand pronated. Solid lines: dynamic measurements with skin-mounted scapula markers. Dashed lines: dynamic motion profiles estimated through multiple linear regression based on static measurements taken with the scapula locator. All rotations measured in degrees

Table 3 Pearson (or Spearman*) correlation values between the angles describing the rotations of the AC joint, the GH joint, and the ST articulation with the scapula locator (and regression equations) and dynamically with the skin-mounted markers during humeral elevation in the coronal plane and sagittal plane

System Correlation	Angle describing the rotation Pearson (or Spearman*) correlation value					
	Abduction			Flexion		
AC joint	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Correlation	0.463	0.624	0.776	0.471	0.745	0.905
GH joint	Elevation plane	Elevation	External rotation	Elevation plane	Elevation	External rotation
Correlation	0.416*	0.923	0.693*	0.071*	0.955	0.82*
ST articulation	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Correlation	0.164	0.726	N/A	0.367	0.777	0.56

3. When measuring axial rotation, an offset of 25° is observed for coronal plane elevation. During sagittal plane elevation there was an initial offset of 10°, which gradually increased to 20° by full arm elevation.

For the ST articulation:

1. There was an offset of 5° between the two methods when measuring protraction during sagittal plane elevation, up to an arm elevation of approximately 75°. For higher elevations the two kinematic profiles deviate, causing the skin marker method to underestimate the ROM by approximately 40° by full arm elevation. During coronal plane elevation, there was an initial offset of 17° which gradually increased to 25° at full arm elevation.
2. Lateral rotation measured by the skin markers produced different motion profiles during both coronal and sagittal plane elevation. In both cases the measured ROMs were underestimated by the skin marker method by more than 50°.
3. It was not possible to compare anterior tilt during coronal plane elevation as a significant regression model could not be generated from the scapula locator data. During sagittal plane elevation, both methods measured similar ROMs, with a 10° offset.

4 DISCUSSION

The scapula locator is regarded as the optimum method for tracking the movement of the scapula non-invasively [**14**]. This study objectively explores the motion profiles of the shoulder complex using both the gold standard (the scapula locator), and a simplified option of placing markers directly over the scapula bony landmarks. The aim of this was to determine whether skin markers could be used to track dynamic movement of the scapula directly, and thus to reduce experimental times considerably. Complete kinematic descriptions of the shoulder were obtained for the ten subjects using both methods of scapula tracking. The recorded motion patterns and ROMs are comparable with those reported in the literature [**8**, **11**] with the exception of the AC joint, particularly lateral rotation, which was between ten and 15 times larger for both movements. As it is only possible to palpate two bony landmarks on the clavicle, it is not possible to measure axial rotation of the clavicle directly. The previous studies estimated clavicle axial rotation by minimizing the rotations at the AC joint. This is feasible because the longitudinal axis of the clavicle is almost perpendicular to the scapular plane, meaning that axial rotation of the clavicle and lateral rotation of the scapula in the scapular plane are equivalent [**22**]. As the current study does not estimate clavicle axial rotation, the lateral rotations of the AC joint in the scapular plane are approximately equal to the sum of clavicle axial rotation and AC joint lateral rotation as measured in the previous studies. By applying a clavicle axial rotation of 60°, it is possible to reduce AC joint rotations to less than 10° [**9**].

In clinical practice, accurate measurement of the lateral rotation of the ST articulation is important as it can be indicative of certain pathology types [**8**]. The results indicate that the skin marker method is unsuitable for assessing ST lateral rotation. However, there is a correlation of 0.726 and 0.787 for coronal and sagittal plane elevation respectively between the two methods when measuring ST lateral rotation (Table 3). This would suggest that it is possible to derive further multiple linear regression models to predict ST lateral rotation accurately with the skin marker methods.

The simplified scapula marker set was found to be particularly useful for assessing GH elevation (Table 3). However, measurements of the GH plane of elevation with the skin marker method were hampered by gimbal lock. Gimbal lock occurs when two of the three rotational axes of the GH joint are aligned with their pivot axes in a single plane. When this occurs, it is no longer possible to represent the orientation of the GH joint. This is likely to occur at low and high humeral elevations. Owing to gimbal lock, there is an offset of 50° between the two methods during coronal plane elevation, and the R^2 values of the polynomial fits are low.

The study is further limited as the volunteers were primarily young and slim. The use of skin markers to track the movement of the scapula would be less feasible with an obese population. Alternative methods of dynamic scapula tracking are thus being developed. A TCS placed on the acromion plateau of the scapula has been found to be reliable when tracking dynamic movement of the scapula up to elevations of 120° [**23**] but it is recommended to calibrate it statically against the scapula locator at the start of each trial [**14**].

In conclusion, this study has shown that, while there are differences in the observed rotations of the shoulder complex when measured with skin-mounted markers in place of a scapula locator, these differences are well defined in most cases, meaning that, with careful consideration, the skin-marker method may be used for measuring three-dimensional shoulder positions quickly and dynamically.

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