Three-Dimensional Rotations of the Scapula During Arm Abduction: Evaluation of the Acromion Marker Cluster Method in Comparison With a Model-Based Approach Using Biplanar Radiograph Images

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Noninvasive methods enabling measurement of shoulder bone positions are paramount in clinical and ergonomics applications. In this study, the acromion marker cluster (AMC) method is assessed in comparison with a model-based approach allowing scapula tracking from low-dose biplanar radiograph images. Six healthy male subjects participated in this study. Data acquisition was performed for 6 arm abduction positions (0°, 45°, 90°, 120°, 150°, 180°). Scapula rotations were calculated using the coordinate systems and angle sequence was defined by the ISB. The comparison analysis was based on root mean square error (RMSE) calculation and nonparametric statistical tests. RMSE remained under 8° for 0° to 90° arm abduction and under 13.5° for 0° to 180° abduction; no significant differences were found between the 2 methods. Compared with previous works, an improved accuracy of the AMC approach at high arm abduction positions was obtained. This could be explained by the different sources of data used as the "gold standard."

Keywords: biomechanics, kinematics, motion analysis

In vivo measurement of scapula orientation remains a major difficulty in the process of upper limb kinematics assessment. Indeed, due to the high amplitude of motion of the shoulder, soft tissue artifacts may strongly affect scapula kinematics measurements made by skin sensors.[1]

Among the in vivo methods that allow measurement of scapula kinematics, the acromion marker cluster (AMC) offers several advantages; beyond being noninvasive, it is easy to carry out and it allows dynamic measurements. This method can either be set up with an electromagnetic system and sensors or with an optoelectronic system and reflective markers. The sensor or a rigid cluster of markers is attached onto the subject's acromion and then the scapula motion is deduced by considering that the acromion cluster and scapula move similarly. This method has been assessed by comparison with palpation[2–6] or intracortical pins.[7,8] These studies concluded that this method was valid for motion not exceeding 100° or 120° of humerus elevation. However, the "gold standards" used to assess the AMC method in these previous works may provide biased results. Palpation has been shown to introduce large discrepancies:[8–10] the study of Bourne et al[10] showed in vivo errors ranging from 2° to 12.5°, and concluded that palpation at full abduction is not accurate nor reliable; they also noticed that palpation accuracy depends on the skill of the measurer. Also intracortical pins inserted in the bones in vivo[7] may affect patients' kinematics by generating discomfort and pain. Therefore, there is a need for further validation of the AMC method using another gold standard.

Several studies[11,12] have proven that model-based tracking techniques can provide very accurate results for measuring both scapula and humerus motions from biplane radiographic images (inaccuracies of 0.25° for the scapula[11]). Their main disadvantage to the patient is the high radiation dose. The EOS system (EOS Imaging, Paris, France) provides low-dose stereoradiographic radiographs and thus has the advantage of being 6 to 10 times less irradiant than standard radiographs.[13] A model-based method using EOS images has been developed to measure scapula and humerus orientations and positions.[14,15] The accuracy of this model-based approach has been assessed thanks to in vitro data: an average error of 1.3 mm was found with model reconstruction[16] and a 2.6° accuracy could be obtained for scapula orientations.[17]

Thus, the current study aims to compare the AMC method to a model-based method using biplane radiographic images from the EOS imaging system in the case of arm abduction positions. The question considered in this study is: Is the AMC method accurate in terms of scapula 3D rotations when compared with this new gold standard (ie, the model-based approach)?

Methods

Subjects

Six healthy male subjects (age: 30.8 ± 8.5 y; height: 1.76 ± 0.08 m; mass: 69 ± 7.5 kg) without any history of shoulder pain participated in the study. All the subjects gave informed consent and ethics approval for the study was granted by the French Committee for Person Protection (CPP).

Protocol

Subjects were asked to randomly perform 6 arm abduction positions: 0º, 45º, 90º, 120º, 150º, and 180º in the frontal plane. An adjustable arm support was used to help the subjects maintain the same

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posture during data acquisition. The arm support was made of an articulated part which enables its extremity to be set in any position. The subjects had to hold the arm support extremity with the right hand (Figure 1) while maintaining their feet in the initially-recorded positions on the ground.

Subjects were equipped with radiopaque markers placed on their thorax at IJ (incisura jugularis), PX (xiphoid process), C7 (cerebral vertebrae 7), and *T*8 (thoracic vertebrae 8) landmarks. Furthermore, with the aid of a physical doctor, an AMC (a quadpod equipped with 4 radiopaque markers) was positioned on the flat part of their acromion with adhesive tape, just above the most latero-caudal point (Figure 1). Biplanar radiograph images were obtained from the EOS system.

Data Processing

Geometric Modeling From Low-Dose Biplanar Radiographs. A personalized scapula model was reconstructed from the biplanar radiography images using dedicated software (Collaboration between LBM, Paris; LIO, Montreal). The model was created based on the set of radiograph images corresponding to the first posture (0° humeral elevation) and then a sequence of rigid/elastic deformations was performed to adjust the scapula shape and to assess its position on the set of radiographs corresponding to the subsequent postures (15). The coordinates of the landmarks required to build the scapula coordinate system (CS) (acromion angle [AA], spine root [TS], and inferior angle [AI]) were extracted from the model.

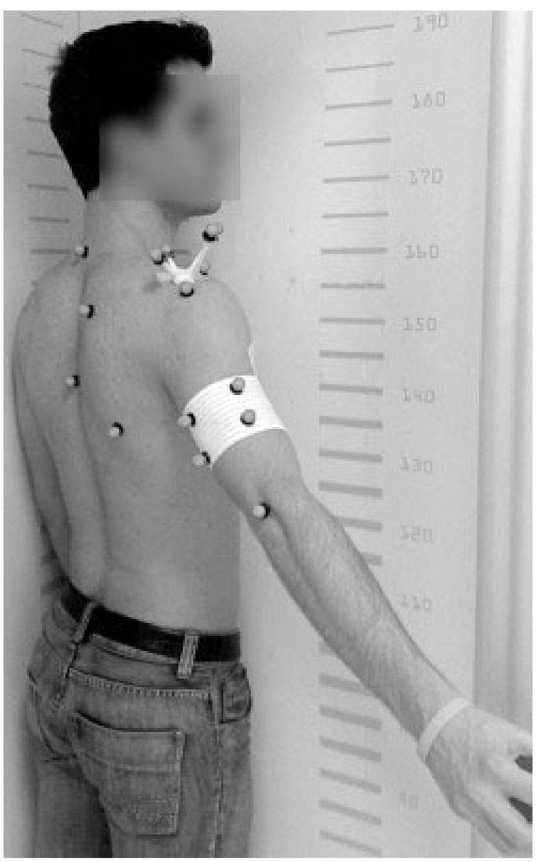

Figure 1 — A subject equipped with markers and the acromion marker cluster, posing in the cabin dedicated to low-dose biplanar radiograph measurements.

Acromion Marker Cluster Calibration and Method. Positions of the reflective markers on the thorax, scapula, and cluster were located and recorded after identification on the radiograph images. The transformation matrix between the cluster and the scapula CS was defined by the initial set of radiograph images (0° humeral elevation). This calibration matrix was used to obtain the scapula CS orientation from the cluster CS orientation in the subsequent postures (Equation 1 [AMC calibration transformation matrix, where *i* is the posture index]):

$$T_{thorax \to scapula,\, position\ i} = T^{calibration}_{cluster \to scapula} \cdot T_{thorax \to cluster,\, position\ i} \tag{1}$$

A second calibration method based on skin marker positions was also performed to provide estimations of potential calibration errors.

Coordinate Systems and Sequence of Rotation Angles. Rotations of the scapula were studied in the CS attached to the thorax of each subject. Both scapula and thorax CS were defined as recommended by the International Society of Biomechanics.[18] Euler angles were then calculated from scapula rotation matrices using a Y-X'-Z'' sequence.

Data Analysis and Statistics. Averages and standard deviations of the rotations were calculated for each of the 2 methods. Differences and root mean square errors (RMSE) of the rotation angles resulting from the 2 different methods were evaluated, and nonparametric tests (Wilcoxon signed rank tests) were chosen to assess whether significant differences existed ($\alpha < .05$) between the results obtained through the 2 methods at each elevation angle.

Results

The AMC method provided accurate results in terms of scapula 3D rotations when compared with the model-based approach that was considered the gold standard. This result is illustrated in Figures 2–4 (data from Table 1). From a quantitative point of view, relatively small discrepancies were obtained for low arm elevations (less than 8° for abductions up to 90°; Table 2). Differences

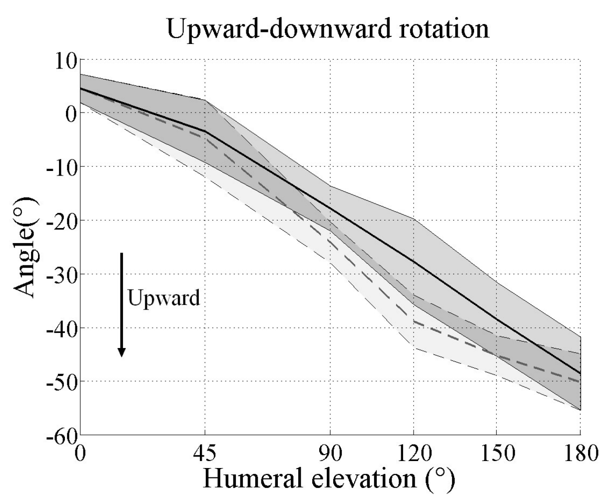

Figure 2 — Scapula upward-downward rotation versus humeral abduction. The model-based approach is illustrated in the pale gray color (average and standard deviations are plotted as dashed lines), and the acromion marker cluster approach is illustrated in the dark gray color (average and standard deviations are plotted as full lines).

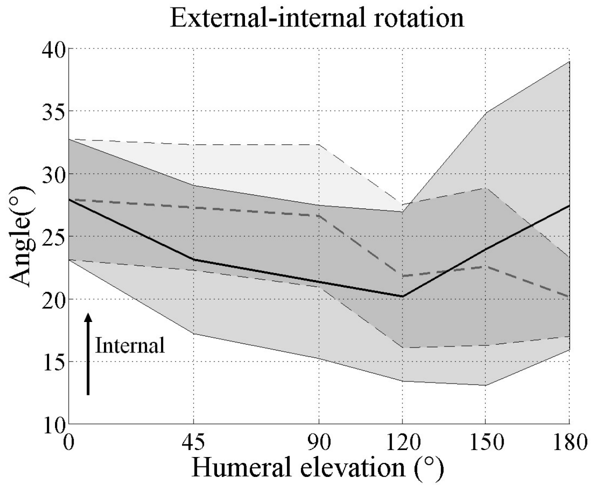

Figure 3 — Scapula external-internal rotation versus humeral abduction. The model-based approach is illustrated in the pale gray color (average and standard deviations are plotted as dashed lines), and the acromion marker cluster approach is illustrated in the dark gray color (average and standard deviations are plotted as full lines).

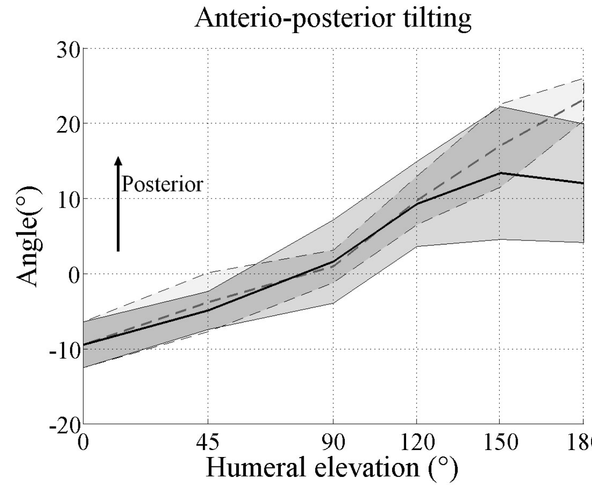

Figure 4 — Scapula anterior-posterior tilting versus humeral abduction. The model-based approach is illustrated in the pale gray color (average and standard deviations are plotted as dashed lines), and the acromion marker cluster approach is illustrated in the dark gray color (average and standard deviations are plotted as full lines).

Table 1 The three scapula rotations for the two measurement methods during humeral abduction

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	4.5 ± 2.6	4.5 ± 2.6	27.9 ± 4.8	27.9 ± 4.8	–9.5 ± 3.0	–9.5 ± 3.0
45°	–4.8 ± 7.2	–3.3 ± 5.9	27.2 ± 5.0	23.1 ± 5.9	–3.8 ± 3.9	–4.9 ± 2.6
90°	–24.2 ± 3.8	–17.7 ± 4.3	26.6 ± 5.7	21.3 ± 6.1	0.9 ± 3.2	1.5 ± 5.5
120°	–38.9 ± 4.9	–27.6 ± 8.0	21.8 ± 5.7	20.2 ± 6.7	9.7 ± 3.2	9.2 ± 5.7
150°	–45.2 ± 3.7	–38.4 ± 7.0	22.5 ± 6.3	24.0 ± 10.8	17.0 ± 5.5	13.3 ± 8.9
180°	–50.1 ± 5.3	–48.4 ± 7.0	20.1 ± 3.1	27.5 ± 11.5	23.1 ± 2.8	11.9 ± 7.9

Abbreviations: AMC = acromion marker cluster.

Table 2 RMSE and differences (average ± standard deviations) for the AMC method compared with the model-based method as the gold standard for the three scapula rotations

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	RMSE	Differences	RMSE	Differences	RMSE	Differences
45°	3.0	–0.7 ± 1.4	6.9	5.1 ± 6.5	2.1	1.2 ± 1.8
90°	8.1	–7.0 ± 5.1	7.5	5.9 ± 6.0	4.1	0.0 ± 4.1
120°	13.5	–12.4 ± 7.1	6.9	2.4 ± 7.3	3.5	1.2 ± 3.7
150°	10.5	–8.4 ± 8.0	9.3	–1.8 ± 9.0	7.1	5.4 ± 6.9
180°	9.4	–4.2 ± 9.6	12.9	–7.9 ± 10.3	12.9	12.9 ± 6.7

Abbreviations: RMSE = root mean square error; AMC = acromion marker cluster.

increased up to 13.5° at higher humeral abduction (Tables 1–2). It can be observed that the AMC method slightly underestimates the upward-downward and anteroposterior rotations for positions above 45° and 120°, respectively. The signed rank tests performed at each elevation angle did not show any significant differences between the 2 measurement methods.

Discussion

This study provides a comparison of the scapular rotations of 6 subjects obtained using 2 in vivo methods: (1) a reference model-based method allowing scapula tracking from low-dose biplanar images and (2) the AMC method. The acromial method has already been assessed as valid by previous studies relying upon palpation or intracortical pins as gold standards,[19] but only for moderate arm abductions.

The current results are in agreement with the scapula rotations described in the literature.[20] Furthermore, the current study emphasizes the same underestimation of scapular motions recorded with the AMC method as reported by van Andel et al.[3] The RMSE up to 100° of abduction are in accordance with those reported in the literature.[3,4,7,8,19] Notably, in a systematic review, Lempereur et al[19] reported errors of 7° during arm abduction for motions below 100° of humeral elevation, which is very close to the present results. However, at higher arm abduction, large RMSE were not found (RMSE up to 13.2°), whereas Karduna et al[7] and Cereatti et al[8] respectively obtained up to 25° and 44.8° of error. These discrepancies may be due to the use of different gold standards. The study by Cereatti et al[8] included a bias due to the use of post-mortem subjects, and the invasive nature of intracortical pins used in the study by Karduna et al[7] may have hindered subjects' natural motions. These differences may also arise from an underestimation of the current reported errors due to measurements performed in static positions only, whereas literature results[7,8] are reported for dynamic measurements.

This study has some limitations. The first limitation concerns the calibration of the AMC method. The present results are free from any calibration errors and should be considered with care. Indeed, the transformation matrix between the cluster and scapula CS was obtained using the biplanar radiographs of the 0° posture, thus it was not possible to compare the scapula rest positions resulting from the 2 methods; only the evolution of the scapular rotations could be compared at different postures. For instance, a calibration based on skin markers could provide discrepancies up to 4° (see Supplementary Material). The second limitation concerns the humeral elevation, which was determined using a protractor but was not recalculated using the humerus position recording from the model-based method as these measurements could not be performed since the humerus markers were not visible on all sets of radiographs. However, arm elevation was adjusted to the subjects' height, and posture was maintained using an adjustable arm support. The third limitation concerns the small number of subjects, as only 6 healthy adult subjects were tested. The testing of children and pathological adults would have broadened the conclusions. Another limitation concerns the location of the AMC; the location at the junction of the scapular spine and the acromion has recently been proven to provide more accurate results[21] than the location chosen here. This location had been chosen to replicate other previous protocols[2,7] and favor comparisons with their results. However, it may lower the accuracy of the AMC method. Finally, the last limitation is that only arm abduction static positions were studied due to the low acquisition frequency of the EOS system, which limits the conclusions since results may be task-specific and velocity-dependent.

In this study, scapular rotations generated by the AMC method were studied. It was shown that few discrepancies exist between the resulting scapula rotations and the rotations generated by a reliable model-based method. In conclusion, the AMC method provides accurate results for low humeral abductions and may also be considered for higher abduction positions.

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Supplementary Material

The following 6 tables provide specific data for each subject.

Supplement Table 1 Scapula rotations for the two measurement methods during humeral abduction for subject 1

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	8,1	8,1	21,1	21,1	–7,8	–7,8
45°	–7,3	–9,2	19,7	13,0	0,9	–1,1
90°	–20,5	–24,2	21,3	12,2	4,5	5,8
120°	–34,1	–37,1	17,1	9,8	12,4	13,8
150°	–43,1	–50,8	15,9	7,5	21,2	22,1
180°	–43,0	–57,6	19,4	9,9	23,7	24,7

Abbreviation: AMC = acromion marker cluster.

Supplement Table 2 Scapula rotations for the two measurement methods during humeral abduction for subject 2

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	4,3	4,3	28,2	28,2	–9,4	–9,4
45°	4,5	5,6	27,9	30,0	–8,6	–7,4
90°	–18,0	–11,8	17,6	18,5	–2,8	–10,0
120°	–31,3	–12,9	17,5	16,9	5,0	–0,2
150°	–39,0	–33,5	18,7	26,3	11,1	3,7
180°	–45,2	–46,4	21,8	34,0	20,8	3,4

Abbreviation: AMC = acromion marker cluster.

Supplement Table 3 Scapula rotations for the two measurement methods during humeral abduction for subject 3

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	1,2	1,2	33,1	33,1	–3,8	–3,8
45°	–0,7	–0,9	32,0	29,9	0,6	–3,5
90°	–26,0	–17,7	28,1	26,2	1,1	4,9
120°	–43,5	–27,1	15,8	21,1	8,6	13,9
150°	–49,9	–32,2	18,4	22,6	15,9	21,8
180°	–58,6	–47,1	17,0	32,2	18,9	6,7

Abbreviation: AMC = acromion marker cluster.

Supplement Table 4 Scapula rotations for the two measurement methods during humeral abduction for subject 4

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	2,7	2,7	22,0	22,0	–10,7	–10,7
45°	–5,2	–3,9	21,5	23,8	–8,2	–7,4
90°	–27,6	–15,7	28,2	29,0	0,2	5,4
120°	–44,0	–28,6	22,1	30,6	14,9	14,4
150°	–48,9	–39,1	25,7	43,0	27,0	21,3
180°	–52,2	–46,0	22,7	45,6	25,7	13,2

Abbreviation: AMC = acromion marker cluster.

Supplement Table 5 Scapula rotations for the two measurement methods during humeral abduction for subject 5

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	7,9	7,9	32,8	32,8	–12,6	–12,6
45°	–1,7	0,3	32,7	19,4	–5,7	–7,4
90°	–24,4	–14,7	29,2	16,2	1,5	–0,0
120°	–37,6	–23,9	27,0	16,9	7,3	3,2
150°	–43,7	–31,2	21,8	16,8	13,7	0,7
180°	–48,3	–36,6	15,5	18,89	22,3	4,2

Abbreviation: AMC = acromion marker cluster.

Supplement Table 6 Scapula rotations for the two measurement methods during humeral abduction for subject 6

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Model-Based	AMC	Model-Based	AMC	Model-Based	AMC
0°	2,6	2,6	30,3	30,3	–12,6	–12,6
45°	–18,6	–11,9	29,8	22,4	–1,7	–2,8
90°	–28,6	–22,2	35,1	25,9	1,2	3,3
120°	–42,7	–35,8	31,3	25,9	10,0	9,9
150°	–46,8	–43,6	34,8	27,6	12,9	10,2
180°	–53,5	–56,6	24,3	24,2	27,2	19,3

Abbreviation: AMC = acromion marker cluster.

The following table provides data regarding calibration errors. Two different calibration methods were used: (1) an ideal calibration based on biplanar radiograph measurements and (2) a calibration based on skin marker position measurements.

Supplement Table 7 Scapula rotations obtained by two different calibration methods and mean calibration errors

	Upward-Downward Rotation (°)		External-Internal Rotation (°)		Anterior-Posterior Tilting (°)	
	Ideal Calibration	Calibration from SkM	Ideal Calibration	Calibration from SkM	Ideal Calibration	Calibration from SkM
0°	4.5	3.2	27.9	29.0	–9.5	–13.0
45°	–3.3	–4.7	23.1	24.2	–4.9	–8.7
90°	–17.7	–19.3	21.3	22.4	1.5	–2.4
120°	–27.6	–29.2	20.2	21.2	9.2	5.0
150°	–38.4	–40.0	24.0	24.9	13.3	9.0
180°	–48.4	–50.1	27.5	28.8	11.9	7.3
Mean error	1.5° ± 0.2°		–1.1°± 0.1°		4° ± 0.4°	

Abbreviations: SkM = skin marker position measurements.