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Article Title: Three-Dimensional Rotations of the Scapula During Arm Abduction: Evaluation of the AMC Method by Comparison With a Model-Based Approach Using Biplanar X-ray

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**Three-dimensional rotations of the scapula during arm abduction: evaluation of the
AMC method by comparison with a model-based approach using biplanar X-ray
images**

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Abstract

Non-invasive 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 to a model-based approach allowing scapula tracking from low dose biplanar X-ray images.

Six healthy male subjects participated in this study. Data acquisition was performed for six 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 RMSE calculation and non-parametric statistical tests.

RMSE remained under 8° for 0-90° arm abduction and under 13.5° for 0-180° abduction; no significant differences were found between the two methods. Compared to 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 gold standard.

Keywords: Biomechanics, Kinematics, Motion analysis.

Abstract word count: 147 words

Word count: 1687 words – 4 figures (as recommended for a technical note)

Introduction

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 artefacts may strongly affect scapula kinematics measurements made by skin sensors¹.

Among the *in vivo* methods that allow measurement of scapula kinematics, the Acromion Marker Cluster (AMC) offers several advantages: beyond being non-invasive, 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 palpation²⁻⁶ or intra-cortical pins⁷⁻⁸. 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 discrepancies⁸⁻¹⁰: 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 intra-cortical 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 golden standard.

Several studies¹¹⁻¹² 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 scapula¹¹). Their main disadvantage to the

patient is the high radiation dose. The EOS™ system (EOS Imaging, Paris, France) provides low-dose stereoradiographic X-rays and thus has the advantage of being 6 to 10 times less irradiant than standard X-rays¹³. A model-based method using EOS images has been developed to measure scapula and humerus orientations and positions¹⁴⁻¹⁵. The accuracy of this model-based approach has been assessed thanks to *in vitro* data: an average error of 1.3mm was found with model reconstruction¹⁶ and a 2.6° accuracy could be obtained for scapula orientations¹⁷.

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 to this new golden standard (i.e. the model-based approach)?

Methods

Subjects

Six healthy male subjects (age: 30.8±8.5 years; 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 six arm abduction positions: 0, 45, 90, 120, 150 and 180 degrees in the frontal plane. An adjustable arm support was used to help the subjects in maintaining the same 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 T8 (Thoracic vertebrae 8) landmarks. Furthermore, an acromion marker cluster (AMC), a quad-pod equipped with four radiopaque markers, was positioned on the flat part of their acromion, just above the most latero-caudal point, with adhesive tape with the aid of a physical doctor (Figure 1).

Bi-planar X-ray images were obtained thanks to the EOS™ system.

Data processing

Geometric modelling from low-dose biplanar X-rays

A personalised scapula model was reconstructed from the bi-planar X-ray images using a dedicated software (Collaboration between LBM, Paris; LIO, Montreal). The model was created based on the set of X-ray images corresponding to the first posture (0°-humeral elevation); then, a sequence of rigid / elastic deformations was performed to adjust the scapula shape and to assess its position on the set of X-rays corresponding to the subsequent postures [15]. The coordinates of the landmarks required to build the scapula coordinate system (CS) (AA, AI and TS) were extracted from the model.

AMC calibration and method

Positions of the reflective markers on the thorax, scapula and cluster were located and recorded after identification on the X-ray images. The transformation matrix between the cluster and the scapula CS was defined by the initial set of X-ray images (0°-humeral elevation). This calibration matrix was used to obtain the scapula CS orientation from the cluster CS orientation in the subsequent postures (Eq. 1).

$$T_{thorax \rightarrow scapula, position i} = T_{cluster \rightarrow scapula}^{calibration} \cdot T_{thorax \rightarrow cluster, position i}$$

Eq. 1. AMC calibration transformation matrix (i is the posture index)

A second calibration method based on skin marker positions was also performed in order 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 ISB¹⁸. 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 two methods. Differences and root mean square errors (RMSE) of the rotation angles resulting from the two different methods were evaluated and non-parametric tests (Wilcoxon signed ranked tests) were chosen to assess whether significant differences exist ($\alpha < 0.05$) between the results obtained through the two methods at each elevation angle.

Results

The AMC method provided accurate results in terms of scapula 3D rotations when compared to the model-based approach considered as golden 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 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 antero-posterior 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 two measurement methods.

Discussion

This study provides a comparison of the scapular rotations of six subjects obtained using two *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 intra-cortical pins as gold standards¹⁹, but only for moderate arm abductions.

The current results are in agreement with the scapula rotations described in the literature²⁰. Furthermore, the current study emphasises the same underestimation of scapular motions recorded with the AMC method as reported by Van Andel et al.³. The RMS errors up to 100° of abduction are in accordance with those reported in the literature^{3,4,7,8,19}; notably Lempereur et al.¹⁹, in a systematic review, 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 RMS errors 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 as for the study by Karduna et al.⁷, the invasive nature of intra-cortical pins 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 X-rays of the 0°-posture, thus it was not possible to compare the scapula rest positions resulting from the two 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: it was determined using a protractor but was not recalculated using the humerus position recording from the model-based method; these measurements could not be performed since the humerus markers were not visible on all sets of X-rays. 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: only six healthy adult subjects were tested, while testing also children and pathological adults would have broadened the conclusions. Another limitation concerns the location of the acromion marker cluster: the location at the junction of the scapular spine and the acromion has recently been proven to provide more accurate results²¹ than the location chosen here. This latter location had been chosen in order to replicate other previous protocols^{2,7} and favour 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 EOSTM system; this limits the conclusions since results may be task-specific and velocity-dependant.

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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Figure 1. A subject equipped with markers and acromion marker cluster (AMC), posing in the cabin dedicated to low-dose bi-planar X-ray measurements.

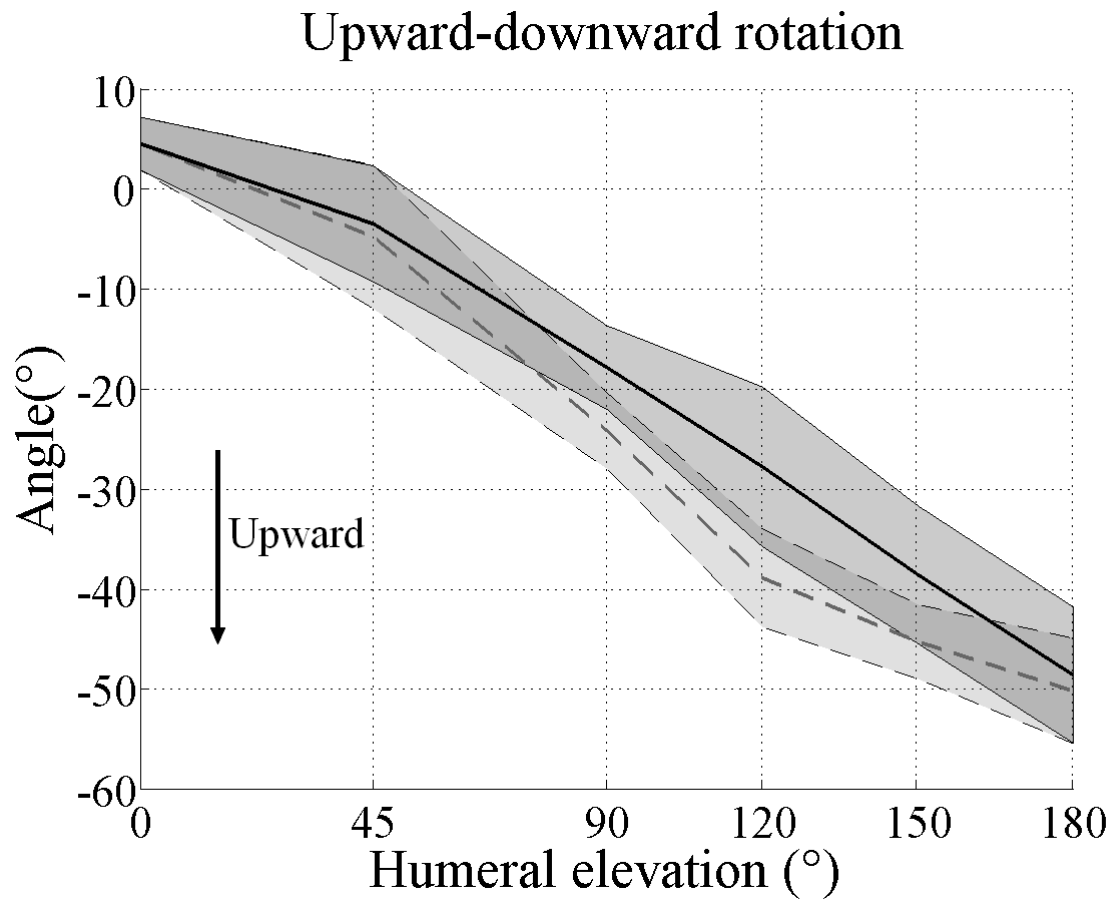


Figure 2. Scapula upward-downward rotation versus humeral abduction. The model-based approach is illustrated in pale grey color (average and standard deviations are plotted as dashed lines), the AMC approach is illustrated in dark grey color (average and standard deviations are plotted as full lines).

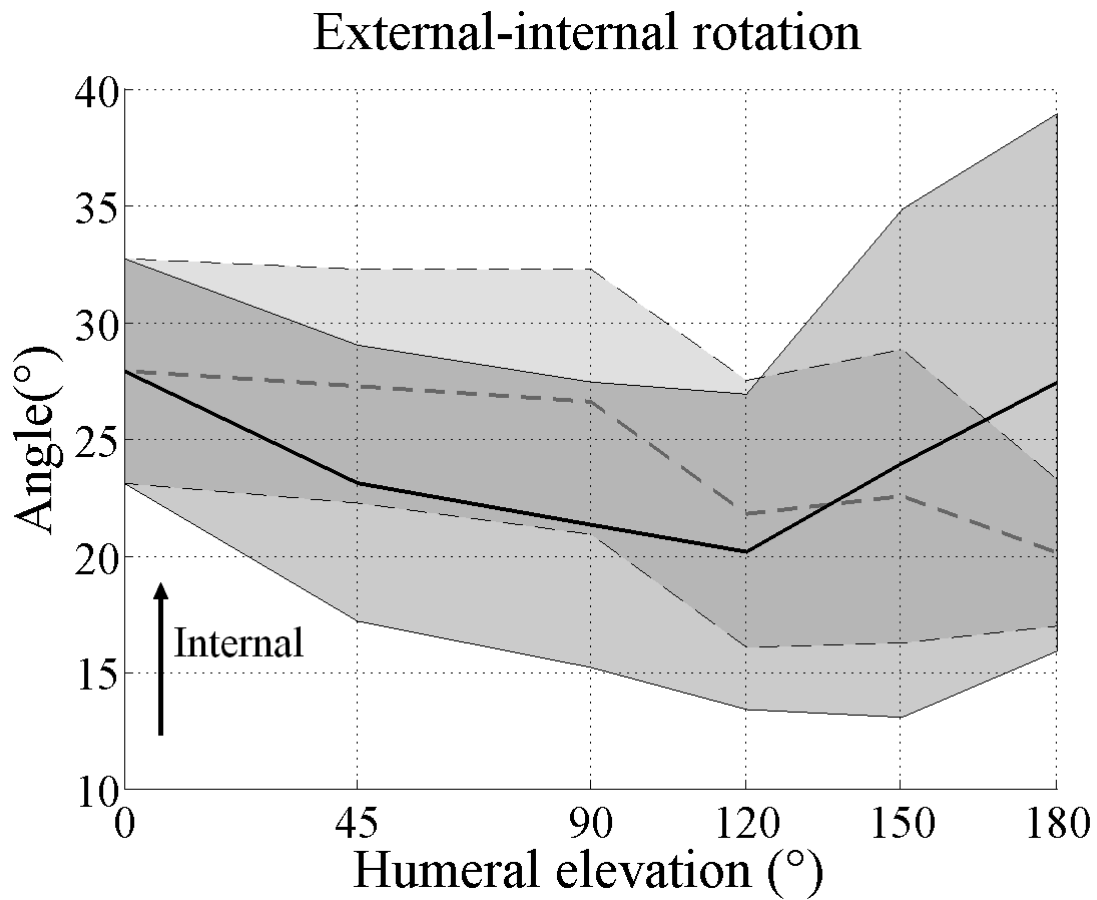


Figure 3. Scapula external-internal rotation versus humeral abduction. The model-based approach is illustrated in pale grey color (average and standard deviations are plotted as dashed lines), the AMC approach is illustrated in dark grey color (average and standard deviations are plotted as full lines).

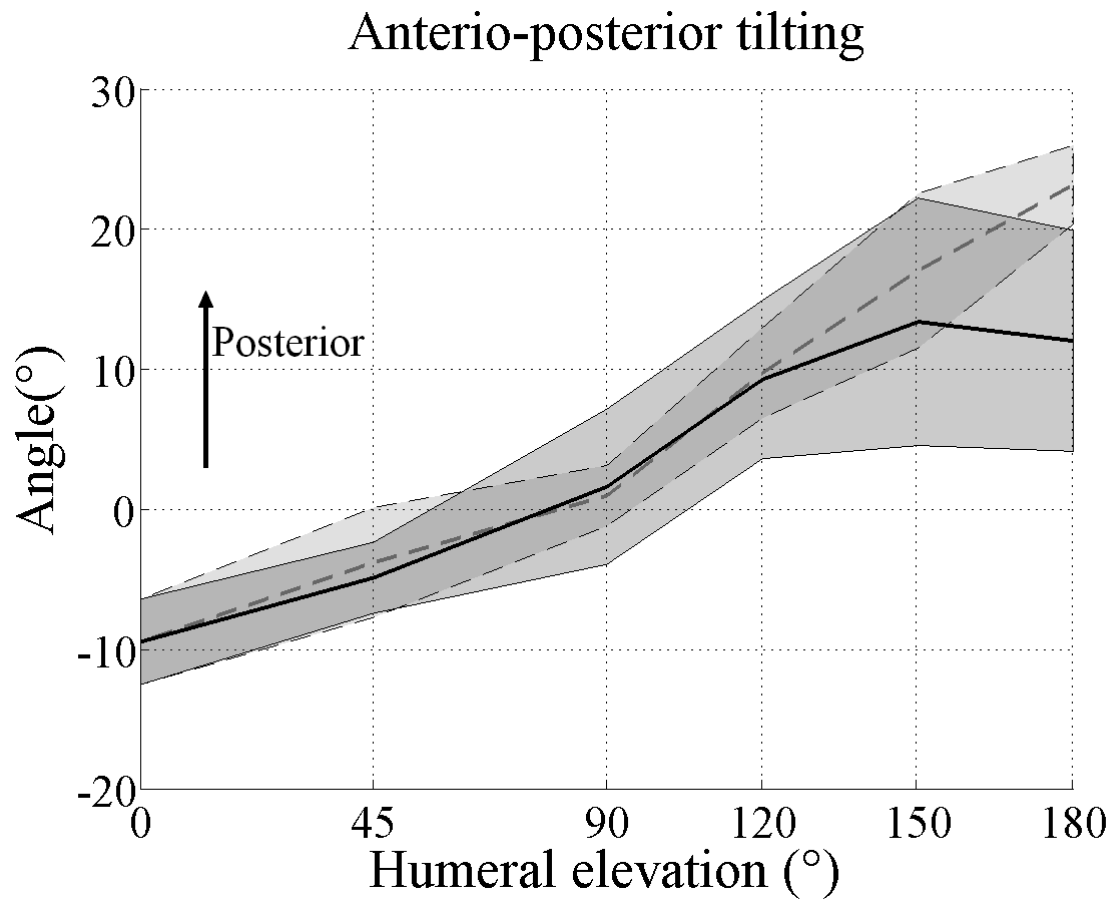


Figure 4. Scapula external-internal rotation versus humeral abduction. The model-based approach is illustrated in pale grey color (average and standard deviations are plotted as dashed lines), the AMC approach is illustrated in dark grey color (average and standard deviations are plotted as full lines).

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

Table 2. RMSE and differences (average ± standard deviations) for the AMC method compared to the model-based method as 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

SUPPLEMENTARY MATERIAL: Specific data for each subject

Supplementary 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

Supplementary 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

Supplementary 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

Supplementary 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

Supplementary 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

Supplementary 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

SUPPLEMENTARY MATERIAL: Calibration error

Supplementary Table 7: Scapula rotations obtained by two different calibration methods (1/ an ideal calibration based on biplanar X-rays measurements, 2/ a calibration based on skin marker positions measurements) 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°	