Recording scapular motion using an acromion marker cluster

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1. Introduction

Scapular movement is an essential component in arm elevation. The position of the scapula serves as an adaptive base of support for the humerus. Abnormal scapular kinematics are believed to contribute to shoulder pain and pathology, i.e., frozen shoulder [1], impingement [2], glenohumeral instability [3] and in joint replacement results [4]. Knowledge of the contribution of scapular motion to the humero-thoracic motion may benefit certain aspects of current clinical practice, such as physical examination, reconstructive surgery and rehabilitation programs. A recent study demonstrated the importance of recognizing the presence of scapular hypoplasia, elevation and rotation deformity before deciding on a treatment plan for persistent internal rotation due to internal rotation contracture in patients with obstetric brachial plexus injury [5].

When using motion capture technology, it is difficult to track the movement of the scapula during dynamic shoulder function, because of its broad, flat shape, substantial soft-tissue covering, and significant skin motion over it. Several methods have been developed for accurate registration of scapular movement. The insertion of bone pins into the scapula of living subjects, combined with a motion capture system, such as an electromagnetic one is obviously the most accurate [6,7]. Despite its high accuracy, such an invasive method is not feasible in clinical practice unless very important decisions depend on it. For diagnostic or evaluation research a number of non-invasive possibilities, based on electromagnetic or optical tracking devices, have been developed to measure scapular movements. These possibilities are detailed in Table 1.

From all the available options to track scapular motion, the acromial method enables dynamic 3D measurement of scapula kinematics. A clinically feasible method requires unconstrained measurement to minimize load and pain for the patient and to allow for natural (including compensatory) movements, especially for (young) children. This method can be included in motion capture protocols, e.g., to evaluate the pre-operative and post-operative status of patients with upper extremity pathologies, especially when dynamic functional movements need to be studied. When upper extremity kinematic data are collected with an optoelectronic system by camera detection of active LED markers, no standard marker cluster is available. A special...
acromion tracker was therefore developed, based on a cluster with three markers. This acromion marker cluster (AMC) is different to the ones used in other studies [6,13] due to its specifically designed light-weight titanium frame (4 g) and small size of the base (15 mm diameter) that can be accurately placed on the flat part of the acromion.

Before applying the AMC, its accuracy would require evaluation, as part of the overall upper extremity 3D movement evaluation using optoelectronic measurements. Generalization from earlier evaluations would not be warranted since the AMC design in this study was very light weight, compared to electromagnetic trackers in previous studies [6,13]. Moreover, the use of this type of AMC should encourage users of these systems to include scapular kinematics in upper extremity evaluation, which is not yet a common procedure [17].

The existing literature is inconclusive concerning the under and overestimation of scapular movement by an acromion sensor. Meskers et al. [13] found a general under-estimation of their acromial method compared to scapula locator (SL) recordings with a maximum rotation error of approximately 9°. Karduna et al. [6] found a maximal root mean square error of 11.4° for the acromial method and reported an over-estimation for external rotation. Therefore, we decided to study the accuracy of this AMC using the SL method to serve as reference [11]. It was hypothesized that no systematic error would be found between the results of the two methods, at least up to 120° humerus elevation. Since replacement of the acromion tracker was found to be a source of variability [13], an assessment of the test/retest reliability of the AMC was also included in our study.

### Table 1

<table>
<thead>
<tr>
<th>Method</th>
<th>Proposed by</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapulohumeral regression</td>
<td>[8, 9]</td>
<td>Unsuitable for shoulder pathology</td>
</tr>
<tr>
<td>Scapula locator</td>
<td>[10–12]</td>
<td>Acceptable method for clinical measurements, although there is always a small error because exact replacement is impossible [5, 10, 12]. Requires static measurement positions</td>
</tr>
<tr>
<td>Skin-mounted acromion tracker</td>
<td>[6, 13]</td>
<td>Valid up to 120° humerus elevation, enables dynamic measurements</td>
</tr>
<tr>
<td>Skin deformation, measured with markers</td>
<td>[14]</td>
<td>Requires minimal soft tissue coverage and muscle volume over the scapula. Preliminary results</td>
</tr>
<tr>
<td>Digital fluoroscopy</td>
<td>[15, 16]</td>
<td>Subjects exposed to radiation. So far, scapular motions only measured in one plane</td>
</tr>
</tbody>
</table>

### 2. Materials and methods

#### 2.1. Subjects

Thirteen healthy subjects (six male and seven female), between 22 and 33 years of age, were recruited for this study. Two different measurement protocols were performed: a validation protocol and a reliability one. Four subjects performed both protocols, seven subjects performed a validation protocol only, and two subjects performed a reliability protocol only. Accordingly, there were eleven validation measurements and six reliability measurements. The right shoulder of all subjects was tested. Approval was obtained from the ethical committee of the Faculty of Human Movement Science of the VU University in Amsterdam, and all subjects provided informed consent.

#### 2.2. Instrumentation

3D kinematic data were collected by means of an Optotrak (Northern Digital Inc., Canada) system with 3 camera-sensors. This system is accurate up to 0.1 mm, and the data were sampled at 50 Hz. Five clusters of markers were used to track the thorax, scapula, scapula locator, upper arm and forearm and all clusters consisted of three markers, except for the forearm cluster which consisted of six markers. The thorax cluster was attached to the sternum with double-sided adhesive tape. The upper arm cluster was attached to a cuff and strapped to the lateral arm just below the insertion of the deltoid. A forearm cuff with six equally distributed markers was strapped just proximally to the ulnar and radial styloids. Scapular movements were recorded using two methods: (1) the AMC attached to the flat part of the acromion with adhesive tape (Fig. 1), and (2) an SL. The SL is a fixture with an attached sensor, holding three pins which can be adjusted to fit the landmarks on the scapula prior to measurement. During the measurement, the investigator keeps the SL in close contact with the bony landmarks of the scapula, slipping over the skin. The SL pins were positioned on the acromial angle (AA), the root of the scapular spine (trigonum spinae (TS)) and the inferior angle (AI) of the scapula.

To link the position of the marker cluster to local anatomical coordinate systems, a standard pointer device was used to digitize 15 bony landmarks according to the ISB standardization proposal for the upper extremity [18]. The proximal landmark of the humerus, the glenohumeral rotation center, was estimated from scapular

![Fig. 1. Positions of the SL with a cluster of three markers (A) and the acromion marker cluster that was placed on the flat part of the acromion (B).](image-url)
of the scapula with the AMC would be approximately 120°. For this protocol the following positions were measured: (1) Humerus forward flexion from 0° to 120° with the elbow in full extension. (2) Humerus abduction from 0° to 120° with the elbow in full extension. (3) Humerus rotation from 60° internal to 90° external, in 90° abduction and the elbow in 90° flexion.

The subjects moved their arm through the desired arc in steps of 30°. The interval from 90° to 120° of humerus elevation (postures 1 and 2) was measured in steps of 10°, because it was expected that the maximum valid measurement of the position of the scapula with the AMC would be approximately 120° humerus elevation [6,13]. These three postures were measured in random order. The AMC and the SL measured scapular motion simultaneously (Fig. 1) and each position was measured for 0.5 s. One successful measurement of each posture was required. One successful measurement of each posture was required.

2.3. Measurement procedures

2.3.1. Validation protocol

To validate the AMC the following postures were studied:

(1) Humerus forward flexion from 0° to 120° with the elbow in full extension.
(2) Humerus abduction from 0° to 120° with the elbow in full extension.
(3) Humerus rotation from 60° internal to 90° external, in 90° abstraction and the elbow in 90° flexion.

The subjects moved their arm through the desired arc in steps of 30°. The interval from 90° to 120° of humerus elevation (postures 1 and 2) was measured in steps of 10°, because it was expected that the maximum valid measurement of the position of the scapula with the AMC would be approximately 120° humerus elevation [6,13]. These three postures were measured in random order. The AMC and the SL measured scapular motion simultaneously (Fig. 1) and each position was measured for 0.5 s. One successful measurement of each posture was required.

2.4. Reliability protocol

To assess the inter-trial variability of the AMC, six subjects performed a reliability protocol. For this protocol the following positions were measured:

(1) Anatomical posture.
(2) 90° and 120° humerus forward flexion with the elbow in full extension.
(3) 90° and 120° humerus abduction with the elbow in full extension.

The first observer positioned the AMC for anatomical calibration, after which both observers measured scapular movements for the different positions using the SL. Subsequently, the AMC was removed and then repositioned by the second observer. This was followed by anatomical calibration. Again both observers measured scapular movement with the SL. The order of examination by the first and second observer was randomized.

2.4.1. Data analysis

BodyMech ([www.bodymech.nl]), a Matlab® based open source package for 3D kinematic analysis, was used and adapted to calculate joint kinematics from recorded 3D marker positions. In this study, motion of the scapula in relation to the thorax was calculated for both methods (AMC and SL), with rotation order protraction/retraction (Y), external/internal rotation (X) and anterior/posterior rotation (Z) [18].

For each posture, a generalized linear model analysis of variance (GLM-ANOVA) with repeated measures (SPSS® 12.0.1) was performed to establish the difference between the SL and the AMC recordings. Independent variables were method (SL and AMC) and angle. Reliability was assessed according to the Generalizability Theory, which is based on analysis of variance (ANOVA) [19]. The components of variance that were estimated with this analysis included the inter-subject variance, the variance related to replacement and the error variance. Variance related to replacement and error variance were used to calculate the standard error of measurement (S.E.M. = ξ{(replacement + error)}).

3. Results

Despite the standardization by means of semicircular pipes, arm elevation resulted in variable humerus positions due to variable elbow flexions, wrist flexions and thorax rotations. Also fatigue during the course of the session, may have been of influence. This resulted in a certain amount of variability in the scapula positions. Moreover, the calculated thoracohumeral elevation rarely exceeded 110°. The results of a recent study [21] showed that the mean maximum humeral elevation appearing in a set of functional tasks is approximately 100°, therefore we accepted the fact that 120° of elevation was not reached by the subjects. Scapula positions as a function of humerus elevation in the validation protocol were approximated by a second order polynomial, in order to compare subjects at equal and re-sampled humerus elevation angles of 20°, 40°, 60°, 80° and 100°.

3.1. Validation protocol

The mean recordings of the SL and the AMC over all subjects and the error between the two methods were calculated for each of the postures. Fig. 3 presents the graphs of these calculated values for the postures forward flexion (Fig. 3a), abduction (Fig. 3b) and internal/external rotation (Fig. 3c). The differences and interaction effects between the two methods for each posture are shown in Table 2.

In general, there was no significant difference between the two methods, except for external rotation during abduction. Overall, the recordings of the AMC showed a larger standard deviation than the recordings of the SL, and the standard deviation increased with humeral elevation (Fig. 3a and b). Although the error graphs show that the mean difference did not exceed 8.4°, the error bars indicate that some individual subject differences reached extreme values of approximately 25°. Further investigation showed that these extreme values occurred during abduction above 90° and in the extremes of internal/external rotation. In these particular cases the scapular movements indicated by the AMC were remarkably lower than those indicated by the SL. Mostly, the AMC under-estimated the scapular movements, compared to the SL, except for protraction and external rotation during forward flexion and spinal tilt at 90° external rotation.

3.2. Reliability protocol

The results of the reliability assessment for the AMC are shown in Table 3. Overall, ICC values for protraction and external rotation were found to be acceptable to good. For spinal tilt the ICC values
were low. A maximal S.E.M. of 8.4° was found in spinal tilt at 120° humeral forward flexion. The amount of measurement error had a maximal value of 8.4°, which is equal to the mean maximal error found in the validation study.

4. Discussion

In general, scapular movements recorded by the AMC are similar to recordings made with the SL. During the internal and external rotation posture the maximum mean difference did not exceed 8.4° (found in protraction). During forward flexion and abduction of the humerus, the maximum mean differences were 6° or lower. These findings are similar to the errors found by Meskers et al. [13], who reported a maximum mean difference of 6° in protraction during forward flexion and 9° in external rotation during abduction. The standard deviations found in this present study, varying from 3.5° to 9.5°, are within the range described by Karduna et al. [6], who found a root-mean-square error varying from 1.1° to 11.4°. The SL is also prone to error, however, the anatomical points of the scapula that are used to align the SL, are the most distal ones. Minor misalignments in placing the SL will, therefore, not cause much effect. Therefore, given the choice to use

![Figure 3. The results of the validation protocol in (a) humerus forward flexion, (b) humerus abduction, and (c) internal and external rotation at 90° humerus abduction. The upper graphs show the mean recordings over all subjects by the SL (blue line, chequered) and the AMC (pink line, squares) with their standard deviation and the lower graphs show the mean difference (error) between both methods with standard deviations (below), all for each of the three scapular movements (protraction, external rotation and spinal tilt). The mean difference was calculated by subtracting the mean recordings of the SL cluster from the mean recordings of the AMC (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).](image-url)
a non-invasive reference method, the SL is considered the best possible solution. An invasive method like 3D RSA would, however, yield the highest accurate golden standard [22].

General under-estimation of scapular movements recorded by the AMC compared to the SL, was also found by Meskers et al. [13] but is partly in contradiction with Karduna et al. [6]. Individual anatomical characteristics such as muscle mass and subcutaneous tissue may represent a possible explanation for this under-estimation. Especially above 90° of humerus elevation the deltoid muscle contraction causes alternation in the shape of soft tissues. Another factor could be skin to bone displacement. Both muscle bulging and skin to bone displacement lead to a loss of contact between the AMC and the acromion. This can result in an under-estimation of scapular movement by the AMC while the scapula continues moving during elevation. These anatomical characteristics, unique to each individual, may also explain the large error observed in some individuals during abduction, particularly above 90° humerus elevation. In addition to general under-estimation, the AMC over-estimated two scapular movements, compared to the SL: protraction and external rotation during forward flexion of the humerus. Karduna et al. [6] also reported an over-estimation during external rotation. During forward flexion the deltoid muscle displaces only the anterior-lateral part of the AMC, while the posterior part still contacts the acromion well. This results in a larger external rotation by the AMC, more than the scapula actually moves. Likewise, protraction may be influenced by the contracting deltoid muscle.

As the deformity caused by the deltoid appears to be an important factor affecting accuracy of the AMC in registering scapular movements, placement of the AMC is a critical issue. The large contribution of variance related to repositioning of the AMC for all postures during protraction demonstrated the dependence of protraction on AMC positioning. For the other two scapular movements the variance caused by repositioning of the AMC was negligible. Meskers et al. [13] also reported an effect of repositioning of the AMC on the recorded scapular movement. They stated that the acromial method of scapular recordings is only precise when the recordings are compared without repositioning the receiver. However, this is not possible in clinical practice.

Table 2
Results of the ANOVA for repeated measurements with scapular movement (protraction, external rotation and spinal tilt) as dependent and method (SL and AMC) and angle as independent variables

<table>
<thead>
<tr>
<th>Posture</th>
<th>Scapular movement</th>
<th>Mean (±S.D.) (°)</th>
<th>Method (significance)</th>
<th>Method × angle (significance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SL</td>
<td>AMC</td>
<td></td>
</tr>
<tr>
<td>1. Humerus forward flexion</td>
<td>Protraction</td>
<td>34.6 (9.6)</td>
<td>38.8 (12.3)</td>
<td>0.028*</td>
</tr>
<tr>
<td></td>
<td>External rotation</td>
<td>23.2 (5.0)</td>
<td>24.9 (5.6)</td>
<td>0.121</td>
</tr>
<tr>
<td></td>
<td>Spinal tilt</td>
<td>−1.4 (3.8)</td>
<td>−3.2 (7.7)</td>
<td>0.286</td>
</tr>
<tr>
<td>2. Humerus abduction</td>
<td>Protraction</td>
<td>26.6 (7.7)</td>
<td>23.5 (12)</td>
<td>0.237</td>
</tr>
<tr>
<td></td>
<td>External rotation</td>
<td>30.6 (7.6)</td>
<td>28.0 (7.3)</td>
<td>0.021*</td>
</tr>
<tr>
<td></td>
<td>Spinal tilt</td>
<td>1.8 (6.3)</td>
<td>−0.3 (9.7)</td>
<td>0.312</td>
</tr>
<tr>
<td>3. Humerus internal/external rotation</td>
<td>Protraction</td>
<td>27.1 (7.0)</td>
<td>21.9 (13.1)</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>External rotation</td>
<td>34.7 (7.7)</td>
<td>31.2 (8.5)</td>
<td>0.090</td>
</tr>
<tr>
<td></td>
<td>Spinal tilt</td>
<td>2.0 (5.8)</td>
<td>−1.1 (9.3)</td>
<td>0.244</td>
</tr>
</tbody>
</table>

* Significant at p < 0.05.  ** Significant at p < 0.01.
Therefore, reducing the error caused by fixation and calibration after repositioning of the AMC requires further investigation. In general, external rotation movements are accurately recorded by the AMC, as shown by the high or acceptable ICC values and insensitivity to repositioning of the AMC. For all scapular movements, the S.E.M. value lies within the found mean maximal error of 8.4° in the validation study.

There are, however, some limitations. Increasing the amount of humerus elevation affected all scapular rotations, and the plane of movement and repositioning of the AMC affected movements in protraction. The small range of spinal tilt (approximately 10°), which was close to the maximal mean error of 8.4° found in the present study, makes recording of this scapular motion by the AMC questionable. This is also reflected in low ICC values for spinal tilt.

Despite the fact that the hypothesis of an unambiguous relationship between the results of the SL and the AMC, at least up to 120° humerus elevation, could not be entirely confirmed, the AMC that was investigated in this study was found to be a valid method to detect abnormalities and differences above 8.4°. This is below the range of abnormal scapular movement found in pathologies such as stroke (e.g. a diminished protraction of 16°, compared to healthy subjects) reported by Meskers et al. [23] and impingement syndrome (e.g. a lower posterior tilting of 9.5°, compared to healthy subjects) [24].

In conclusion, we found that the AMC allows dynamic and unconstrained recording of scapular motion. We recommend the use of an AMC as part of motion capture protocols evaluating upper extremity functional movements. Interpretation of results of the AMC are however not recommended above 100° elevation, and only deviations and differences above 8.4° can be concluded. These values can, however, be considered a clinically meaningful measure, except for spinal tilt.

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### Conflict of interest

The authors declare that they have no competing interests.

### References


