Journal of Electromyography and Kinesiology 44 (2019) 46–55

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

# A new method of estimating scapular orientation during various shoulder movements: A comparison of three non-invasive methods

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ARTICLE INFO

*Keywords:*
Shoulder
Scapula
Acromion marker cluster
Motion analysis

ABSTRACT

The conventional acromion marker cluster (AMC) method used to estimate scapular orientation cannot adequately represent complex shoulder movements due to soft tissue artifacts. The regression method may have nonlinear error changes depending on humeral elevation angle and elevation plane. Therefore, we aimed to develop a new method of estimating scapular orientation using curved surface interpolation during various shoulder movements, and to compare its accuracy with conventional and regression methods. Thirteen healthy men were recruited. AMC and refractive markers for bony landmarks were placed on the skin. During the preprocess, several shoulder postures, including different arm elevations and elevation planes, were measured using the motion capture system. Premeasured data were used to calibrate the positional relationship between AMC and scapula using curved surface interpolation. Subsequently, scapular orientations were estimated by measuring AMC and body markers of any shoulder posture. To evaluate the accuracy of our methods, 25 elevation postures and six tasks involving postures common to activities of daily living were applied. For tasks requiring greater arm elevation angles, the root mean square error was less in our method than in the conventional and regression methods. Therefore, our method could improve the accuracy of estimating scapular orientation in various elevation postures.

## 1. Introduction

The shoulder has a wide range of motion because of its anatomical structure. This enables dynamic movements involved in activities of daily living (ADL) and sports-related movements. To decrease mechanical stress to the glenohumeral joint or soft tissue, and to achieve smooth movements of the shoulder, the scapula requires cooperative three-dimensional movements with humeral movements (Burkhart et al., 2003). Understanding scapular kinematics during shoulder movements provides important information for diagnosing and treating shoulder disorders and for improving the performance of ADL and sports (Fayad, 2008; Meyer et al., 2008). A recent systematic review reported that scapular movements changed in patients with shoulder disorders (Struyf et al., 2011). However, it has also been reported that there was no difference in the scapular movements of patients with shoulder disorders compared with asymptomatic controls (Ratcliffe et al., 2014). Therefore, additional evidence is needed to better understand the relationship between shoulder and scapular movements.

Tracking scapular movement using markers attached to the body surface is difficult because the scapula moves under the skin and soft tissue. Skin markers cannot adequately trace the trajectory of the scapular landmarks during arm movements (Matsui et al., 2006). Therefore, the acromial method was developed to estimate scapular orientation (McQuade, 1998). Additionally, the acromion marker cluster (AMC) method was developed to estimate scapular orientation when applying the acromial method using the optical motion capture system (van Andel, 2009); this method has been widely used for measuring various shoulder and clavicle movements (Lempereur et al., 2014; Bet-Or et al., 2017). The marker cluster consists of multiple lightweight, small-based markers affixed to the skin during the acromion process. The positional relationship between the AMC and scapular landmarks is calibrated using premeasured motion data, and the scapular orientation is then estimated by calibrating measured AMC data. In most studies, this calibration process was performed with the arm at the resting position (0° of shoulder elevation) (van Andel, 2009; Janes et al., 2012; Warner et al., 2012). The error of the estimated scapula orientation significantly increased beyond 120° of thoraco-humeral (TH) elevation (Karduna, 2001). Furthermore, the positional relationship between the AMC and scapula is not constant, due to soft tissue deformity at high arm elevation angles that results in decreased

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https://doi.org/10.1016/j.jelekin.2018.11.007
Received 17 April 2018; Received in revised form 23 October 2018; Accepted 8 November 2018

scapular estimation accuracy. To improve the accuracy of the AMC method at high degrees of humeral elevation, the double calibration approach was developed (Brochard et al., 2011). However, this approach can be used only for single-plane humeral movements, and not for ADL or sports-related movements that involve multiplane movements. Thus, Nicholson et al. developed the regression method using three multiple linear regression equations to estimate scapular orientation (Nicholson et al., 2017). They reported that the error of the regression method was less than approximately 8°. Moreover, Rapp et al. compared the estimation errors of the regression method with those of the AMC method with double calibration in several functional positions (Rapp et al., 2017). The estimation errors for the regression method were approximately 4–8°, and the error for the regression method was smaller than that of the AMC for the whole measured position. These reports suggest that estimation errors of scapular orientation can be reduced by using these several premeasured TH orientations. However, these previous studies developed regression equations from certain postures, and verified estimation error at specific ADL postures. Therefore, the estimation error distribution in various shoulder elevation planes and elevation angles remains unclear. If the estimation error distributions were represented nonlinearly by a wider variation range of shoulder orientations, it is possible that estimation error of the shoulder orientation could be reduced by a non-linear interpolation, depending on TH elevation plane and elevation angle.

To reduce the estimation error of scapular orientation using AMC, we aimed to develop a new estimation method for scapular orientation using non-linear interpolation, and to compare the estimation accuracy of our method with that of the conventional AMC method, calibrated at only the arm at rest position, and the recently reported regression method. We hypothesized that our method would improve estimation accuracy compared with the other methods in various shoulder elevation postures.

## 2. Materials and methods

### 2.1. Subjects

The right arms of 13 healthy men (age, 21.1 ± 2.4 years; height, 174.4 ± 7.0 cm; weight, 72.1 ± 10.9 kg) were measured. None had a history of musculoskeletal injury or neuromuscular disease involving the upper arms. At the time of measurement, the participants did not have any pain in their right shoulder at rest or in motion and reported no pain during the previous one week. Participants were randomly recruited from our institution and regularly performed various sports (baseball, gymnastics, and archery) from a recreational to a university athlete level.

Oral and written informed consent was obtained from all participants. This study was approved by our institutional ethical committee (No. 16028).

### 2.2. Instrumentation

Kinematic data were collected using an optical motion capture system (MAC3D system; Motion Analysis Corporation, USA) with a sampling rate of 240 Hz. A cluster of small, light-weight markers were applied to the skin over the flat part of the acromion (Fig. 1A). This cluster consisted of three 4-mm refractive markers placed in a triangular formation. The 12-mm reflective markers were applied to the C7 and Th8 spinous process, sternal notch, xiphoid process, medial epicondyle, and lateral epicondyle (Wu et al., 2005). A scapular locator (SL) was used to palpate the scapular bony landmarks (Fig. 1B). SL has three adjustable pins to fit the acromial angle, trigonum spinae, and inferior angle of the scapula (Brochard et al., 2011). A 4-mm refractive marker was fixed on the head of each locator pin. The investigator kept the SL in close contact with the bony landmarks of the scapula during measurement.

### 2.3. Measurement tasks

To evaluate estimation error distribution, we measured 25 postures with the combination of several elevation planes and elevation angles. These postures were assumed in a resting position, with 30–180° elevation in 0° (coronal plane) to 90° (sagittal plane) and the elbows fully extended. Elevation and elevation angles were set in steps of 30°. We referred to these tasks as the "elevating postures" (Fig. 2A). During the experiment, subjects were seated on a chair with a semicircular adjustable guide to standardize the postures (Fig. 2B). We instructed them to point their middle finger at the marks on the guide without shoulder pain and discomfort or compensatory trunk motion.

To evaluate functional postures, the following six postures were measured: hand to head, forward reach, lateral reach, hand to mouth, 45° of arm elevation in 45° of the elevation plane (45° elevation), and 135° of arm elevation in 45° of the elevation plane (135° elevation) (Fig. 3). We referred to these tasks as the "functional postures". Additionally, we measured kinematic data in hand to spine, external shoulder rotation, and extension for the regression method, which is described later.

Subjects held both arms in each instructed posture for 3 s. The AMC, SL, and other landmarks were measured simultaneously. Whole measurements were performed by one observer who had extensive experience with human anatomy and anatomical landmark palpation.

### 2.4. Estimation of scapular orientation

To calculate the positional relationships between the AMC, scapular landmarks, humerus, and trunk, the local coordinate system (LCS) of the scapula ($\Sigma_S$), humerus ($\Sigma_H$), and thorax ($\Sigma_T$) was determined (Wu et al., 2005). The LCS of the AMC ($\Sigma_A$) was determined using the AMC markers (Fig. 4A). $R_{Ai}$ and $R_{S\text{-}Ai}$ ($\alpha_i$, $\beta_i$, $\gamma_i$) were the coordinate transformation from the $\Sigma_{Ai}$ to $\Sigma_{Ti}$ and from the $\Sigma_{Ai}$ to $\Sigma_{Si}$ at arbitrary posture

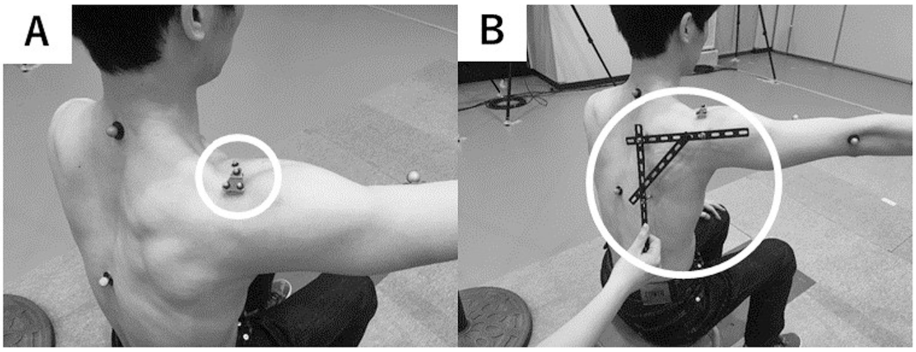


**Fig. 1.** (A) The acromion marker cluster that was placed on the flat part of the acromion process. (B) The positions of the scapular locator.

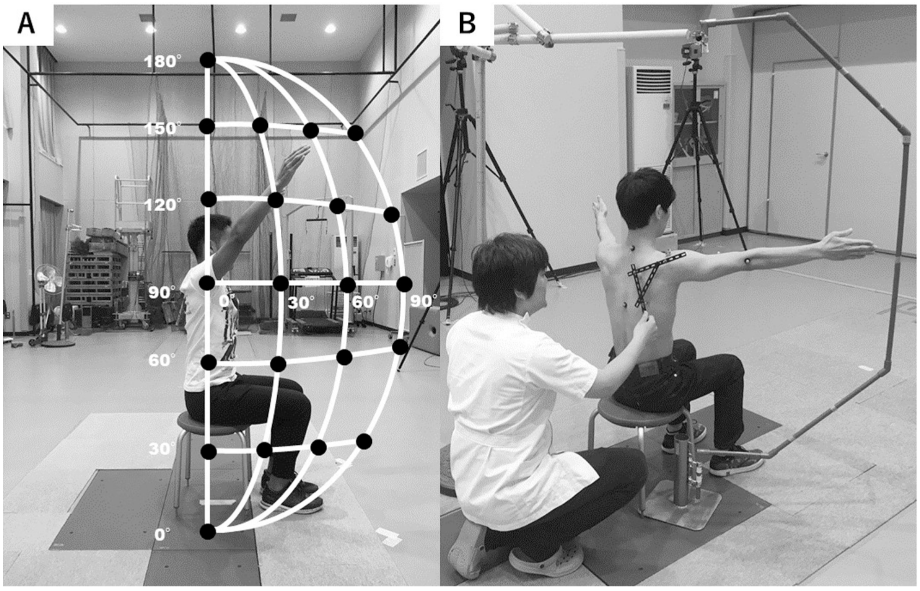


**Fig. 2.** (A) Elevating postures. (B) Experimental set-up.

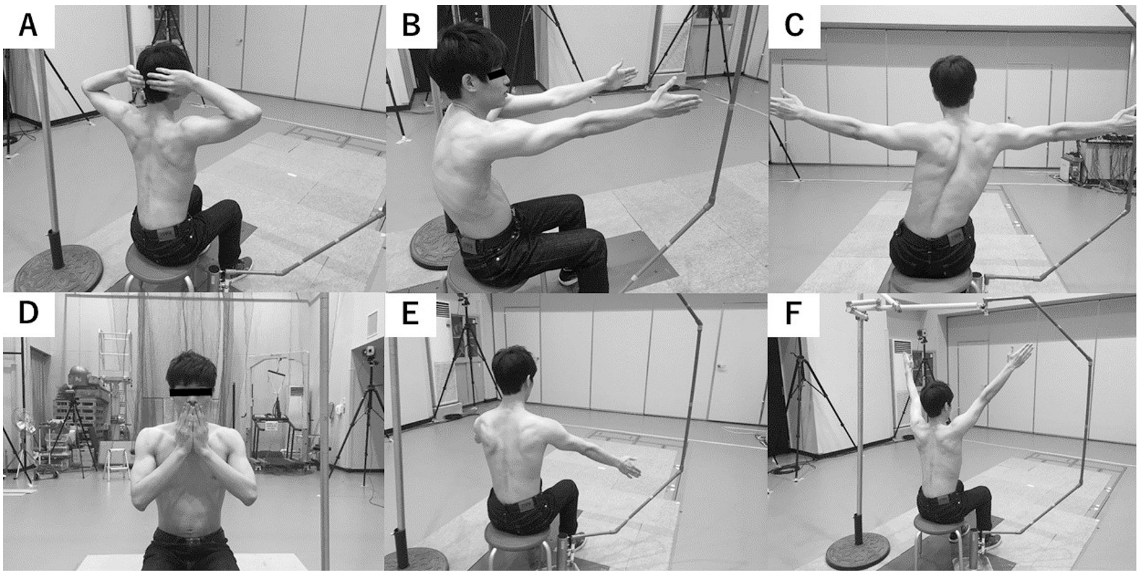


**Fig. 3.** Functional postures: (A) hand to head; (B) forward reach; (C) lateral reach; (D) hand to mouth; (E) 45° elevation; (F) 135° elevation.

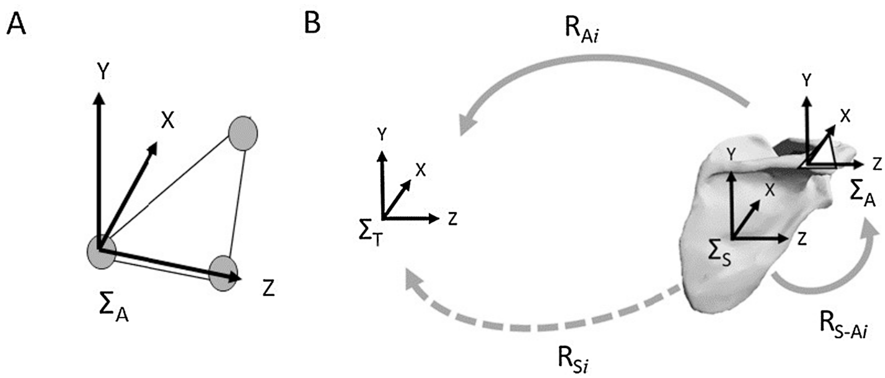


**Fig. 4.** (A) The coordinate system of the acromion marker cluster (AMC). (B) The coordinate transformations of the AMC method.

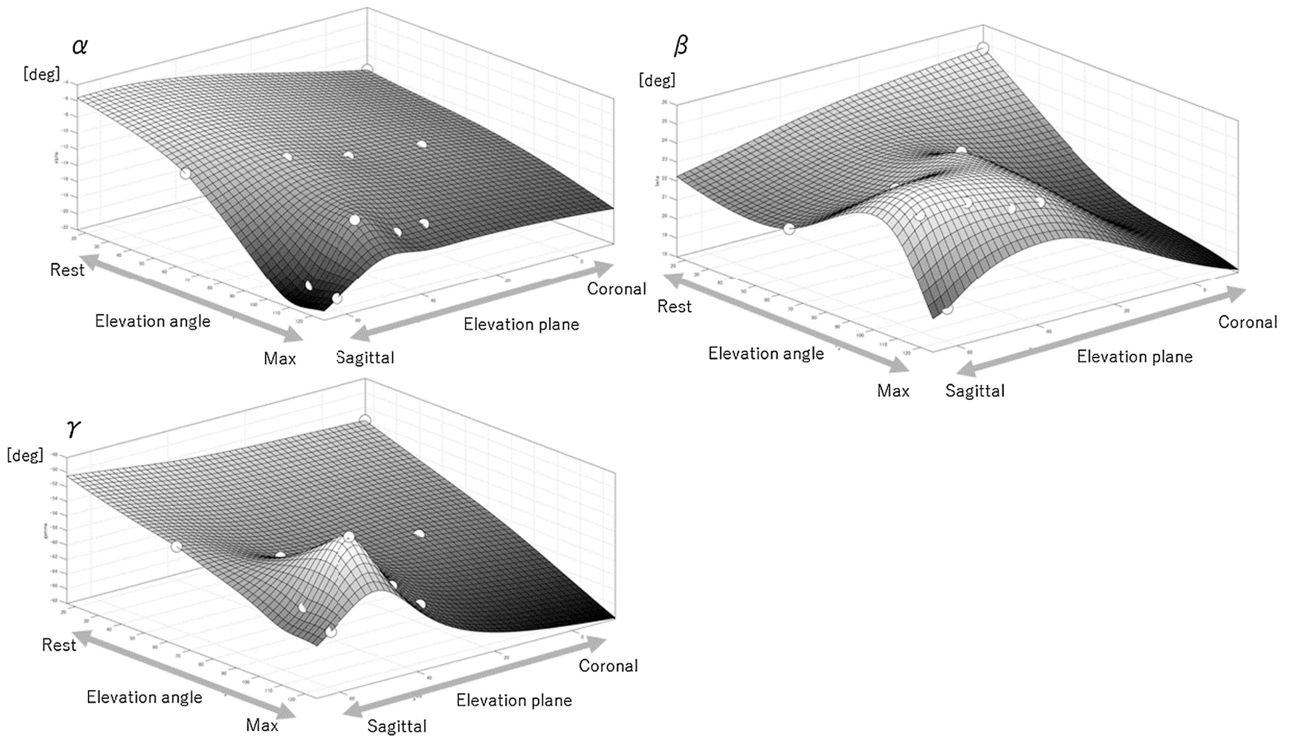


**Fig. 5.** An example of thin-plate spline interpolation for $R_{S\text{-}A}$.

*i*, respectively. The $\alpha_i$, $\beta_i$, and $\gamma_i$ were the Euler angles of $R_{S\text{-}Ai}$, which were related to the x-, y-, and z-axis of the scapular LCS, respectively. Hence, scapular orientation $R_{Si}$ was determined using the following equation:

$$R_{Si} = R_{Ai}R_{S-Ai}(\alpha_i, \beta_i, \gamma_i)$$

The scapular orientation with respect to the thorax ($\Sigma_{Ti}$) was calculated using the Euler angle rotation order: external/internal rotation (y-axis), upward/downward rotation (x-axis), and anterior/posterior tilt (z-axis) (Fig. 4B).

### 2.4.1. Our new estimation method

To improve estimation accuracy, it was necessary to modify $R_{S\text{-}Ai}$ with successive changes in the arm posture. Therefore, $R_{S\text{-}Ai}$ ($\alpha_i$, $\beta_i$, $\gamma_i$) was modified by humeral movements involving TH elevation plane angle $\theta_i$ and elevation angle $\varphi_i$. The $\alpha_i$, $\beta_i$, and $\gamma_i$ were interpolated by the following calibration functions: $\alpha_i = \alpha(\theta_i, \varphi_i)$, $\beta_i = \beta(\theta_i, \varphi_i)$, and $\gamma_i = \gamma(\theta_i, \varphi_i)$. The $\alpha$ () was calculated using $\alpha_j$, $\theta_j$, and $\varphi_j$ for the 10 premeasured postures *j* using thin-plate spline interpolation (Bookstein, 1997) (Fig. 5). These postures were as follows: arm at rest position, 90° and 150° of arm elevation in steps of 30° from 0° to 90° of the elevation planes, and 180° of arm elevation in 30° of the elevation plane (Fig. 6). The $\beta$ () and $\gamma$ () were calculated similarly. We selected these postures to improve the accuracy of high arm elevation positions. However, to avoid time-consuming premeasurements, we set a limit of 10 postures for each subject.

### 2.4.2. Conventional method

Using the conventional method for comparison, $R_{S\text{-}A0}$ ($\alpha_0$, $\beta_0$, $\gamma_0$) was a constant value that was calculated using the resting position (*i* = 0) (van Andel, 2009). Therefore, scapular orientation $R_{S\text{-}CONi}$ was represented $R_{Ai}$ $R_{S\text{-}A0}$ ($\alpha_0$, $\beta_0$, $\gamma_0$).

### 2.4.3. Palpation method

The scapular orientation used as a reference was represented by the coordinate transformation $R_{SLi}$ from $\Sigma_{Si}$ to $\Sigma_{Ti}$. $\Sigma_{Si}$ was determined by measuring the body marker using the SL (Fig. 7).

### 2.4.4. Regression method

According to Rapp's study, multiple linear regression equations were calculated to estimate the scapular orientation (Rapp et al., 2017). The equations were generated using the pre-measured postures: arms at rest, abduction, external rotation, extension, flexion, 30° elevation at 30° of elevation plane, hand to mouth, hand to head, forward reach, and hand to spine. After generating the regression equations, the scapular orientations were estimated.

All calculations were performed using the MATLAB platform (MATLAB R2018a; MathWorks, Natick, MA, USA.)

## 2.5. Evaluation of accuracy

To compare the accuracy of each estimation method, the Friedman test was performed within estimation methods. The Wilcoxon-signed rank test with Bonferroni correction was performed to compare the new, conventional, and regression methods with the palpation method. All statistical analyses were performed using SPSS version 24 (IBM Corp, Armonk, NY, USA), and the significance level was set at $\alpha = 0.05$.

The error was calculated as the angular difference between the new and palpation methods. Angular differences for conventional and regression methods were also calculated. The estimation error of the scapular orientation was evaluated using the root mean square error (RMSE) of these angular differences.

# 3. Results

## 3.1. Elevating postures

Mean values for the new, conventional, regression, and palpation methods across the 25 elevating postures are displayed in Table 1;

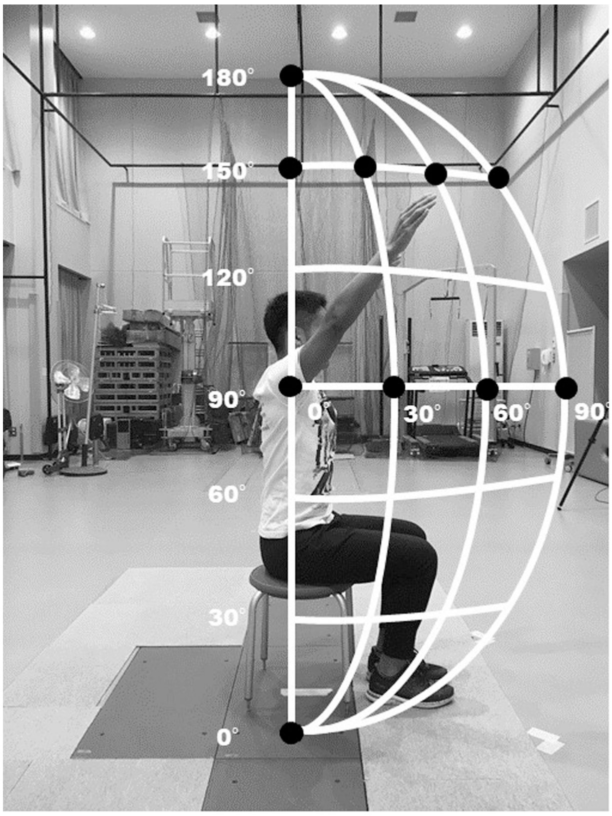


**Fig. 6.** Calibration postures for thin-plate spline interpolation.

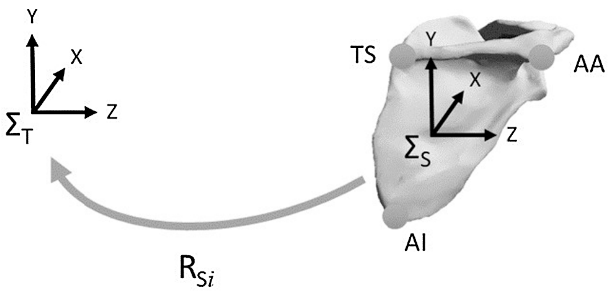


**Fig. 7.** The coordinate transformation of the palpation method.

RMSE is displayed in Table 2.

For the elevating postures, post-hoc tests revealed that there were some significant differences between the new and palpation methods. These significant differences are represented by the bold values in Table 1. Likewise, significant differences of the conventional and regression methods are represented in Table 1.

The maximum RMSE of our method was 8.1°; the RMSE of almost every posture was less than 5° in our method. The maximum RMSE of the conventional method was 14.2°. The RMSE was mostly 5–8° between 30° and 90° of elevation angle; however, this increased beyond the 120° of elevation angle. The maximum RMSE of the regression method was 8.0°. The RMSE was approximately 4–8° in almost every posture.

### 3.2. Functional postures

The scapular orientations for all methods in the functional postures are displayed in Fig. 8. RMSE of functional postures is displayed in Fig. 9. For the functional postures, post-hoc analysis revealed that our method and the palpation method had significant differences in hand to head and forward reach. The conventional and palpation methods significantly differed in lateral reach and hand to mouth. The regression and palpation methods significantly differed in hand to head, forward reach, and hand to mouth. The range of RMSE of our method was 3.0–8.6°. However, RMSE of the conventional method was 3.0–11.6°. Additionally, RMSE of the regression method was 1.3–10.4°. The RMSE of our new method and the regression method decreased compared with that of the conventional method for most tasks and axes of the scapular LCS. The error of our new method was less than that of the conventional method for high arm elevation angles, such as hand to head, lateral reach, and 135° elevation. However, the error of our new method was greater than that of the regression method for forward reach. Moreover, there was no obvious difference in RMSE among the new, conventional, and regression methods for hand to mouth and 45° elevation. The RMSE of the regression method was smaller than our method for hand to head and forward reach. The RMSE for lateral reach and 135° elevation was notably smaller in our method than in the regression method.

## 4. Discussion

To estimate scapular orientation in various shoulder postures, we developed a new estimation method based on the AMC using curved fitted interpolation. Using this new method, we first calibrated the positional relationships between the AMC and the scapula that were influenced by STA for variations in the TH elevation plane and elevation angle. We then compared estimation errors of the new method with the palpation method, the conventional AMC method, and the recently-developed regression method. The scapular orientation estimation error in 25 elevating postures and 6 functional postures was investigated. The elevating postures were set in steps of 30° at 0–180° of elevation angle along 0–90° of the elevation plane. Our new method was able to estimate scapular orientation more accurately in various humeral postures, especially in higher elevation angles, compared with the conventional and regression methods. Moreover, the RMSE of the new method was 3–8° even in the functional postures, which was comparable to that of the regression method. Therefore, based on these results, the new method was able to improve the estimation accuracy of scapular orientation in various shoulder positions.

Previous studies commonly used the SL method for reference data to validate other estimation methods (van Andel, 2009; Brochard et al., 2011; Warner et al., 2012). Therefore, we adopted SL as a reference for comparisons. In our palpation method using SL, the scapular orientations in 0° and 90° of elevation plane had similar angles to those in previous studies; thus, our palpation method is considered to be a sufficient reference for comparison with other estimation methods (van Andel, 2009, Brochard et al., 2011).

### 4.1. Scapular orientation estimations for elevating postures

Several previous studies reported that the estimation error of the conventional method increased when TH elevation angles were more than 90° (Karduna, 2001; van Andel, 2009; Brochard et al., 2011). This increased error was caused by soft tissue artifacts (STAs), such as contraction of the deltoid and skin movement at TH elevation angles more than 90°. To solve this problem, Nicholson et al. estimated scapular orientation using regression equations (Nicholson et al., 2017), which were generated using the TH orientations and the acromion position (without acromion orientation) for calibration. They reported that the error of the regression method was less than 8° compared with the fluoroscopy. Additionally, Rapp et al. examined the estimation accuracy of the regression method at several functional postures (Rapp et al., 2017); they reported that the regression method decreased the estimation error. In this study, the calibration procedure was performed using several premeasured postures in multiple arm elevation planes

**Table 1**
The scapular orientations in the elevating postures.

| Upward (+)/Downward (−) rotation | | Elevation angle | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevation plane | Estimation method | 0° | | 30° | | 60° | | 90° | | 120° | | 150° | | 180° | |
| 0° | Palpation | 0.0 | (3.5) | 1.2 | (4.8) | 10.0 | (6.3) | 24.4 | (7.1) | 40.0 | (4.8) | 49.6 | (4.9) | 56.1 | (3.7) |
| | Our method | −0.1 | (3.5) | 0.9 | (4.5) | 9.8 | (5.4) | 24.3 | (7.0) | 40.2 | (5.0) | 49.6 | (5.0) | 54.8 | (6.2) |
| | Conventional method | 0.0 | (3.6) | 1.9 | (4.8) | 9.8 | (3.5) | 22.8 | (4.6) | **33.3** | **(5.5)** | **39.9** | **(7.1)** | **45.1** | **(8.3)** |
| | Regression method | −2.4 | (2.4) | **6.1** | **(4.9)** | **14.5** | **(5.4)** | 26.4 | (6.2) | 39.5 | (5.3) | **47.3** | **(5.0)** | 54.3 | (6.6) |
| 30° | Palpation | | | 2.5 | (5.7) | 10.2 | (7.3) | 21.9 | (4.7) | 36.9 | (5.1) | 44.9 | (4.3) | 54.5 | (4.3) |
| | Our method | | | −0.1 | (4.9) | 9.9 | (5.7) | 22.0 | (4.7) | 37.4 | (4.3) | 44.9 | (4.2) | 54.4 | (4.4) |
| | Conventional method | | | 2.9 | (4.3) | 12.2 | (3.6) | 22.0 | (3.8) | 33.1 | (5.4) | **38.9** | **(6.8)** | **45.0** | **(8.3)** |
| | Regression method | | | 3.1 | (5.7) | 13.1 | (6.3) | **25.7** | **(5.9)** | 37.4 | (6.4) | 44.1 | (6.2) | 53.5 | (6.3) |
| 60° | Palpation | | | 1.9 | (4.6) | 7.6 | (5.6) | 18.7 | (4.7) | 33.4 | (4.0) | 43.3 | (4.2) | 53.4 | (3.3) |
| | Our method | | | −3.0 | (7.6) | 7.1 | (5.5) | 18.7 | (4.7) | 33.8 | (6.3) | 43.4 | (4.2) | 54.2 | (5.1) |
| | Conventional method | | | 1.6 | (6.8) | 10.2 | (4.2) | 20.4 | (3.6) | 31.1 | (5.2) | 37.9 | (6.9) | **44.3** | **(7.8)** |
| | Regression method | | | 2.0 | (5.7) | **12.1** | **(6.3)** | **24.6** | **(6.1)** | 34.9 | (6.9) | 42.6 | (7.4) | 52.7 | (5.6) |
| 90° | Palpation | | | 2.4 | (4.2) | 6.8 | (5.6) | 19.4 | (5.9) | 34.1 | (4.7) | 44.0 | (3.9) | 53.5 | (4.3) |
| | Our method | | | **−2.7** | **(5.7)** | 4.2 | (4.7) | 19.4 | (6.0) | 34.6 | (5.0) | 43.9 | (3.8) | 54.4 | (5.7) |
| | Conventional method | | | 2.5 | (4.8) | 8.1 | (4.1) | 20.9 | (5.2) | 32.1 | (3.8) | 39.0 | (6.6) | **44.2** | **(6.9)** |
| | Regression method | | | 2.0 | (6.7) | 11.2 | (5.1) | **25.2** | **(6.3)** | 36.0 | (6.1) | 43.9 | (4.4) | 53.4 | (4.6) |

| Internal (+)/External (−) rotation | | Elevation angle | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevation plane | Estimation method | 0° | | 30° | | 60° | | 90° | | 120° | | 150° | | 180° | |
| 0° | Palpation | 31.5 | (4.3) | 27.1 | (4.9) | 24.9 | (4.5) | 20.0 | (5.7) | 19.0 | (5.5) | 22.4 | (6.8) | 24.4 | (6.9) |
| | Our method | 31.6 | (4.1) | 25.5 | (5.2) | 23.3 | (4.2) | 19.8 | (5.9) | 19.8 | (6.9) | 22.5 | (6.9) | 24.7 | (8.1) |
| | Conventional method | 31.6 | (4.3) | 25.2 | (6.1) | 23.7 | (5.5) | 21.2 | (6.6) | 22.0 | (6.8) | 26.6 | (9.0) | **34.5** | **(10.0)** |
| | Regression method | 29.1 | (7.0) | 25.0 | (6.9) | 23.8 | (6.1) | 21.4 | (7.3) | 20.3 | (5.8) | 21.9 | (6.7) | 28.9 | (7.6) |
| 30° | Palpation | | | 33.5 | (4.7) | 33.5 | (5.3) | 31.7 | (5.1) | 29.5 | (5.4) | 28.4 | (5.8) | 27.3 | (8.1) |
| | Our method | | | **30.3** | **(4.8)** | 32.9 | (6.2) | 31.7 | (5.0) | 30.8 | (5.1) | **28.6** | **(5.8)** | 27.3 | (8.4) |
| | Conventional method | | | 32.3 | (4.7) | 34.4 | (6.2) | 32.8 | (6.6) | 33.0 | (6.8) | 32.3 | (6.8) | 36.3 | (10.2) |
| | Regression method | | | 31.6 | (4.9) | **30.6** | **(4.0)** | 29.9 | (5.1) | 27.6 | (6.1) | 27.7 | (6.1) | 30.1 | (6.4) |
| 60° | Palpation | | | 37.1 | (3.7) | 39.1 | (4.0) | 38.2 | (5.0) | 35.9 | (5.3) | 34.9 | (4.4) | 28.0 | (6.3) |
| | Our method | | | 35.1 | (6.5) | 37.6 | (5.5) | 38.1 | (4.9) | 37.8 | (4.0) | 35.0 | (4.2) | 28.8 | (8.8) |
| | Conventional method | | | 38.4 | (3.8) | 40.5 | (4.0) | 40.9 | (4.4) | 40.8 | (5.8) | 39.7 | (6.5) | **37.3** | **(8.5)** |
| | Regression method | | | 36.8 | (4.2) | 38.0 | (4.4) | 35.4 | (5.4) | 33.8 | (6.7) | 32.2 | (6.4) | 30.8 | (6.3) |
| 90° | Palpation | | | 39.1 | (3.9) | 42.3 | (4.3) | 42.4 | (5.3) | 41.7 | (3.9) | 37.5 | (3.5) | 29.3 | (5.4) |
| | Our method | | | 34.7 | (8.6) | 41.8 | (8.8) | 42.4 | (5.4) | 41.3 | (5.1) | 37.4 | (3.4) | 29.4 | (7.2) |
| | Conventional method | | | 38.4 | (5.3) | **46.4** | **(4.9)** | 47.6 | (5.1) | 48.2 | (6.5) | **45.0** | **(7.1)** | 39.0 | (9.1) |
| | Regression method | | | 40.1 | (6.4) | 42.3 | (6.3) | 39.8 | (7.0) | 38.5 | (6.2) | 36.0 | (4.6) | 30.7 | (6.9) |

| Anterior (−)/Posterior (+) tilt | | Elevation angle | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevation plane | Estimation method | 0° | | 30° | | 60° | | 90° | | 120° | | 150° | | 180° | |
| 0° | Palpation | −6.2 | (4.3) | −5.5 | (3.0) | −4.1 | (3.9) | −0.8 | (3.5) | 4.8 | (5.1) | 8.9 | (6.3) | 13.6 | (7.8) |
| | Our method | −6.2 | (4.2) | −5.8 | (3.2) | −3.9 | (3.9) | −1.1 | (3.3) | 5.8 | (6.1) | 9.0 | (6.3) | 12.7 | (9.5) |
| | Conventional method | −6.2 | (4.2) | −5.1 | (3.7) | −1.3 | (4.1) | 3.3 | (6.8) | 9.5 | (8.3) | 10.5 | (10.1) | 11.3 | (12.0) |
| | Regression method | **−8.8** | **(4.0)** | −4.0 | (3.5) | −1.9 | (3.8) | 1.1 | (4.7) | 5.2 | (5.0) | 7.9 | (6.3) | **10.1** | **(6.9)** |
| 30° | Palpation | | | −5.5 | (4.0) | −3.1 | (4.3) | −0.1 | (4.5) | 3.9 | (5.7) | 7.1 | (5.9) | 10.7 | (9.4) |
| | Our method | | | −3.8 | (3.9) | −3.4 | (3.8) | −0.1 | (4.5) | 3.9 | (6.3) | 7.0 | (5.8) | 10.7 | (9.4) |
| | Conventional method | | | −4.1 | (3.5) | −1.3 | (5.2) | 2.2 | (7.5) | 6.2 | (8.8) | 7.9 | (8.4) | 9.4 | (10.6) |
| | Regression method | | | −4.3 | (4.0) | −2.0 | (4.3) | 0.9 | (4.6) | 3.7 | (5.5) | 5.5 | (5.8) | 9.1 | (7.0) |
| 60° | Palpation | | | −4.9 | (4.4) | −3.1 | (3.5) | −1.3 | (4.5) | 1.9 | (5.0) | 5.8 | (5.1) | 12.2 | (6.8) |
| | Our method | | | −4.5 | (4.5) | −3.6 | (5.7) | −1.4 | (4.4) | 3.0 | (5.7) | 5.9 | (5.0) | 10.5 | (9.6) |
| | Conventional method | | | −3.9 | (4.7) | −2.5 | (4.7) | 1.2 | (7.3) | 3.5 | (9.3) | 5.0 | (8.4) | 9.4 | (9.2) |
| | Regression method | | | −5.1 | (4.7) | −2.8 | (4.7) | 0.4 | (5.3) | 2.3 | (5.6) | 4.4 | (5.4) | **8.6** | **(6.5)** |
| 90° | Palpation | | | −4.8 | (3.6) | −3.2 | (3.8) | −0.2 | (4.5) | 1.2 | (5.1) | 4.2 | (5.3) | 11.2 | (6.8) |
| | Our method | | | −3.8 | (7.0) | −3.6 | (5.4) | −0.3 | (4.4) | 2.2 | (5.9) | 4.2 | (5.1) | 9.8 | (9.2) |
| | Conventional method | | | −5.0 | (5.1) | −3.2 | (5.5) | 0.2 | (8.4) | 2.6 | (9.7) | 4.3 | (9.9) | 7.8 | (10.8) |
| | Regression method | | | −4.9 | (4.9) | −2.4 | (4.6) | 1.1 | (5.7) | 2.1 | (5.9) | 4.6 | (5.0) | 8.8 | (6.3) |

Mean angles and standard deviation in degrees. Significant differences ($p < 0.05$) are indicated in bold.

before the estimation of the scapula orientation. To save time and to adjust the number of postures with the regression method, the number of premeasured postures was limited to 10 postures. The base posture was the arm at rest position, and other positions were more than 90° of arm elevation in various elevation planes, where STA significantly affected the estimation accuracy. Moreover, we used thin-plate spline (TPS) for curve fitting interpolation to approximate the gap of the positional relationship between the AMC and scapula with changing elevation plane and elevation angle. The maximum RMSE of the new method was 8° at the elevating postures. In contrast, the maximum RMSE of the conventional method was 14.2°. The RMSE of the conventional method from 0° to 120° of elevation angle in this study was

**Table 2**
The root mean square errors (degree) for each estimation method in the elevating postures.

| Upward/Downward ration | | Elevation angle | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Elevation plane | Estimation method | 0° | 30° | 60° | 90° | 120° | 150° | 180° |
| 0° | Our method | 0.3 | 3.2 | 4.4 | 0.4 | 3.7 | 0.3 | 4.8 |
| | Conventional method | 0.1 | 4.5 | **6.7** | **7.0** | **9.8** | **11.8** | **12.7** |
| | Regression method | 4.1 | **6.0** | **6.1** | **6.7** | 3.3 | 3.2 | 4.7 |
| 30° | Our method | | 4.6 | 3.9 | 0.2 | 2.6 | 0.3 | 0.3 |
| | Conventional method | | 3.4 | **5.9** | **5.2** | **6.9** | **8.3** | **12.0** |
| | Regression method | | 3.2 | 4.7 | **5.6** | 4.2 | 3.6 | 4.8 |
| 60° | Our method | | **7.8** | 3.3 | 0.2 | 3.9 | 0.5 | **5.2** |
| | Conventional method | | 4.7 | **5.2** | **5.9** | **5.9** | **8.8** | **11.8** |
| | Regression method | | 4.1 | **6.4** | **7.5** | **6.2** | **6.9** | **5.8** |
| 90° | Our method | | **7.5** | 4.6 | 0.3 | 3.2 | 0.2 | 4.0 |
| | Conventional method | | 3.3 | 4.6 | **6.4** | **7.3** | **8.1** | **11.1** |
| | Regression method | | 5.0 | **6.9** | **8.0** | **5.9** | 2.8 | 2.7 |
| **Internal/External rotation** | | **Elevation angle** | | | | | | |
| Elevation plane | Estimation method | 0° | 30° | 60° | 90° | 120° | 150° | 180° |
| 0° | Our method | 0.3 | 3.6 | 4.1 | 1.7 | 2.7 | 0.7 | 4.7 |
| | Conventional method | 0.1 | 4.8 | 4.7 | 4.9 | **6.2** | **8.3** | **13.6** |
| | Regression method | 4.7 | **5.3** | **5.7** | **6.2** | 2.9 | 3.1 | **7.6** |
| 30° | Our method | | 4.5 | 3.9 | 0.2 | 2.8 | 0.5 | 0.6 |
| | Conventional method | | 4.3 | 3.8 | **5.8** | **7.5** | **8.1** | **14.1** |
| | Regression method | | 3.3 | 4.3 | **5.3** | 4.3 | **5.4** | **6.9** |
| 60° | Our method | | **6.0** | 4.5 | 0.4 | 3.8 | 0.5 | **5.7** |
| | Conventional method | | 4.7 | **5.1** | **6.4** | **9.8** | **9.0** | **11.7** |
| | Regression method | | 4.2 | 4.5 | **6.2** | **6.6** | **5.2** | **7.1** |
| 90° | Our method | | **8.1** | **6.2** | 0.2 | 3.5 | 0.5 | 4.2 |
| | Conventional method | | 3.8 | 4.8 | **9.0** | **10.5** | **10.8** | **14.2** |
| | Regression method | | **5.1** | 4.3 | **6.4** | **7.2** | 4.2 | **6.9** |
| **Anterior/Posterior tilt** | | **Elevation angle** | | | | | | |
| Elevation plane | Estimation method | 0° | 30° | 60° | 90° | 120° | 150° | 180° |
| 0° | Our method | 0.2 | 3.1 | 3.9 | 0.6 | 4.0 | 0.6 | 3.8 |
| | Conventional method | 0.1 | 2.7 | 4.7 | **7.2** | **8.1** | **8.9** | **9.4** |
| | Regression method | 3.2 | 3.1 | 3.6 | 3.4 | 1.6 | 2.0 | **6.2** |
| 30° | Our method | | **5.1** | 3.0 | 0.4 | 4.5 | 0.4 | 0.6 |
| | Conventional method | | 3.4 | 3.2 | **5.2** | **7.7** | **6.0** | **10.4** |
| | Regression method | | 2.0 | 2.2 | 2.2 | 1.8 | 3.1 | **7.4** |
| 60° | Our method | | 4.1 | **5.4** | 0.3 | 3.4 | 0.4 | **5.8** |
| | Conventional method | | 3.2 | 3.9 | **5.6** | **7.0** | **6.1** | **7.0** |
| | Regression method | | 2.7 | 2.4 | 3.7 | 2.3 | 3.2 | **5.1** |
| 90° | Our method | | **6.5** | **5.2** | 0.2 | 3.2 | 0.6 | 3.1 |
| | Conventional method | | 3.2 | 4.0 | **6.0** | **6.9** | **6.5** | **9.1** |
| | Regression method | | 3.1 | 3.5 | **5.1** | 4.7 | 2.4 | **6.2** |

comparable to that in previous studies included in a previous systematic review (Lempereur et al., 2014). The RMSE of the conventional method increased at more than 120° of the elevation angle, which was in contrast to the finding of a previous study reporting that the estimation accuracy decreased (Karduna, 2001), and RMSE of 7 of the 25 elevating postures increased by more than 10°. Furthermore, the maximum RMSE of the regression method was 8.0°, which was lower than the conventional method. However, the RMSE of 17 of 25 elevating postures increased more than 5° in the regression method, whereas only 6 of the 25 elevating postures in our method had over 5° RMSE. In the new and regression methods, 6 and 10 of the 15 elevating postures without the 10 calibration postures were used for TPS interpolation, respectively. Both the new and regression methods improved the estimation accuracy of the postures with over 90° elevation. Other TH orientation and parameters (AMC posture or orientation) are necessary as well. However, the RMSE of the new method decreased in a wide range of shoulder postures compared with the regression method, with a good estimation accuracy of 5° or less. According to the results of the conventional method, it was considered that the change of the error was complicated by STA due to elevation plane and elevation angle changes. Therefore, it seemed that our new method, performed with curved fitted interpolation using TH elevation plane and elevation angle as input variables, improved estimation accuracy in a wide range of elevating postures compared with the regression method.

### 4.2. Scapular orientation estimations for the functional postures

For the functional postures, which included greater arm elevation angles in postures such as hand to head, lateral reach, and 135° elevation, both the new and regression methods resulted in improved estimation accuracy compared to the conventional method. The estimation accuracy of hand to head was slightly better in the regression method than in our new method, which was due to the difference of the pre-measured postures. Regression equations, including the hand to

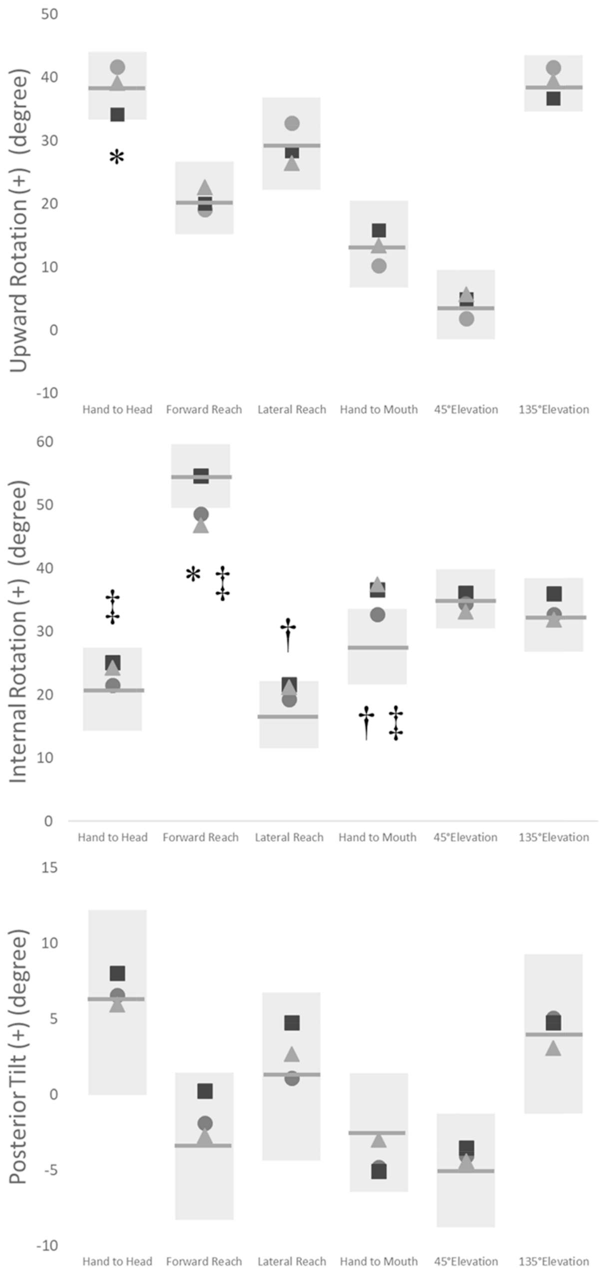


**Fig. 8.** Mean scapular orientation angles for each method in functional postures. The gray bars represent the average ± 1 SD during palpation. The center dark gray lines represent the mean for palpation. The circles, squares, and triangles represent the mean angles of new, conventional and regression methods, respectively. *, † and ‡ represent significant difference for new, conventional, and regression methods ($p < 0.05$).

head position, were generated for the pre-measured postures. However, the RMSE of our method was also approximately less than 5°; thus, our method had good estimation accuracy in the hand to head posture, with similar results to the regression method (MacLean et al., 2014). The estimation accuracy of the new and regression methods also improved in 135° elevation, and the RMSE was slightly better in the new method than in the regression method. It was considered that our method generated the curved fitted interpolation using various elevating positions, thereby effectively correcting STA in this posture. For lateral reach, the RMSE of our method was smaller than that of the regression method. Rapp et al. reported that the RMSE of the regression method was approximately 6–9° (Rapp et al., 2017). In this study, the RMSE values of regression methods were similar with the findings of Rapp et al. (2017). The regression method used the supero-inferior and antero-posterior positions of the acromion with TH orientation to generate regression equations. The scapula appeared to move toward the lateral direction primarily during the lateral reach. However, the regression method did not consider the lateral transition of the acromion or sufficiently improve estimation accuracy. In contrast, our method corrected the relationship between the AMC and the scapula using TPS and simultaneously measured the AMC orientation that responded to the orientation of the acromion with STA. Hence, it seemed that our method could include actual postural change of the scapula by using TPS. The regression method used acromion positions; however, the acromion orientations were not used for generating regression equations. Therefore, the estimation error of our method was considered small, suggesting that the estimation accuracy could be sufficiently improved using our method. Accurate estimations of scapular orientation for ADL movements, in which the arm moves in high elevation angles and wide elevation planes, are possible using our method.

For forward reach, there was no significant difference in improvements of estimation accuracy between the new and conventional methods. In contrast, the regression method improved the estimation accuracy for upward rotation and posterior tilt, because forward reach posture was included in generating the regression equations, as with the hand to head posture. The RMSE of scapular orientation using the AMC was reportedly 4.2–6.0° compared with the use of bone pins during forward reaching (Bourne et al., 2007). In our study, the estimation error of the new methods was slightly larger than Bourne's results. It is possible that the acromion slides further under the skin during forward reach compared to during flexion, and thus the gap between the AMC and the scapula could be larger during forward reach than during other postures. Therefore, caution is required when interpreting the results of movements such as forward reach. To improve the estimation accuracy of this posture, it may be effective to include the forward reach posture in calibration postures when generating TPS equations.

For hand to mouth and 45° elevation, there was no obvious difference in the RMSE between the new, conventional, and regression methods. We selected the premeasured postures to improve the accuracy during high elevation angles for calibration. Therefore, there were few differences in the RMSE between the new and conventional methods for the lower elevation postures.

### 4.3. Characteristics of the new method

The AMC was originally considered as the best method to directly evaluate scapular orientation; however, performing the AMC in higher TH elevation is difficult as estimation error occurs by STA. In contrast, the regression method attempts to reduce the effect of STA by reducing the numbers of the scapular land markers, as compared with the AMC method. In the regression method, humeral orientations and the position of the acromion are employed to predict scapular orientation using the regression equations. The regression method does not have sufficient scapula land marker to generate the scapular LCS. Therefore, the regression method lacks the data of scapular orientation calculated from the scapular LCS at the arbitrary shoulder posture when scapular orientation is estimated using the regression equations. If the influence of the STA can be sufficiently corrected, it is possible to estimate scapular orientation more accurately with the AMC in various humeral postures. In this study, the new method appeared to significantly decrease the estimation error caused by STA. We selected the pre-measured postures wherein STAs are more like to occur and used the curved fitted interpolation to correct the effects of STA. Therefore, our method estimated the change of the scapular orientation more directly from the body surface by reducing STA as much as possible. However, our method did not improve the estimation accuracy for forward reach. The reason for this might be that the regression method using the positional data of an acromion marker was more effective in this posture, wherein

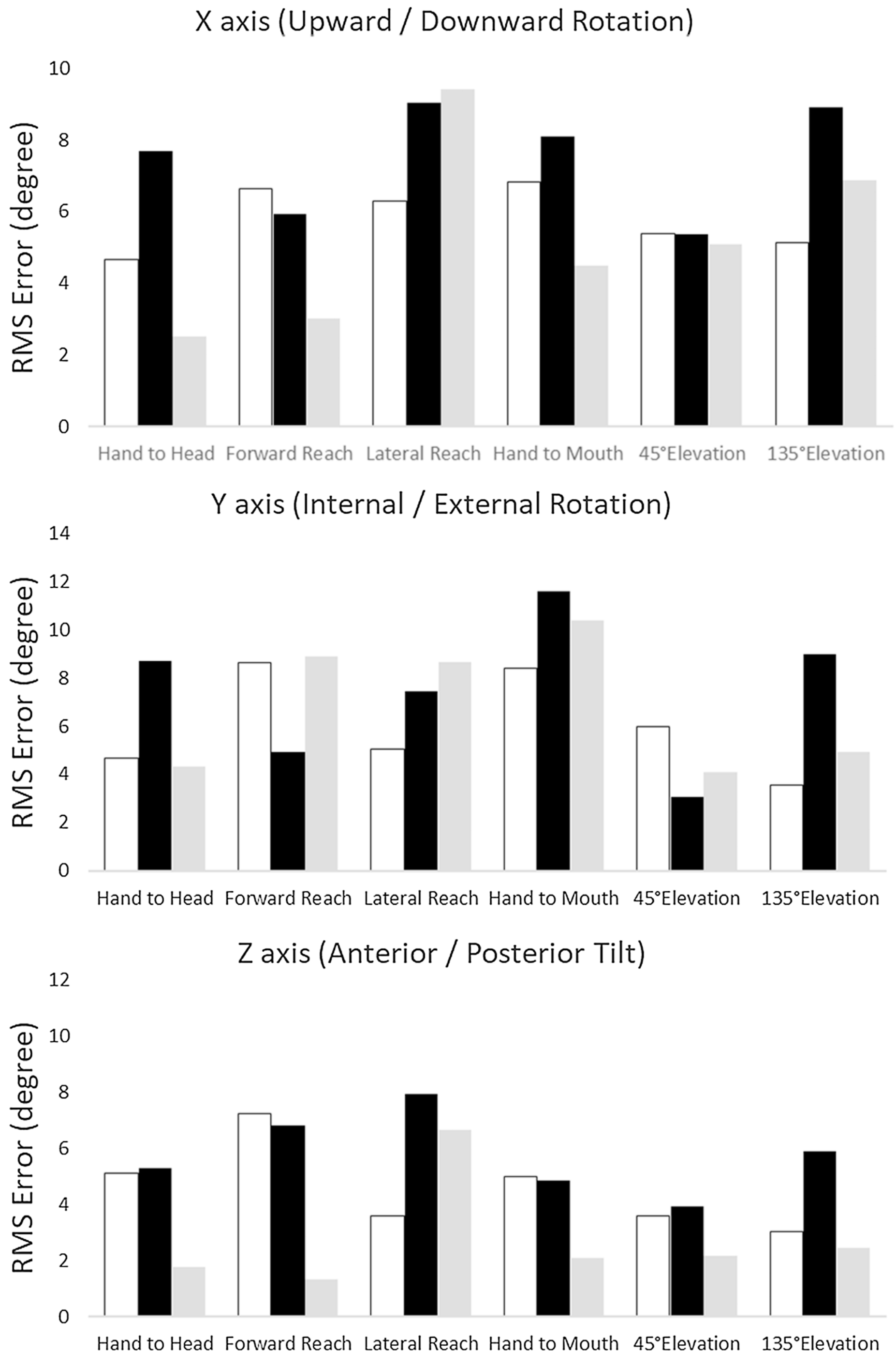


**Fig. 9.** Root mean squared errors (RMSE) for the new, conventional, and regression methods in the functional postures. The white bars, black bars, and light gray bars represent the RMSE of the new, conventional, and regression methods, respectively.

the scapular transition was larger. However, it may be necessary to improve estimation accuracy for specific arm postures by modifying pre-measured postures; further studies are needed for this purpose.

### *4.4. Limitations*

There were some limitations in this study. First, estimating the scapular orientation outside the elevation planes and elevation angles in the premeasured postures was difficult. Therefore, error could be increased for hand behind back and shoulder maximal horizontal adduction/abduction. Arm elevation planes and elevation angles with wider area were thus selected for specific tasks so that calibration could be performed. Second, our method required a preprocess that included premeasuring several postures for calibration, similar to the regression method. For this preprocess, it took us approximately 3–5 min to measure all 10 postures with the AMC and SL. This procedure would have been completed faster if the number of postures had been reduced. However, estimation accuracy and measurement time were considered trade-offs. Spending more time than necessary for premeasurements should be avoided because it is burdensome for study subjects. Our results indicated that the number of premeasuring postures used in this study was adequate. Finally, subjects in this study were healthy young men. The scapular muscle volume and skin mobility of elderly people and patients with shoulder disorders may differ from those of healthy subjects. Therefore, it is possible that changes in the positional relationship between the AMC and scapula could differ in other populations compared to those of the subjects in this study. However, the physical characteristics of each subject were considered for calibration. Therefore, the new estimation method could possibly be used for elderly adults or patients with shoulder disorders. However, further studies evaluating these and other specific populations are warranted to confirm the accuracy of our estimation method.

## 5. Conclusions

We developed a new estimation method using curve fitting interpolation and investigated the estimation accuracy of scapular orientations in 25 elevating postures and six functional postures. Our method was able to improve the estimation accuracy in various elevating postures, particularly for higher arm elevating positions, and resulted in estimations similar to those of the regression methods for lower elevating positions with the exception of the forward reaching posture. In the future, our method might be able to improve the estimation accuracy of the forward reaching posture if this posture is added into the calibration process. However, the estimation accuracy of our method for arm postures other than those included in the calibrated postures is still unclear, as they were not examined. This study was performed with only healthy male subjects, and thus future studies should clarify whether our method is applicable for patients with shoulder disorders.

## Conflicts of interest

The authors declare that there is no conflict of interest.

## Financial disclosure

The authors state that there is no financial disclosure and personal relationships with other people or organizations that could inappropriately influence the present work.

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