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ORIGINAL PAPER

Evaluation of three-dimensional in vivo scapular kinematics and scapulohumeral rhythm between shoulders with a clavicle hook plate and contralateral healthy shoulders

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Abstract

Purpose Acromioclavicular-coracoclavicular ligament injury occurs frequently, and the clavicle hook plate technique is an easy-to-use treatment method. However, complications such as subacromial impingement syndrome, synovitis, erosion, osteolysis, post-operative pain, and post-operative limitations in range of motion have been reported. We aimed to evaluate the use of the clavicle hook plate in the shoulder joints and to compare in vivo three-dimensional (3D) scapular kinematics and scapulohumeral rhythm between the shoulders with a clavicle hook plate and contralateral normal shoulder joints.

Methods Ten male patients (aged 40.5 ± 14.4 years) who underwent clavicle hook plate fixation for an acromioclavicular-coracoclavicular ligament injury were selected. Computed tomography and fluoroscopy were conducted on both the shoulder joints, and 3D models were created. Using a 3D-2D model-image registration technique, we determined the 3D coordinates of the scapula, and we measured the scapular kinematics and scapulohumeral rhythm.

Results The values for upward rotation, posterior tilt, and external rotation in the two groups increased in proportion with humeral elevation, showing significant differences between the two groups ($p < 0.05$). Overall, the value in the clavicle hook plate group (group H) was smaller than that in the control group (group C) by 23.5% (6.7°) of upward rotation and 64.8% (18.9°) of posterior tilt. However, the external rotation in group H was greater than that in group C by 32.3% (2.3°). In overall value, there was a significant difference not in upward rotation and external rotation, but in posterior tilt. During humeral elevation, the overall changes in scapulohumeral rhythm were 4.65 ± 2.45 in group H and 3.8 ± 0.8 in group C, and statistical differences were not detected between the two groups.

Conclusions Clavicle hook plate fixation changes the scapular kinematics and scapulohumeral rhythm; thus, when clavicle hook plate fixation is complete, the implant should be promptly removed.

Keywords Scapular kinematics · Scapulohumeral rhythm · Clavicle hook plate · 3D/2D model-image registration technique

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Introduction

Acromioclavicular-coracoclavicular ligament injury occurs frequently, accounting for approximately 9–12% of all shoulder joint injuries. Considering that majority of the patients with acromioclavicular joint injuries are young adults in their 20's [1–3], an appropriate treatment is greatly important to restore the function. Among various interventions, the clavicle hook plate technique has been widely conducted due to its ease to perform and satisfactory results [4, 5], but complications, such as subacromial impingement syndrome, subacromial synovitis, subacromial erosion, and subacromial osteolysis, have often been reported [6–8]. These complications are assumed to be caused by improper positioning between the clavicle hook plates and subacromial spaces. According to an anatomical study [9], among those who undergo clavicle hook plate fixation, some experience pain in the rear scapula and complain of having limited shoulder joint movement, indeed. In this context, this study will address whether these problems occur because of either the changes in scapular kinematics that result from structural problems with the clavicle hook plates or simply secondary postoperative complications. We hypothesized that clavicle hook plate fixation changes the shoulder joint kinematics and scapulohumeral rhythm (SHR). Thus, we conducted a study to compare in vivo 3D scapular kinematics and SHR between shoulder joints with a clavicle hook plate and contralateral normal shoulder joints.

Materials and methods

Subjects

This study is a prospective study and the population is of males aged 20 to 55 years, who were diagnosed with an acromioclavicular-coracoclavicular ligament injury. Inclusion criteria were as follows: (1) patients who underwent fixation with a 3.5-mm LCP Clavicle Hook Plate (DePuy Synthes®, Oberdorf Switzerland) at the author's hospital and (2) the Rockwood classification (grade III and above) [10]. Exclusion criteria were as follows: (1) patients who had shoulder joint arthritis according to radiographic data, (2) patients who underwent shoulder joint surgery before this surgery, (3) patients who had shoulder joint trauma (e.g., dislocation) or shoulder joint disease before, (4) patients who had erosion or osteolysis of the acromion, (5) patients who had shoulder joint pain, and (6) patients who has multiple trauma, including shoulder. Ten male adults were prospectively selected. Their mean age was 40.5 years (SD 14.4; range 20–55), and all subjects had an injury of the left shoulder. The average time from injury to surgery was 4.8 days (SD 2.5; range 0–14 days). The mechanisms of the injuries included a traffic crash (five cases) and fall on hands (five cases). Computed tomography (CT) scans and fluoroscopy procedures were conducted the day before the clavicle hook plate was removed at 3 months (Fig. 1).

All patients gave written consent after the study was explained to them. The research ethics committee of the university approved this study (approval no. YWMR-15-8-072).

Image acquisition and 3D modeling

Subjects underwent fluoroscopy procedures with a C-arm fluoroscope (Infinix Active; Toshiba, Tochigi, Japan), which provided fluoroscopic images of the shoulder joints on both sides at 30 frames/s. The radiography beam was radiated in the direction of the scapular plane, perpendicular to the scapula. Subjects were told to stand with their bodies tilted at a 30° angle to the scapular plane while supporting a Styrofoam rod in their back at a 30° angle. Scapular plane abduction was conducted in conditions that allowed the subjects to evaginate at the maximum angle (i.e., on the side of their body, lying straight, 0°), with their arms in thumb-up position and elbow joints fully extended. One cycle was defined as the duration that the tested arm at the original 0° position is gradually abducted in the scapular plane as maximally as comfortable and back to the initial position. Both procedures were conducted twice, and a 30–40-seconds break was provided between each cycle to make the muscles surrounding the shoulder joints relax. The distance between the fluoroscopy intensifier and bed was maintained at one metre during the process. In addition, calibration files were obtained from the C-arm fluoroscope using a calibration jig to obtain undistorted images for fluoroscopy.

The fluoroscopic images were obtained in full scope of the shoulder joints on both shoulders by using CT scans (SOMATOM Sensation 16; Siemens Medical Solutions, Malvern, PA) with a 1-mm slice pitch (image matrix, 512 × 512; pixel size, 0.9765625 × 0.9765625 mm). Three-dimensional (3D) models of the humerus and scapula were created from the CT images by using ITK-SNAP (Penn Image Computing and Science Laboratory, Philadelphia, PA). Then, an anatomic coordinate system was applied to the 3D scanning and modeling of the humerus and scapula by using a previous study formula [11, 12]. The origin of the humerus was defined as the centroid of the articular surface of the humeral head; the *y*-axis was in the direction parallel to the humeral shaft, and the *z*-axis was the line perpendicular to the plane connecting the origin and the furrow between the biceps tubercle. The origin of the scapula was defined as the midpoints of the line that connects the superior and inferior bony edges of the glenoid. The *y*-axis was defined as the vertical axis in the upward direction, and the *z*-axis was defined as the vertical axis in the forward direction (Fig. 2).

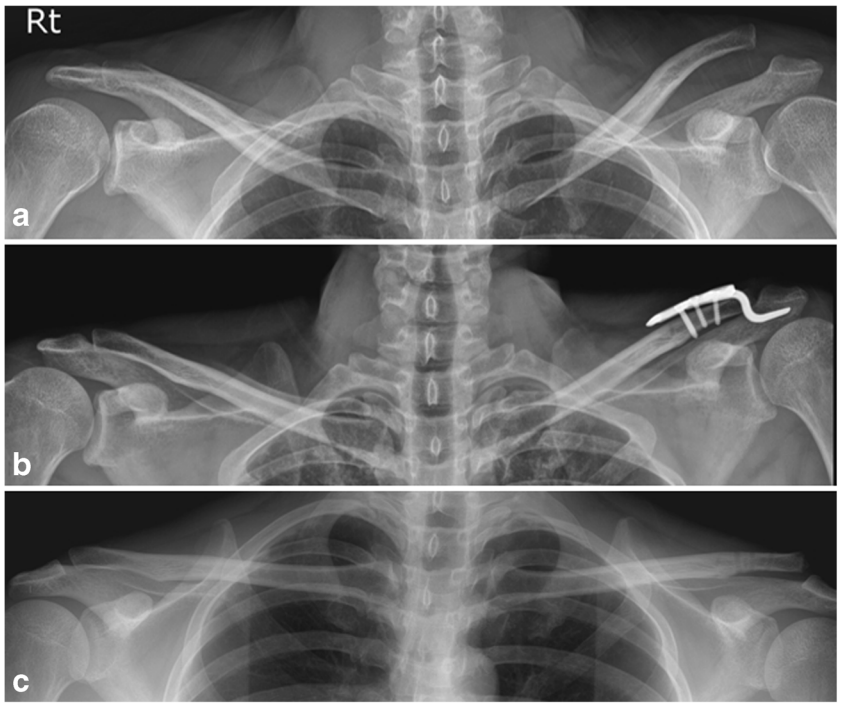

Fig. 1 Representative image for left shoulder acromioclavicular-coracoclavicular ligament injury (Rockwood classification grade V) (**a**), after hook plate fixation (**b**), and hook plate removal after 3 months (**c**)

Model-image registration and data processing

The position and orientation of the 3D models of the humerus and scapula were determined by using Joint-Tract (www.sourceforge.net/projects/jointtrack), an open-source software developed by the University of Florida through model-image registration techniques (Fig. 3). Although there was no shoulder kinematics study with this Joint-Tract, we referred the articles about knee joint kinematics using Joint-Tract [13, 14] and applied this software to shoulder kinematics because we thought that this open-source software is accurate and reasonable for kinematics and could be used to evaluate shoulder kinematics. The size and orientation of the 3D models were fit to the fluoroscopic images. This 3D model for an image registration was conducted by the first author for a series of fluoroscopic images. The precision of this method has been confirmed in the previous study, showing the translation values were 0.53 mm for in-plane translation (horizontal to the image plane), 1.6 mm for out-of-plane translation (vertical to the image plane), and 0.54° for the rotation angle [15].

Humeral and scapular kinematics relative to the radiographic coordinate system were determined by using Cardan angles (*zxy* order) [16]. The humeral elevation was defined as *z*-axis rotation. The scapular motion was defined as the *x*-axis for anterior-posterior tilt, *y*-axis for internal-external rotation, and *z*-axis rotation for upward-downward rotation (Fig. 2). Data of the scapular kinematics were recorded for every 15° in humeral elevation angles, and these values were calculated by using codes of MATLAB (The Mathworks Inc., Natick, MA, USA). The values for posterior tilt and external rotation of the scapula are usually changed back to 0° at the beginning for each subject to minimize the effects on the other scapular locations. Instead, we calculated the angles at the two locations with subjects in resting position.

SHR was defined as $(\Delta H - \Delta S)/\Delta S$ by referring to the study by Matsuki et al. [17], where ΔH indicates the increment of the humeral elevation angle, and ΔS represents the scapular upward angle. The overall SHR between the arm at its side and the maximum elevation positions was calculated every 15° in accordance with humeral elevation divided by two stages. First, $\Delta S/\Delta H$ was computed as the slope of the polynomial regression line by using scapular upward rotation as the independent value and humeral elevation angle as the dependent value. Then, the SHRs were calculated as follows: $1/(\Delta S/\Delta H) - 1$.

Statistical analysis

Statistical analyses were performed using PASW 20.0 (SPSS Inc., Chicago, IL, USA), and the values were considered statistically significant when $\alpha = 0.05$ or $p < 0.05$. To compare the scapular kinematics and SHR between the two groups (injured shoulders treated with a clavicle hook plate, group H, and contralateral normal shoulders, group C), Friedman's test was used to analyze the data since all data did not satisfy the normality assumption. If the result of Friedman's test was significant, the variable was further analyzed by using the Wilcoxon signed-ranks. Moreover, the data were presented as median (i.e., the value that is the middle of the distribution) and interquartile range (i.e., the range of values within reside

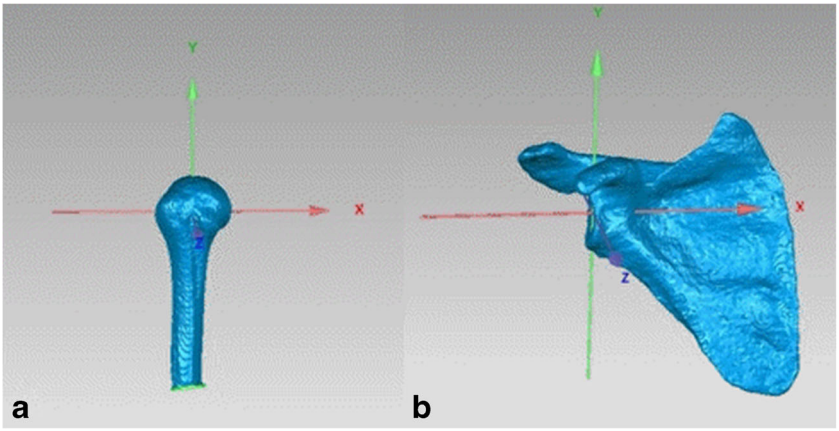

Fig. 2 The *xyz* axes in accordance with the anatomic coordinate system of the humerus (**a**) and scapula (**b**)

the middle 50% of the distribution, IQR). The lower bound of IQR is called the first quartile (Q1) and the upper bound the third quartile (Q3). Thus, IQR was determined as Q1–Q3.

Results

The results were compared between the two groups in regard to upward rotation, posterior tilt, and external rotation of the scapula, and SHR in accordance with humeral elevation as shown in Fig. 4 and as summarized in Tables 1, 2, 3, and 4.

Scapular upward rotation

As shown in Table 1 and Fig. 4a, the upward rotation values of the scapula increased significantly in the two groups in accordance with the values of humeral elevation ($p < 0.05$), but they were significantly lower in group H than in group C (range 45°–120°, $p < 0.05$). The median values of overall changes in the upward rotation were 21.6° (IQR = 21.2–28.5) in group H and 28.3° (IQR = 20.7–28.8) in group C, showing that the range of upward rotation in group H exhibited reduced by 6.7° compared to group C, but there was no significant difference. The median values for upward rotation in the resting position was smaller in group H (9.1°; IQR = 8.6–10.4) than in group C (15.2°; IQR = 14.9–17.7), but no significance was found.

Scapular posterior tilt

The scapular posterior tilt values increased in proportion with humeral elevation in both groups (Table 2; Fig. 4b), but they were significantly lower in group H than in group C when the humeral elevation angle was greater than 120° ($p < 0.05$). The median value of overall changes in the posterior tilt was 10.3° (IQR = 9.0–12.5) in group H and 29.2° (IQR = 21.0–30.1) in group C, showing the range of motion reduced by 18.9° in group H, and there was a significant difference ($p < 0.05$).

Scapular external rotation

The values for scapular external rotation increased in proportion with humeral elevation in group H, whereas the values in group C were dramatically increased starting at around 90° (Table 3; Fig. 4c). The external rotation values were significantly higher in group H than those in group C (range 75°–90°, $p < 0.05$). The median values of overall

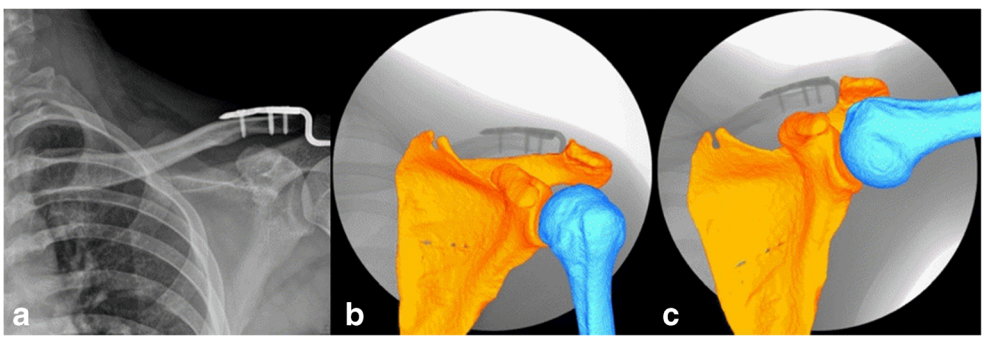

Fig. 3 Three-dimensional (3D) models of the shoulder joints by using the 3D-2D model-image registration technique. A representative hook plate fixation (**a**) and the corresponding model at initial position (**b**) and at the maximal abduction (**c**)

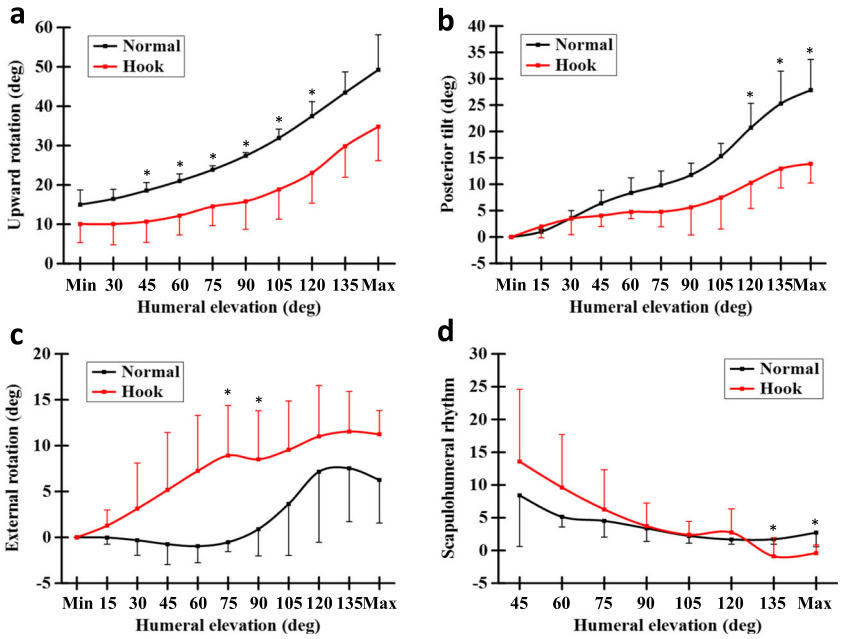

Fig. 4 Changes in the scapular upward rotation (**a**), scapular posterior tilt (**b**), scapular external rotation (**c**), and scapulohumeral rhythm (**d**) in accordance with humeral elevation. The asterisk indicates a significant difference in the value

changes in the external rotation were 9.6° (IQR = 9.5–11.1) in group H and 7.3° (IQR = 1.2–10.8) in group C, showing no significant difference.

SHR

SHR values for both group H and group C gradually decreased as the humeral elevation angles increased (Table 4; Fig. 4d). Compared to group C, group H showed greater SHR values in the early stage of the humeral elevation, but less only at both 135° and the maximum position of humeral elevation angle ($p < 0.05$). The median values of overall SHRs during humeral elevation in group H (6.5°; IQR = 2.2–7.1) were greater than those in group C (4.5°; IQR = 3.0–4.6), but there was no significant difference.

Discussion

Few studies have compared shoulder joint kinematics in cases with clavicle hook plate fixation. Kim et al. [18] conducted surgery on patients with multiple distal clavicle fractures by using clavicle hook plates, obtained CT scans of patients in prone position at 0° and in full abduction, analyzed the clavicle movement, and compared relative

Table 1 Scapular upward rotation in accordance with humeral elevation in degrees

Humeral elevation angle	Group C	Group H	*p* value
Minimum	15.2 (14.9–17.7)	9.1 (8.6–10.4)	0.138
30	17.5 (17.1–17.6)	8.1 (7.3–9.5)	0.080
45	18.1 (17.6–20.3)	9.0 (7.6–10.1)*	0.043
60	20.3 (19.8–22.6)	10.1 (9.1–12.8)*	0.043
75	24.0 (23.3–24.6)	13.0 (11.0–17.2)*	0.043
90	27.2 (26.9–27.5)	12.2 (11.9–22.7)*	0.043
105	32.8 (29.7–33.0)	14.6 (14.4–26.7)*	0.043
120	39.4 (33.8–39.4)	18.5 (18.4–30.5)*	0.043
135	45.9 (38.3–45.9)	25.4 (25.4–36.2)	0.080
Maximum	47.3 (43.5–47.6)	30.2 (30.2–41.7)	0.080
Overall	28.3 (20.7–28.8)	21.6 (21.2–28.5)	0.893

Values are presented as median (interquartile range, Q1–Q3). The asterisk (*) indicates a significant difference between groups

Table 2 Scapular posterior tilt in accordance with humeral elevation in degrees

Humeral elevation angle	Group C	Group H	*p* value
15	1.0 (0.7–1.3)	1.1 (0.2–4.1)	0.500
30	2.9 (2.5–4.9)	2.2 (1.4–6.5)	0.893
45	5.6 (4.8–8.6)	3.2 (2.3–6.0)	0.080
60	8.3 (6.3–10.9)	5.3 (5.0–5.5)	0.080
75	11.3 (7.3–11.7)	4.2 (4.0–4.6)	0.080
90	12.1 (9.8–12.7)	4.3 (3.7–4.8)	0.080
105	14.7 (13.8–15.8)	5.7 (5.7–6.2)	0.080
120	23.6 (16.3–24.2)	8.4 (7.8–8.8)*	0.043
135	29.0 (19.5–29.7)	12.0 (11.6–12.7)*	0.043
Maximum	29.7 (22.5–31.1)	13.0 (12.7–13.4)*	0.043
Overall	29.2 (21.0–30.1)	10.3 (9.0–12.5)*	0.043

Values are presented as median (interquartile range, Q1–Q3). The asterisk (*) indicates a significant difference between groups

Table 3 Scapular external rotation in accordance with humeral elevation in degrees

Humeral elevation angle	Group C	Group H	*p* value
15	0.2 (− 0.3–0.4)	1.2 (0.6–2.6)	0.138
30	0.5 (− 2.0–0.8)	3.7 (1.6–7.2)	0.138
45	0.5 (− 2.1–0.6)	4.3 (2.8–11.0)	0.080
60	− 0.1 (− 1.2–0.1)	6.6 (4.4–12.9)	0.080
75	− 0.7 (− 1.4–0.3)	10.5 (6.3–13.4)*	0.043
90	0.5 (− 0.7–3.4)	8.2 (5.7–13.4)*	0.043
105	1.1 (0.7–9.3)	9.3 (7.2–14.4)	0.345
120	3.9 (2.0–14.5)	10.2 (7.9–16.3)	0.686
135	7.2 (2.1–12.6)	10.3 (8.4–15.9)	0.686
Maximum	7.7 (1.9–9.6)	10.3 (9.8–13.7)	0.225
Overall	7.3 (1.2–10.8)	9.6 (9.5–11.1)	0.345

Values are presented as median (interquartile range, Q1–Q3). The asterisk (*) indicates a significant difference between groups

scapular kinematics between the beginning and end of the shoulder motion. The group that underwent hook plate fixation had higher values for the decrease in posterior tilt and the increase in external rotation, and these findings corresponded with those of our study. However, Kim et al. [18] also reported a decrease of 16° for the posterior tilt and an anterior translation of 2.2 mm more for the external rotation. These results are difficult to compare with the results of our study in terms of absolute values. The values for posterior tilt and external rotation in our study were not absolute values obtained from the measurements; instead, they were obtained by calculating the internal rotation and anterior translation values of clavicles with a fixed scapula. Furthermore, Kim et al. [18] statistically analyzed the points at the beginning and end of the shoulder motion, whereas our study only analyzed dynamic movements. Therefore, the differences can only be confirmed indirectly, and we cannot directly compare the differences to those in our study.

Table 4 Scapulohumeral rhythm in accordance with humeral elevation in degrees

Humeral elevation angle	Group C	Group H	*p* value
45	4.6 (4.5–8.1)	11.1 (8.1–19.5)	0.500
60	5.1 (4.8–6.3)	12.2 (3.2–16.2)	0.225
75	3.2 (2.7–6.7)	7.8 (1.9–8.1)	0.500
90	2.2 (1.8–5.1)	4.3 (1.7–5.5)	0.686
105	1.5 (1.4–3.2)	2.6 (2.4–3.8)	0.893
120	1.3 (1.2–2.4)	1.9 (1.5–1.9)	0.893
135	1.5 (1.4–2.5)	0.5 (− 0.4–0.7)*	0.043
Maximum	1.7 (1.5–4.6)	0.1 (− 0.2–0.3)*	0.043
Overall	4.5 (3.0–4.6)	6.5 (2.2–7.1)	0.686

Values are presented as median (interquartile range, Q1–Q3). The asterisk (*) indicates a significant difference between groups

The values in resting position showed some differences between group H and group C, but they were not statistically significant. The reason why the differences in the resting position were statistically nonsignificant at the beginning but became significant later could be because clavicle hook plate fixation causes changes during acromioclavicular joint exercises, thereby changing scapular kinematics.

The values for upward rotation and posterior tilt decreased significantly in group H. These are the positions of limited scapular movement in terms of raising one's arms. The scapular values for external rotation may be increased significantly to compensate this limitation, thereby resulting in greater external rotation of the humerus to allow the movement of raising arms. Furthermore, the posterior tilt of the scapula had significantly low values in group H for angles greater than 120°, which can result in shoulder impingement syndrome. Moreover, the long-term maintenance of clavicle hook plates can cause rotator cuff impingement, which results in a rotator cuff tear [8].

The SHR, which is defined as coordinated motion of the humerus and scapula, was first introduced by Inman et al. [19] as having a constant rate of 2:1. Many researchers have since reported SHRs of normal or pathological shoulder joints that ranged from 1.35:1 to 7.9:1 [19–24]. Furthermore, recent studies have reported that mainly in the early stages of arm elevation, glenohumeral motion is greater than upward rotation of the scapula, which results in higher SHR values [20, 25, 26]. In our study, the SHR was 3.4:1 in group C and 4.5:1 in group H, and the values for SHR were greater during the initial phases of arm elevation. Yano et al. [27] reported groups with greater glenohumeral joint motion relative to scapular motion and groups with greater scapular motion relative to glenohumeral joint motion. They found significant differences in scapular upward rotation between the two groups when 42 healthy subjects were divided and compared in two groups. They further reported that half of the 42 subjects showed higher SHR values when lowering the arm during the initial phases of arm elevation, which corresponds with the higher SHR values in the initial phases of our study, which presumably contributed to the higher SHR values in initial phases. Yano et al. [27] also reported a mean SHR measurement of 3.5, which is similar to the value in group C in our study. The exceptionally high SHR values and the high overall SHR values that were shown in the initial phases in our study can be attributed to the small number of cases. Moreover, the high SHR value in group H is assumed to be because scapular motion is more limited than glenohumeral motion.

This study has the following limitations. First, the number of cases may not be enough. However, similar studies [11, 18, 28] showed statistically significant results with five to ten patients. Second, fluoroscopic imaging was limited to the

scapula and humerus, which makes it difficult to examine the thoracic portion. This can cause differences in patients' positions during the fluoroscopy procedure. However, we asked participants to maintain the positions as possible to avoid this problem. Otherwise, this study has merits in that it was non-invasive, allowing dynamic motion analysis, and errors were not generated because of skin slippage. Third, we could not evaluate accurately the impact of the hook plate on shoulder kinematics. Actually, we have to consider both trauma and plate effect for injured shoulder in our study. Fourth, we did not consider the dominant or non-dominant side although it impacts the shoulder kinematics significantly, [17, 29], and not compare with another type of treatment (suture for instance) or after removal of the implants. If we evaluated shoulder kinematics after hook plate removal, we could get a more persuasive conclusion that the hook plate should be removed early.

Clavicle hook plate fixation is easy to perform, and it is associated with good results. In this study, we could conclude that a treatment by clavicle hook fixation in acromioclavicular injury in young active male causes significant changes in the upward rotation, external rotation, and posterior tilt of shoulder kinematics and SHR; so, we could assume that the clavicle hook plate should be removed early. In order to confirm that assumption, we have to do further study including shoulder kinematics after hook plate removal.

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Compliance with ethical standards

This study was approved by the Ethics Committee and the Institutional Review Board of the Wonju College of Medicine, Yonsei University (YWMR-15-8-072). All patients gave written consent after the study was explained to them.

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