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ORIGINAL ARTICLE

Effects of short malunion of the clavicle on in vivo scapular kinematics

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Background: Short malunion of the clavicle after fracture can change scapular kinematics and alter clinical outcome. However, the effects of malunion on kinematics and outcomes remains poorly understood because there have been no in vivo studies measuring changes during active motion with malunion. This study aimed to measure and to compare in vivo 3-dimensional (3D) scapular kinematics between normal shoulders and shoulders with short malunion using 3D–2-dimensional model image registration techniques.
Methods: Fifteen patients with clavicle fracture who had been treated conservatively were enrolled in this study. In these patients, the angle of scapular upward rotation, posterior tilting, and external rotation were compared between shoulders with short malunion and contralateral, normal shoulders. A 3D–2-dimensional model image registration technique was used to determine the 3D orientation of the scapula.
Results: Scapular upward rotation increased following increase of the arm elevation angle and also showed a significant difference by arm elevation in both groups ($P = .04$). Posterior tilting of the scapula gradually increased as the arm abduction angle increased, and this varied significantly between groups ($P = .01$). Shoulders with short malunion also showed a more internally rotated position than the contralateral, normal shoulders between 100° and the maximum abduction angle ($P = .04$).
Conclusion: Our results suggest that clavicle shortening of >10% greatly affects scapular kinematics in vivo. Further studies will be needed to determine the clinical implications of short malunion of the clavicle.
Level of evidence: Basic Science Study; Kinesiology
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Keywords: Clavicle; fracture; short malunion; scapular kinematics; shoulder; image registration technique

It was once commonly accepted among orthopedic surgeons that conservative management in diaphyseal clavicle fracture results in satisfactory outcomes.[16,18,20] However, recent studies have challenged this idea, suggesting that conservative management results in less satisfying results than previously thought.[6,24] When we conservatively treated patients with diaphyseal fracture, we observed complications, such as fatigue, poor cosmesis, delayed return to work, and nonunion.[2] Indeed, conservative management is associated with an increased frequency of clavicle shortening, which may lead to pain and decreased muscle strength.[14] Consequently, many

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groups now recommend anatomic reduction and restoration of the length of the clavicle. Evidence also supports this choice, as surgical management is associated with fewer complications than conservative management.[2,3,6]

Although surgical management results in fewer adverse events, faster union, and better functional outcomes than conservative management,[2] the effect of anatomic reduction of the clavicle on clinical outcomes remains a topic of considerable debate.[19,21] In clavicle fractures, some degree of bone length shortening is generally expected with conservative treatment, and according to some studies, nearly half of all fractures result in short malunion.[4,17] Eskola et al[4] found that shortening >15 mm is significantly associated with increased frequency of pain in patients treated with conservative management. In addition, Hill et al[6] found no reduction in range of motion or weakening of muscle strength in patients whose clavicle had been shortened by >20 mm; however, pain and localized tenderness were noted in these patients.

The causes for this pain have not yet been clearly defined, but shortening of the clavicle is considered a possible origin of scapular dyskinesis. Matsumura et al[12] performed a cadaveric study that revealed a change in scapular kinematics after the clavicle was shortened by >10% of its original length. However, no study has similarly demonstrated kinematic changes in an in vivo setting. An in vivo study of change in scapular kinematics due to shortening of the clavicle during active arm abduction in the scapular plane is needed to confirm the findings of the previous cadaveric study.

Thus, the aim of this study was to measure and to compare in vivo 3-dimensional (3D) scapular kinematics between normal shoulders and shoulders with short malunion using 3D–2-dimensional model image registration techniques. We hypothesized that scapular kinematics would differ significantly between normal shoulders and shoulders with short malunion.

Materials and methods

Subjects

This retrospective case-control study was conducted with patients who underwent conservative treatment with a broad arm sling for unilateral clavicle fracture at our institution. From August 2012 to August 2014, 38 patients who underwent conservative treatment using an arm sling for clavicle shaft fracture were reviewed. Six patients were excluded from the pre-questionnaire and physical examination. There were 3 patients with multidirectional instability of the shoulder, 2 patients with a history of injury or surgery before the clavicle fracture in both shoulders, and 1 patient with evidence of limited range of motion on passive movement. Thus, we excluded these 6 patients and explained study participation to the remaining 32 patients. Seven of these patients refused to participate in the study; 10 patients were excluded because they did not meet the definition of short malunion. As a result, 15 patients were included in this study. Patients included in the study were a mean of 12.4 months after injury (mean, 12.4 ± 0.8 months; range, 11.1-13.7 months). Patients had no subjective pain or dysfunction of the shoulder that required medication and physiotherapy. The length of the clavicle was defined as the distance between the most ventral points of the proximal and distal ends.[12] It was measured using 3D reconstructed images from computed tomography (CT). In accordance with a study by Matsumura et al,[12] we defined short malunion as >10% shortening of the length of the clavicle compared with the length of the uninjured side. The mean age of the patients was 29.5 years (mean, 29.5 ± 0.6 years; range, 22-40 years), and all subjects were men. Data were analyzed within subjects by comparing injured shoulders with short malunion with the contralateral, normal shoulders of the same patients. Of the 15 patients who were included in this study, 13 had the clavicle fracture on the dominant side and 2 on the nondominant side. The fracture resulted from a motor vehicle accident in 9 patients, contact sports in 4 patients, and a fall in 2 patients. In all 15 subjects, the fracture was type 2B according to the Robinson classification system.[18] To minimize radiation exposure to the subjects, the test time was kept as short as possible, and our fluoroscopy was modified under appropriate Food and Drug Administration guidelines.

Image acquisition and 3D modeling

Subjects were oriented in a sitting position with the torso 30° to the plane of a single-plane fluoroscopic x-ray system (Infinix Active; Toshiba, Tochigi, Japan) so that the scapular plane was perpendicular to the x-ray beam (Fig. 1). All images were obtained at 30 Hz. Patients abducted their arms, starting from the side of the trunk along the direction of the scapular plane to the maximal elevation possible at a rate of about 3 seconds per cycle. During abduction, the elbow was maintained in a fully extended position, and the arm was externally rotated with the thumb pointing up. This movement was practiced by each subject before the actual measurement until he felt comfortable. A total of 3 trials were performed with a 40-second break between each trial; median values were used for analysis. CT scans (SOMATOM Sensation 16; Siemens Medical Solutions, Malvern, PA, USA) of bilateral shoulders were performed with a 1-mm slice pitch (image matrix, 512×512; pixel size, $0.9765625 \times 0.9765625$ mm). CT images were segmented, and 3D models of the humerus, scapula, and clavicle were constructed (ITK-SNAP; Penn Image Computing and Science Laboratory, Philadelphia, PA, USA). Following the program's instructions (Geomagic Studio, Morrisville, NC, USA), an anatomic coordinate system to our 3D bone model was generated (Fig. 2). The method suggested by Matsuki et al[11] was used to construct X-, Y-, and Z-axes in each model. The humeral origin was positioned at the centroid of the humeral head, the Y-axis was parallel to the humeral shaft, and the Z-axis was defined as a line through the intertubercular groove from the origin. The scapular origin was set as the midpoint of the line that connects the most superior and inferior bone edges of the glenoid. The Y- and Z-axes were pointed superiorly and anteriorly, respectively.

The scapular kinematics relative to the x-ray coordinate system was determined by using Euler and Cardan angles.[5] Motion of the scapula was defined as anterior-posterior tilt about the X-axis, internal-external rotation about the Y-axis, and upward-downward rotation about the Z-axis.

Image registration and data processing

The positions of the humerus, clavicle, and scapula in 3D space were determined from single-plane x-ray images through model image

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