

CLINICAL ARTICLE

Application of Image Registration to Analyze the Clavicular Rotation of Normal Upper Limb Motion in the Sagittal Plane

Peng Su, MM^{1,2}, Jun-lin Zhou, MD¹ , Feng Liu, MM², Yi Zhang, MD²

¹Department of Orthopaedics, Beijing Chaoyang Hospital, Capital Medical University and ²Department of Orthopaedics, Beijing Shijingshan Hospital, Capital Medical University, Beijing, China

Objective: To use image registration techniques to study the clavicular rotation of the shoulders in the sagittal plane.

Methods: From 28 April 2019 to 20 May 2019, 13 healthy adults (7 males and 6 females) with no history of shoulder trauma surgery or chronic pain were recruited. Patients' ages ranged from 22 to 42 years, with a mean age of 26.5 years. Three-dimensional composite images of the sternum–clavicle–humerus were taken using CT images of upper limb movement in the sagittal plane in the 13 healthy adults. Four different postures were registered: (i) anatomical supine position; (ii) elbow joints lifted anteriorly in the supine position; (iii) posterosuperior hyperextension of the elbow joints in the prone position; and (iv) posteroinferior hyperextension of the elbow joints in the prone position. Image data from the humerus and clavicle in three of the postures were processed to calculate Euler angles for movements in the sagittal plane. SPSS 19 was used to perform statistical analyses.

Results: There was no significant difference in the angles of change in the clavicle and humerus between the dominant and non-dominant sides under different movement patterns. For upper limb movements in the sagittal plane, the clavicle displayed different Euler angles in different postures. The rotation angle from the anatomical to the horizontal position was the smallest angle, with an average value of 7.1°, whereas the rotation angle from horizontal to posterosuperior hyperextension was the largest, with an average value of 37.2°. When the upper limb moved from anterior protraction to a posterosuperior extension, the intrinsic rotation angle of the clavicle reached its maximum, with an average value of 27.9°; when moved from the anatomical to the horizontal position, 9.1% of the sagittal rotation was executed by the clavicle. During rotation from the horizontal position to posterosuperior hyperextension and from the anatomical to posterior extension, the clavicle showed relatively higher weights at 29.5% and 37.0%, respectively.

Conclusion: Our results showed that dominance was not a consideration when studying clavicular rotation. Image registration is an effective method that can be used to study upper limb scapular movements. Through comparing and analyzing the data, two postures had relatively large changes in the rotation angle. This can help improve indicators of clavicular rotational function during physical examinations and postoperative functional evaluations.

Key words: Clavicular rotation; Image registration; Shoulder movements; Upper extremity; Upper limb motion

Introduction

For over a century, researchers have attempted to identify simple principles that account for the generation of upper limb movements in human subjects¹. Upper limb

movement is important for evaluation of stroke recovery; however, there is no standard for its measurement due to the complexity of the movement. Currently, consensus is lacking on the use of kinetic and kinematic measures (metrics) for

Address for correspondence Jun-lin Zhou, MD, Department of Orthopaedics, Chaoyang Hospital of Capital Medical University, No. 8 of Worker's Stadium South Road, Chaoyang District, Beijing, China 100020 Tel: +86-10-85231327; Fax: 010-85231240; Email: zhoujunlin145@163.com

Disclosure: The authors declare that they have no competing interests.

Received 29 May 2020; accepted 30 December 2020

motor recovery. In reviewing 225 studies, Schwartz *et al.* found 151 different metrics used for measuring upper limb movements².

Most upper limb motor outcome measures at the activity level of the International Classification of Functioning (ICF) mainly quantify the time or degree of task completion on ordinal scales without considering movement quality. To identify true motor recovery, measures should be able to distinguish between restitution of premorbid movement patterns and the use of alternative (compensatory) movement patterns during task accomplishment. This requires the characterization of motor behavior at two levels: the performance level, describing the movements of the end effector (i.e. hand) in space, and the movement quality level, describing the joint rotations in body-centered coordinates. At the performance level, the speed, precision, and straightness of endpoint movement can be measured. At the movement quality level, spatial and temporal characteristics of individual joint and segment (i.e. trunk) movement are described, as well as interjoint coordination and muscle activation patterns³.

Upper limb movement involves the motion of the clavicle, scapula, and humerus. The sternoclavicular joint, composed of the clavicle and sternum, is the starting joint of the shoulder girdle movement. The human clavicle is the only bone of the shoulder girdle forming a synovial joint with the trunk and is essential for stability and movements, for circulation, ventilation and tension, and even for the muscles of expression of the throat, shoulder and thorax⁴.

Clavicle fractures constitute approximately 2.6%–4% of all fractures, with lateral end fractures comprising 21%–28% of all clavicle fractures⁵. The current treatment of choice involves internal fixation with superior or anterior clavicle plating; however, their clinical success and patient satisfaction are decreasing. The use of intramedullary devices is on the rise, but data describing the intramedullary canal parameters are lacking⁶. Therefore, determining how the clavicle rotates is important for comprehensively understanding shoulder function, as well as providing a potential target for disease treatment. However, it is difficult to measure clavicular motion in different postures as it is affected by the motion of the sternum and scapulae and by respiratory movement. In previous studies, the subjects examined were either living bodies or cadavers. Several methods were used in these studies, including the optical and magnetic motion capture system, model-image registration, and sensor implantation. However, the results were neither consistent nor convincing. First, the results of clavicular rotation in studies around the year 2000 vary greatly, especially in the sagittal plane. Second, numerous studies have used three-dimensional (3D) motion capture to quantify clavicular motion, but this method is markedly inaccurate in measuring the rotation angle of the clavicle in the sagittal plane^{7–11}. There is no optimal method to measure the rotation angle of the clavicle in the sagittal plane *in vivo*.

Image registration is the process of overlaying images (two or more) of the same scene obtained at different times from different viewpoints and/or by different sensors; it involves geometrical alignment of the two images (the reference and sensed images)¹². Image registration provides a highly advantageous approach for identifying, correlating, and quantifying regional changes in anatomy and function¹³. Commonly used image registration approaches include intensity-based methods and feature-based methods that use handcrafted image features¹⁴. The interpretation and review of single-photon emission CT (SPECT) or positron emission tomography (PET) images registered with MRI, CT, digital subtraction angiography (DSA), or ultrasound (US) images often contribute additional and new information to the workup of subjects beyond that obtained from the individual procedures¹³. Image registration has become more important. It enables integration of different images into one representation such that the complementary information can be accessed more easily and accurately¹⁵.

With the development of medical imaging technology, the objectives of image registration have changed considerably. Image registration was originally developed to measure *in vivo* kinematics of total knee arthroplasty; however, in the present study we used image registration techniques to study the clavicular rotation of the shoulders in the sagittal plane. The purpose of this study is: (i) to prove that image registration is an effective method of studying complex shoulder movement and the characteristics of clavicular rotation while in sagittal motion; (ii) to measure and analyze sternoclavicular images of healthy individuals moving their upper limbs in different dimensions in the sagittal plane, with the advantages of being non-invasive, accurate, and involving limited radiation exposure; and (iii) to investigate clavicular rotation using 3D sternal images in different anatomical positions.

Materials and Methods

Study Participants

From 28 April 2019 to 20 May 2019, we recruited 13 healthy adults (7 male and 6 female) with no history of shoulder trauma surgery or chronic pain. The inclusion criteria were: (i) the participants were healthy adults; (ii) the shoulder joint could complete the four movements of the rest position, the horizontal position, the posterior upper extension position, and the posterior lower extension position, and the patients agreed to undergo CT examination of the shoulder joint in the four positions; (iii) the reconstruction and registration of CT images of the scapula in the four positions was completed, and corresponding rotation angles were measured; and (iv) the study design was basic medical research.

The exclusion criteria were: (i) history of shoulder trauma or surgery; (ii) history of chronic shoulder pain; (iii) could not cooperate to complete the specified action; (iv) unable to accept the radiation exposure required in this study; and (v) personal privacy issues. Patient ages ranged

from 22 to 42 years, with a mean of 26.5 years. Body mass indexes ranged from 18.9 to 39.2 kg/m², with a mean of 24.2 kg/m². The left shoulder was dominant in 2 participants and the right was dominant in 11. The appropriate review board approved this study and all participants provided informed consent. A total of 26 shoulders (13 cases) were assigned to two groups according to the participants' dominant side.

Image Acquisition

A Discovery CT750 HD (GE Healthcare, Milwaukee, WI, USA) CT scanner was used. The parameter settings for the CT scans were as follows: slice thickness, 0.625 mm; slice increment, 0.625 mm. The scanning positions were: (i) anatomical supine position; (ii) elbow joints lifted anteriorly in the supine position; (iii) posterosuperior hyperextension of the elbow joints in the prone position; and (iv) posteroinferior hyperextension of the elbow joints in the prone position. The scanning range spanned from the inferior to 2 cm below the sternal angle plane and the superior to the acromial end of the clavicle, including the parts above the deltoid trochanter proximal to the humerus (Fig. 1).

Image Registration

The raw image data was imported into MIMICS 21 (Materialise NV, Leuven, Belgium) to form a 3D composite image of the four positions containing the sternum–clavicle–humerus. According to the recommendations of the International Society of Biomechanics, we adhered to the principle of immobilizing the sternum during clavicular motion and the

rotation of the clavicle was expressed using Euler angles¹⁶. The 3D image of the sternum in the supine position was regarded as the registration target and registration was performed on the 3D composite images of the other positions. Finally, we obtained superimposed sternal images in the four postures and 3D images of the clavicle and humerus in different positions (Fig. 2).

Data Collection and Processing

The connecting line between the center of the sternal end and the acromial end of the clavicle was taken as the axis and the conoid tubercle was used as a reference to measure the Euler angle. For the humerus, the connecting line between the start and end of the intertubercular groove was taken as the axis and used to measure the sagittal angle.

The raw image data of each participant was divided into three groups according to postural changes: position a–b, position b–c, and position a–d. The 3D composite image of the sternum–clavicle–humerus in the supine position was regarded as the standard in capturing the descriptions of the clavicular Euler angles in different positions. Then, the angular range of the humerus in the sagittal plane was calculated.

Parameters

Angles

Euler angles¹⁷: Start with the frame coincident with a known frame {A}. Rotate {B} first about Y_B by an angle θ , then about X_B by an angle ψ , and, finally, about Z_B by an angle ϕ . In this representation, each rotation is performed about an

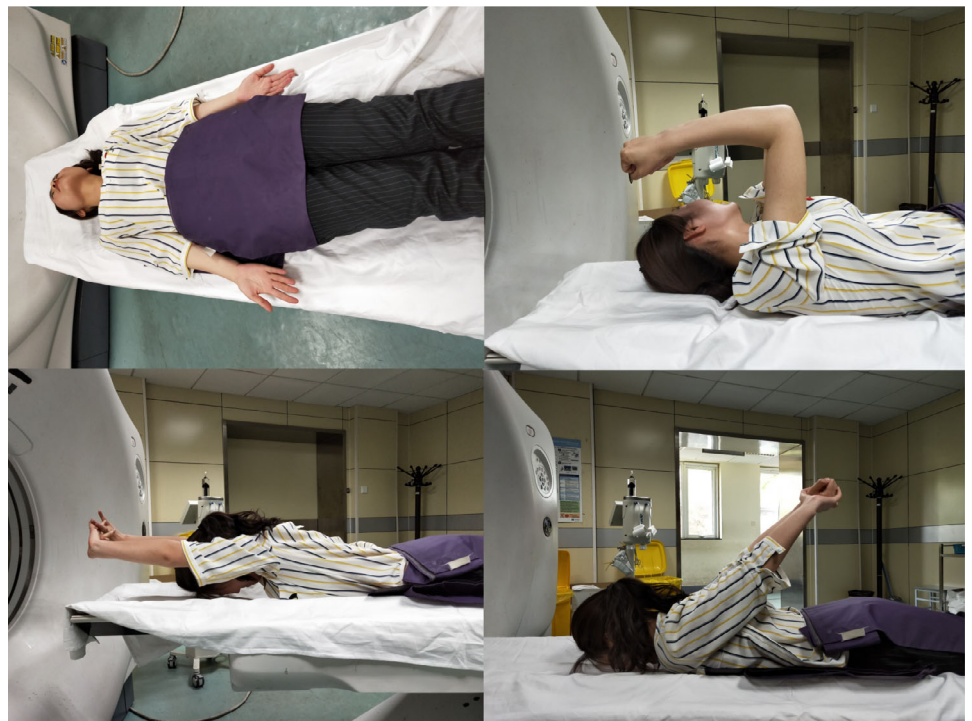


Fig. 1 Posture of the volunteers during the CT projection is demonstrated. The scanning positions were: (A) anatomical supine position, (B) elbow joints lifted anteriorly in the supine position, (C) posterosuperior hyperextension of the elbow joints in the prone position, and (D) posteroinferior hyperextension of the elbow joints in the prone position.

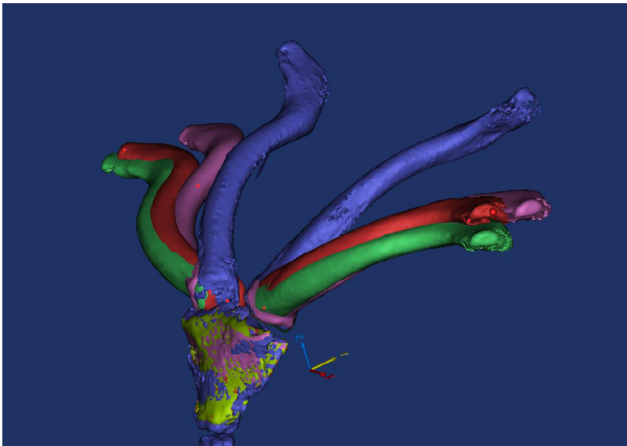


Fig. 2 Image registration effect demonstration. Three-dimensional images of the clavicle and humerus in four different positions. (A) Green, anatomical supine position; (B) pink, elbow joints lifted anteriorly in the supine position; (C) purple, posterosuperior hyperextension of the elbow joints in the prone position; and (D) red, posteroinferior hyperextension of the elbow joints in the prone position.

axis of the moving system {B} rather than one of the fixed reference {A}. Such sets of three rotations are called Euler angles. Note that each rotation takes place about an axis whose location depends upon the preceding rotations. Because the three rotations occur about the axes Y, X, and Z, we will call this representation Y-X-Z Euler angles.

Clavicular nutation angle: The rotation order of the clavicle is y-x-z, and the corresponding angle is nutation angle θ .

Clavicular precession angle: The rotation order of the clavicle is y-x-z and the corresponding angle is the precession angle ψ .

Clavicular intrinsic rotation angle: The rotation order of the clavicle is y-x-z, and the corresponding angle is intrinsic rotation angle ϕ .

Humeral rotation angle: This is the angle of the humeral thoracic joint in the sagittal plane.

Measurement methods and significance

After image registration, the spatial 3D coordinates of the markers of the clavicle and the proximal humerus under different attitudes were known. The measurement is calculated based on the definition of the Euler angle and the rotation order of Y-X-Z. The description method of the Euler angle and corresponding bone marker were selected according to the ISB recommendation on definitions of joint coordinate systems¹⁶. The three angles of the Euler angle represent the angle of rotation in order of the axis of rotation, which is related to the order of rotation.

Statistical Methods

Independent sample *t*-tests were performed on the two groups of data obtained from scanning the three postures on the dominant and non-dominant sides. $P < 0.05$ was regarded as the test criterion.

The clavicle rotation angles of the active shoulder and the non-active shoulder were quantitatively studied. The independent sample *t*-test was used and the value of $\alpha = 0.05$. A quantitative study of the rotation angle of the clavicle in three different postures was carried out. The statistical method used was the χ^2 -test, with a value of $\alpha = 0.05$ and a value of $\alpha = 0.017$ between groups.

Image data from the humerus and clavicle were processed to calculate Euler angles and weights (clavicular intrinsic rotation angle/humeral rotation angle) for different positions in the sagittal plane. Analysis of variance was applied and $P < 0.05$ was regarded as the test criterion. Least significant difference post hoc tests were used for between-group comparisons and $P < 0.017$ was regarded as the test criterion. SPSS 19 (IBM, Armonk, NY) was used to perform statistical analyses.

Results

No Significant Difference between the Dominant and Non-dominant Sides

Table 1 compares the clavicle and humerus in different positions on the dominant and non-dominant sides. There was no significant difference in the angles of change in the

TABLE 1 Comparison of the dominant and non-dominant sides for different motion postures

| Dominant: non-dominant | Postures | t-value | P-value |
|--|----------|---------|---------|
| Clavicular nutation angle θ | 1: a-b | 0.211 | 0.650 |
| | 2: b-c | 0.048 | 0.829 |
| | 3: a-d | 1.938 | 0.177 |
| Clavicular precession angle ψ | 1: a-b | 1.971 | 0.173 |
| | 2: b-c | 0.012 | 0.915 |
| | 3: a-d | 1.943 | 0.176 |
| Clavicular intrinsic rotation angle ϕ | 1: a-b | 1.402 | 0.248 |
| | 2: b-c | 0.006 | 0.940 |
| | 3: a-d | 0.061 | 0.807 |
| Humeral rotation angle | 1: a-b | 0.601 | 0.446 |
| | 2: b-c | 0.030 | 0.865 |
| | 3: a-d | 0.391 | 0.538 |

clavicle and humerus between the dominant and non-dominant sides under different movement patterns. Therefore, all shoulders (13 cases, 26 shoulders) could be included in the statistical analysis.

Clavicle Displayed Different Euler Angles in Different Postures

The clavicular nutation angle was $\theta = 51.4^\circ \pm 7.1^\circ$ and the clavicular intrinsic rotation angle was $\varphi = 47.2^\circ \pm 7.8^\circ$. The humeral rotation angle (anatomical position – posterosuperior)

was $228.5^\circ \pm 13.9^\circ$ and the humeral rotation angle (anatomical position – posteroinferior) was $30.0^\circ \pm 12.2^\circ$ (Figs 3–5).

The clavicular Euler angles and weights for different postures (clavicular intrinsic rotation angle/humeral rotation angle) are shown in Table 2.

Significant Changes in the Rotation Angle between Specific Positions

For upper limb movements in the sagittal plane, the clavicle presented different Euler angles in different positions. The

Fig. 3 Scatter diagram of the clavicular nutation angle and the humeral rotation angle (78 sets of paired data).

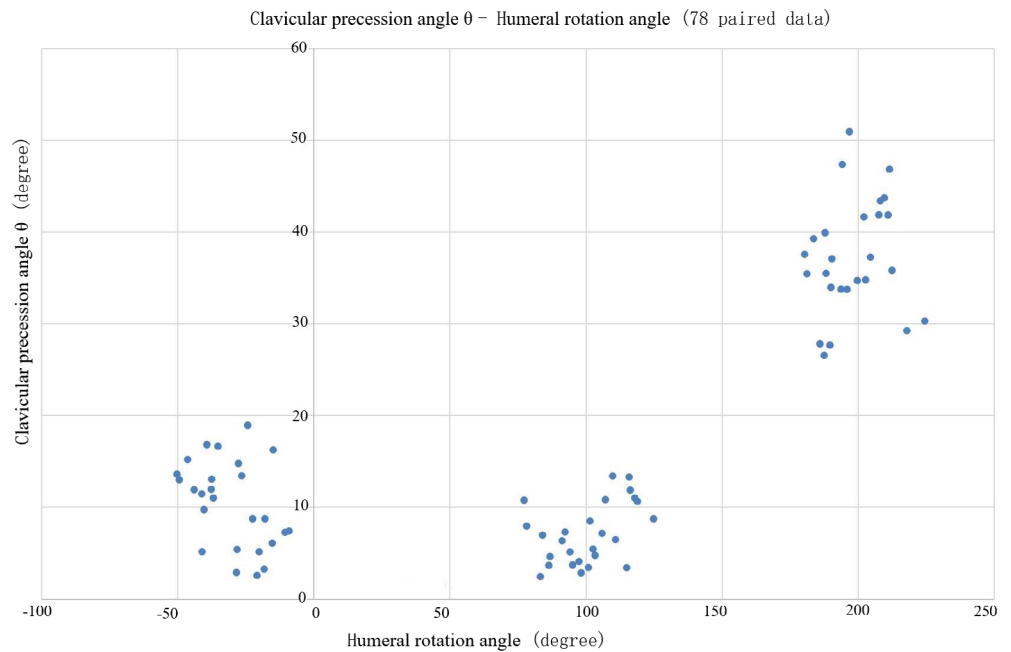
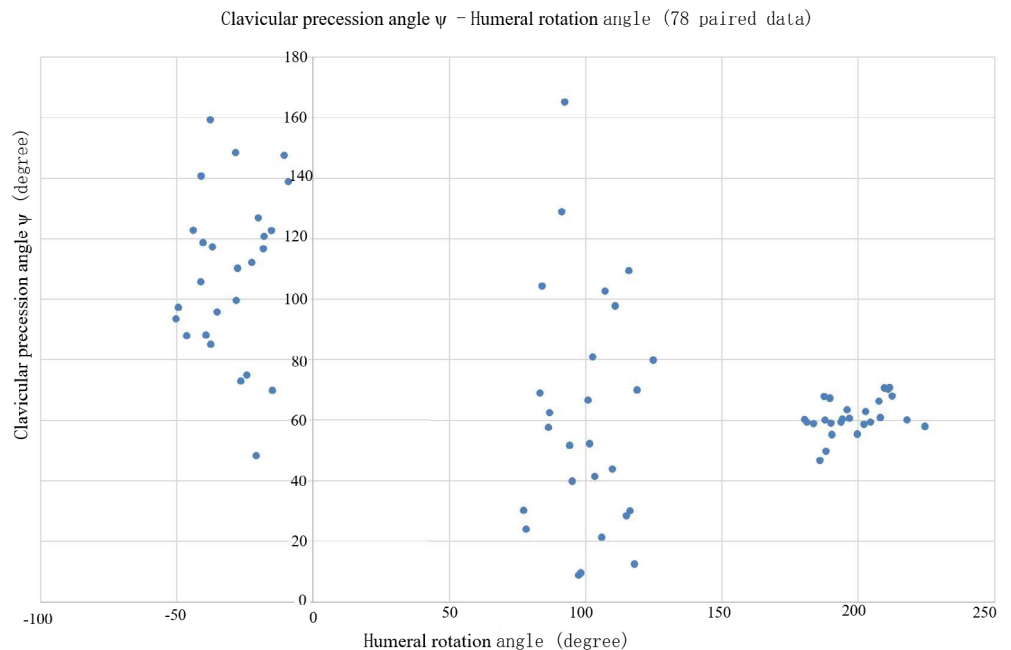


Fig. 4 The scatter diagram of the clavicular precession angle and the humeral rotation angle (78 sets of paired data).



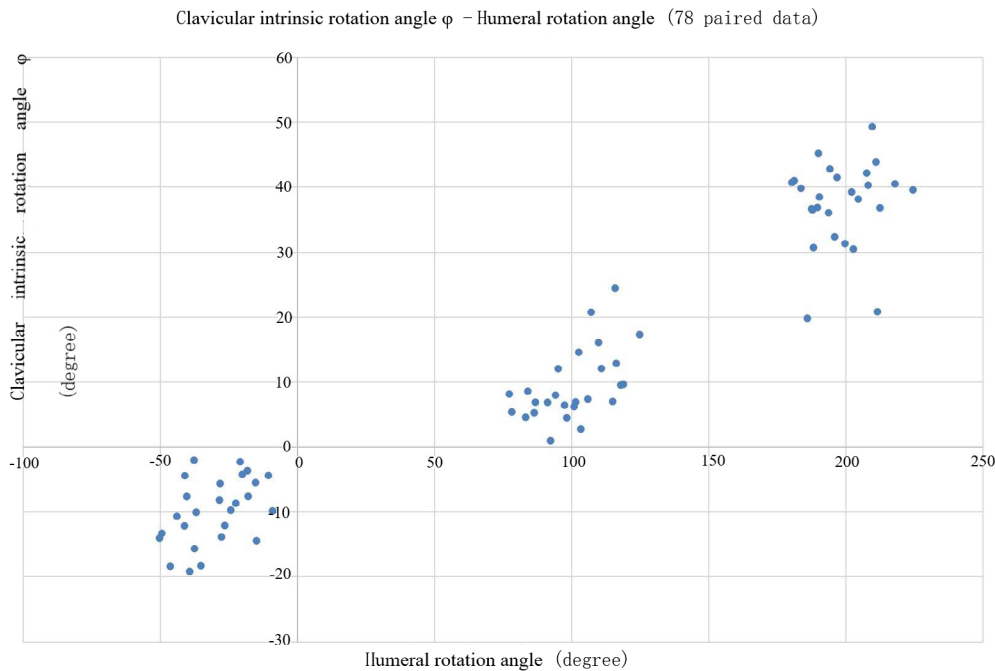


Fig. 5 Scatter diagram of the clavicular intrinsic rotation angle and the humeral rotation angle (78 sets of paired data).

rotation from the anatomical to the horizontal position was the smallest, with an average value of 7.1° , whereas the rotation from the horizontal position to posterosuperior hyperextension was the largest, with an average value of 37.2° . From the anatomical position to posterosuperior hyperextension, the clavicle rotated in a posterosuperior direction of approximately 60° , and during posterior extension, the clavicle rotated in the posteroinferior direction. When the upper limb moved from anterior protraction to posterosuperior extension, the intrinsic rotation angle of the clavicle reached its maximum, with an average value of 27.9° . During upper limb movement from the anatomical to the horizontal position, 9.1% of the sagittal rotation was executed by the clavicle, which had the smallest weight. During rotation from the horizontal position to posterosuperior hyperextension and from the anatomical to posterior extension, the clavicle showed relatively higher weights, at 29.5% and 37.0%, respectively.

Discussion

CT Images Are Applicable in Analyzing Movement Characteristics of a Single Joint in Complex Joint Motion

This research showed that in the study of multi-joint compound motion, CT images are registered to a single joint, which effectively reduces the measurement error caused by adjacent joint motion, and can be used to independently analyze the movement characteristics of a single joint in complex joint motion. The advantages of using this technique are: (i) the data was obtained from active motion in living bodies; (ii) the procedures were noninvasive and

participants were exposed to a limited dose of radiation; and (iii) the interference of skin, soft tissues, respiratory movement, and other joint movements were eliminated so that the results were relatively accurate.

Image Registration Was Used to Analyze Clavicular Kinematics

Some studies using cadavers have examined passive motion, whereas studies using skin markers have not been able to measure the relative movement of skin and bones; other studies using bone markers are more invasive⁸⁻¹¹. Image registration is a technique that uses aligned and superimposed medical images for evaluation. Aside from using ionizing radiation, this technique does not require an invasive operation and is fairly accurate^{18, 19}. Image registration has been applied to investigate shoulder kinematics¹⁹ but has seldom been used to analyze clavicular kinematics.

Results of Rotation Angle of the Clavicle Differ from Previous Studies

In terms of the sagittal rotation angle of the clavicle, the results of this study differ considerably from those of previous studies. Previous clavicular rotation results vary widely; during upper limb abduction, the measurements of elevation angles were from 7° to 16° , posterior contraction angles ranged from 16° to 31° and rotation angles from 23° to 33° ^{9, 20-23}. However, in this study, clavicular intrinsic rotation and nutation angles were 47.2° and 54.7° , respectively, showing a marked deviation. The possible reasons are: (i) differences in research methods (e.g. with intervening soft tissue and the use of skin markers) can lead to significant errors, especially for intrinsic rotation of the clavicle; (ii) cadaver kinematics do

TABLE 2 Clavicular Euler angles and percentages for different postures (clavicular intrinsic rotation angle/humeral rotation angle)

| Euler angles and percentages | Postures | Mean \pm SD ($^{\circ}$) | Discrete coefficient | F-value | P-value | P-value between groups |
|--|----------|------------------------------|----------------------|---------|---------|-------------------------------------|
| Clavicular nutation angle θ | 1: a-b | 7.1017 \pm 3.3451 | 0.4710 | 289.479 | 0.000 | 2-1:0.000 2-3:0.000 |
| | 2: b-c | 37.2193 \pm 6.3162 | 0.1697 | | | |
| | 3: a-d | 10.3968 \pm 4.7379 | 0.4557 | | | |
| Clavicular precession angle ψ | 1: a-b | 61.0550 \pm 39.3016 | 0.6437 | 25.259 | 0.000 | 1-3:0.019 3-1:0.000 3-2:0.000 |
| | 2: b-c | 61.0944 \pm 5.9187 | 0.0969 | | | |
| | 3: a-d | 108.4663 \pm 27.0598 | 0.2495 | | | |
| Clavicular intrinsic rotation angle ϕ | 1: a-b | 9.3871 \pm 5.5264 | 0.5887 | 79.536 | 0.000 | 2-1:0.000 2-3:0.000 |
| | 2: b-c | 27.9161 \pm 7.2887 | 0.2611 | | | |
| | 3: a-d | 9.8814 \pm 5.0647 | 0.5125 | | | |
| Humeral rotation angle | 1: a-b | 100.6685 \pm 13.3248 | 0.1324 | 225.974 | 0.000 | 3-1:0.000 3-2:0.000 |
| | 2: b-c | 97.7587 \pm 14.9998 | 0.1534 | | | |
| | 3: a-d | 30.0406 \pm 12.1954 | 0.4060 | | | |
| Clavicular intrinsic rotation angle/humeral rotation angle (%) | 1: a-b | 9.1372 \pm 4.6785 | 0.5120 | 24.503 | 0.000 | 1-2:0.000 1-3:0.000 |
| | 2: b-c | 29.5233 \pm 9.3781 | 0.3177 | | | |
| | 3: a-d | 37.0144 \pm 23.5103 | 0.6352 | | | |

not include active motion; and (iii) differences in measurement methods. In this study, the connecting line between the centers of the sternal end and the acromial end of the clavicle was taken as the axis and the conoid tubercle was used as the reference to measure the rotation angle, providing more authentic and reliable measurement results.

Two Positions in the Shoulder Joint Scoring System Should Be Paid More Attention

The effectiveness of the existing shoulder joint score was evaluated and analyzed according to the results of the study. Common scoring systems currently used for the assessment of injuries to the clavicle, acromioclavicular joint, and sternoclavicular joint include the Oxford Shoulder Score, the Constant Score, and the Nottingham Clavicle Score. However, there are two disadvantages in using these scores: (i) they do not specifically measure injuries to the clavicle, acromioclavicular joint or sternoclavicular joint and, thus, cannot precisely determine the degree of post-injury dysfunction; and (ii) although these scores provide some reference for evaluating shoulder function, this works as a result of composite movements of multiple joints. Hence, these scoring systems are more general in their evaluation of the range of shoulder joint movements in daily life, without detailed assessments of individual bones and joints²⁴⁻²⁷. Our results showed that the clavicular nutation angle gradually increased when the upper limb moved from the anatomical position to the posterosuperior extension. Therefore, this position can better evaluate the function of the sternoclavicular joint. During movement from the horizontal position to posterosuperior hyperextension and from the anatomical position to posterior extension, the clavicular intrinsic rotation angle was relatively large and bore a large weight on upper limb rotation in the sagittal plane. This position enables better evaluation of the function of the acromioclavicular joint. These two positions are most effective in evaluating the sagittal motion of the clavicle during assessments of the shoulder joint's complex motion. We suggest that more attention should be paid to these two positions in the shoulder joint scoring system.

Study Limitations

There are a few limitations in this study that should be recognized. First, our sample was small and, thus, the age range of participants was restricted. Second, only four postures were investigated, without consideration of the movement process. However, the maximum static range of motion could also effectively reflect the function of the clavicle. Third, we did not strictly control the posture of the forearm during movement, which may have affected the kinematics of the humerus and, thereby, influenced the clavicle. Because of the presence of the humerus and scapula between the forearm and the clavicle, the authors suggest that this effect can be ignored. Finally, we used a supine or prone position, both of which are affected by gravity. Because all measurements in this study were made under muscular tension, the results may be somewhat less

robust than those obtained for the angle of movement in an upright position.

Conclusion

Our results showed that dominance was not a consideration when studying clavicular rotation. This is consistent with previous research findings that there were no statistically significant differences between dominant and nondominant shoulders for forward elevation or abduction²⁸.

Image registration is an effective method for studying upper limb scapular movements. There were significant changes in the intrinsic rotation angle of the clavicle during upper limb rotations from a horizontal position toward a posterosuperior direction on the sagittal plane and a vertical position toward posterior extension. These two positions can help provide a better indication of clavicular rotational function during physical examinations and postoperative functional evaluations.

Acknowledgments

The authors would like to thank Editage (www.editage.com) for English language support. This work was supported by the Scientific Research Project of Key Medical Disciplines in Shijingshan District, Beijing (2018). The funding agency had no role in the study design, in the collection, analysis and

interpretation of data, in the writing of the report, or in the decision to submit the article for publication.

Supporting Information

Additional Supporting Information may be found in the online version of this article on the publisher's web-site:

Supplementary Figure S1. (A) Three points were selected to mark the end of the clavicular sternum, the end of the clavicular acromial, and the end of the clavicular acromial. The three-dimensional space coordinates of each point were recorded. (B) The three points of each pose define a plane. (C) When the first rotation is made, the angle between the perpendicular lines of two planes is nutation angle θ . (D) Preparing for the second spin. (E) For the second rotation, the angle between the two markers at the end of the sternum of the clavicle and that at the end of the acromion of the clavicle in the same plane is the angle of precession ψ . (F) For the third rotation, the markers at the end of the sternum of the clavicle and the end of the acromion of the clavicle of the two attitudes with the angle of the two attitudes overlap. Taking their connecting line as the axis, the included angle of the markers at the conical eminence of the clavicle of the two attitudes is the angle of rotation φ .

References

- Miranda JGV, Daneault JF, Vergara-Diaz G, et al. Complex upper-limb movements are generated by combining motor primitives that scale with the movement size. *Sci Rep*, 2018, 8: 12918.
- Kwakkel G, Van Wegen E, Burridge JH, et al. Standardized measurement of quality of upper limb movement after stroke: consensus-based core recommendations from the second stroke recovery and rehabilitation roundtable. *Int J Stroke*, 2019, 14: 783–791.
- Levin MF, Hiengkaew V, Nilanont Y, et al. Relationship between clinical measures of upper limb movement quality and activity poststroke. *Neurorehabil Neural Repair*, 2019, 33: 432–441.
- Ljunggren AE. Clavicular function. *Acta Orthop Scand*, 1979, 50: 261–268.
- Kandemirli SG, Kabar F, Cakir Kandemirli G, Gulleroglu NB, Yazici Z. Clavicle duplication following physal injury. *Surg Radiol Anat*, 2019, 41: 373–376.
- Aira JR, Simon P, Gutiérrez S, Santoni BG, Frankle MA. Morphometry of the human clavicle and intramedullary canal: a 3D, geometry-based quantification. *J Orthop Res*, 2017, 35: 2191–2202.
- Hamming D, Braman JP, Phadke V, LaPrade RF, Ludewig PM. The accuracy of measuring glenohumeral motion with a surface humeral cuff. *J Biomech*, 2012, 45: 1161–1168.
- Karduna AR, McClure PW, Michener LA, Sennett B. Dynamic measurements of three-dimensional scapular kinematics: a validation study. *J Biomech Eng*, 2001, 123: 184–190.
- Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. Motion of the shoulder complex during multiplanar humeral elevation. *J Bone Joint Surg Am*, 2009, 91: 378–389.
- Ludewig PM, Cook TM, Shields RK. Comparison of surface sensor and bone-fixed measurement of humeral motion. *J Appl Biomech*, 2002, 18: 163–170.
- Matsuki K, Matsuki KO, Mu S, et al. In vivo 3D analysis of clavicular kinematics during scapular plane abduction: comparison of dominant and non-dominant shoulders. *Gait Posture*, 2014, 39: 625–627.
- Zitová B, Flusser J. Image registration methods: a survey. *Image Vision Comput*, 2003, 21: 977–1000.
- Weber DA, Ivanovic M. Correlative image registration. *Semin Nucl Med*, 1994, 24: 311–323.
- Nandish S, Prabhu G, Rajagopal KV. Multiresolution image registration for multimodal brain images and fusion for better neurosurgical planning. *Biom J*, 2017, 40: 329–338.
- de Vos BD, Berendsen FF, Viergever MA, Sokooti H, Staring M, Išgum I. A deep learning framework for unsupervised affine and deformable image registration. *Med Image Anal*, 2019, 52: 128–143.
- Wu G, van der Helm FC, Veeger HE, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand. *J Biomech*, 2005, 38: 981–992.
- Craig JJ. *Introduction to Robotics: Mechanics and Control*, 3rd edn. Upper Saddle River, NJ: Pearson Education; 2005; 43–44.
- Moro-oka TA, Hamai S, Miura H, et al. Can magnetic resonance imaging-derived bone models be used for accurate motion measurement with single-plane three-dimensional shape registration? *J Orthop Res*, 2007, 25: 867–872.
- Bey MJ, Kline SK, Zuel R, Lock TR, Kolowich PA. Measuring dynamic in-vivo glenohumeral joint kinematics: technique and preliminary results. *J Biomech*, 2007, 41: 711–714.
- Kozono N, Okada T, Takeuchi N, et al. In vivo kinematic analysis of the glenohumeral joint during dynamic full axial rotation and scapular plane full abduction in healthy shoulders. *Knee Surg Sports Traumatol Arthrosc*, 2017, 25: 2032–2040.
- Sahara W, Sugamoto K, Murai M, Tanaka H, Yoshikawa H. The three-dimensional motions of glenohumeral joint under semi-loaded condition during arm abduction using vertically open MRI. *Clin Biomech (Bristol, Avon)*, 2007, 22: 304–312.
- Fung M, Kato S, Barrance PJ, et al. Scapular and clavicular kinematics during humeral elevation: a study with cadavers. *J Shoulder Elbow Surg*, 2001, 10: 278–285.
- McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *J Shoulder Elbow Surg*, 2001, 10: 269–277.
- Barwood SA, French JA, Watson LA, Balster SM, Hoy GA, Pizzari T. The Specific AC Score (SACS): a new and validated method of assessment of isolated acromioclavicular joint pathology. *J Shoulder Elbow Surg*, 2018, 27: 2214–2223.
- Taft TN, Wilson FC, Oglesby JW. Dislocation of the acromioclavicular joint. An end-result study. *J Bone Joint Surg Am*, 1987, 69: 1045–1051.
- Skare Ø, Liavaag S, Reikerås O, Mowinckel P, Brox JI. Evaluation of Oxford instability shoulder score, Western Ontario shoulder instability index and Euroqol in patients with SLAP (superior labral anterior posterior) lesions or recurrent anterior dislocations of the shoulder. *BMC Res Notes*, 2013, 6: 273.
- Charles ER, Kumar V, Blacknall J, et al. A validation of the Nottingham Clavicle Score: a clavicle, acromioclavicular joint and sternoclavicular joint-specific patient-reported outcome measure. *J Shoulder Elbow Surg*, 2017, 26: 1732–1739.
- Barnes CJ, Van Steyn SJ, Fischer RA. The effects of age, sex, and shoulder dominance on range of motion of the shoulder. *J Shoulder Elbow Surg*, 2001, 10: 242–246.