

# Three-dimensional morphometric analysis of the lateral clavicle and acromion: Implications for surgical treatment using subacromial support

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## Abstract

**Objectives:** Dislocations and periarticular fractures of the acromioclavicular joint are common injuries of the shoulder girdle. When surgical intervention is indicated, subacromial support is one option to restore the alignment between scapula and the distal/lateral clavicle. Devices used for subacromial support rely on a form of subacromial ‘hook’. The shape, inclination and orientation of which is often mismatched to the anatomy of the inferior surface of the acromion, which may lead to painful acromial osteolysis and rotator cuff abrasion causing impingement. The primary goal of this study was to characterize the geometrical parameters of the acromion and distal clavicle, and their orientation at the acromioclavicular joint.

**Methods:** Computed tomography scans of 120 shoulders were converted into digital three-dimensional models. Measurements of the acromion inclination and acromion width relative to the torsional angle as well as the clavicle depth were taken. A numerical optimization of the anatomical parameters (including torsional and inclination angles, height and width) was performed to find the combination of those parameters with the lowest interpatient variability.

**Results:** The mean clavicle depth was found to be 11.1 mm. The mean acromion width was 27 mm. The combination of torsional and inclination angles with lowest interpatient variability was found at 80° and 16°, respectively.

**Conclusion:** There is a high interpatient variability in the morphology of the inferior surface of the acromion. Subacromial support using a ‘hook’ can be optimized for contact surface area, which should lead to fewer complications after the restoration of acromioclavicular orientation using acromial support strategies.

## Keywords

Clavicle, acromion, acromioclavicular joint, hook plate, optimization

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## Introduction

Separations of the acromioclavicular joint (ACJ) and fractures of the distal clavicle are common injuries of the shoulder girdle. The severity of the ACJ injury depends on the energy and direction of the applied forces on the intrinsic (ACJ capsule and acromioclavicular) and extrinsic (coracoclavicular and acromiocracoid) ligaments and the musculoperiosteal envelope (deltoid and trapezius entheses, and the intervening periosteum). Combinations of vertical, horizontal and rotational displacements of the ACJ are observed clinically, while diagnosis is often limited to a radiological assessment. The difficulty of achieving a

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**Table 1.** Evaluated data set with relevant metadata grouped by data provider.

Provider	CT (#)	Gender (#)		Side (#)		Height (cm)		Weight (kg)		Age (years)	
		Female	Male	Left	Right	Mean	STD	Mean	STD	Mean	STD
Leuven	30	15	15	17	13	169.2	9.4	73.0	18.0	51.8	14.2
Fukuyama	50	24	26	25	25	159.7	11.0	56.4	12.4	63.0	12.2
Innsbruck	40	22	18	20	20	170.4	10.3	N/A	N/A	58.4	7.6
All	120	61	59	62	58	165.6	11.4	62.6	16.8	58.6	13.5

precise diagnosis of structural ACJ injuries and the variety of treatment options has resulted in a lack of consensus in how to treat them.<sup>1,2</sup> A recent randomized controlled trial has found no evidence of improved general health after operative treatment.<sup>3</sup> Nevertheless, this study involved mainly Rockwood Grade III injuries and there is broad consensus that surgical treatment is indicated for higher-energy injuries with greater structural disruption, such as Rockwood Grade IV–VI.<sup>4–6</sup>

Various techniques, including hook plate osteosynthesis, are utilized for ACJ stabilization.<sup>7</sup> Using hook plates offers many advantages: even without a direct suture, the temporary stabilization of the ACJ results in a scarring of the torn extrinsic and intrinsic ligaments, providing good results for both vertical and horizontal stability, respectively. The procedure is reliable, easy to teach (i.e. reproducible) and does not require arthroscopic equipment for regions in which this is not available. Nevertheless, adverse events such as subacromial bursal impingement, heterotopic ossification, infection and hook-related complications (painful osteolysis, acromial penetration and fracture) have been reported.<sup>8</sup> Recent evidence suggests that the shape of the hook does not match the anatomy of the inferior surface of the acromion: the hook often appears directed posteriorly, towards the posterolateral corner of the acromion, if the plate is aligned with the neutral axis of the distal clavicle, and it is not well adapted to the inclination of the acromion.<sup>9,10</sup> Both factors may contribute to an increased point-force loading of the thin cortex of the inferior acromion which, when combined with residual horizontal instability, may provoke osteolysis. Hook plate removal after healing is therefore an integral part of the surgical procedure and even recommended by some manufacturers.<sup>11,12</sup>

The primary goal of this study was to model the acromial inclination using statistical methods applied to three-dimensional (3D) volume rendered computed tomography (CT) scans of non-injured shoulder girdles and to establish whether this could be correlated with the anterior to posterior (AP) torsional angle, and/or to define an anatomical region where the interpatient variability of these angles is minimized. As a secondary goal, we aimed to understand whether it was possible to optimize specific important relevant features of a supporting hook, including the torsional and inclination angles, length and height. This information could be used to develop novel internal fixators with optimized hook

characteristics with consequential reduction in the risk of complications.

## Materials and methods

### Study design

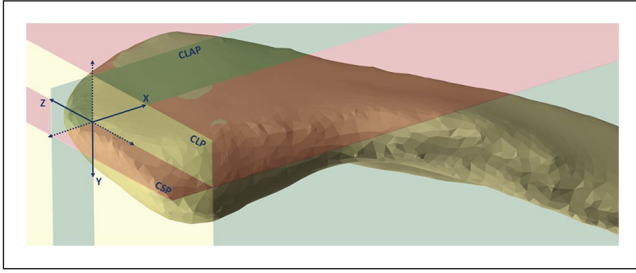
This study included a retrospective 3D morphological analysis of the acromion and lateral clavicle and their spatial relationship.

### Shoulder dataset

CT scans of 120 shoulders (69 patients; see Table 1) were acquired, segmented and converted into 3D CAD (computer-aided design) models for digital analysis. Scans performed during patient treatment unrelated to this study at three hospitals (KULeuven, Leuven, BE; Fukuyama City Hospital, Fukuyama, JP; Universitätsklinik für Unfallchirurgie Innsbruck, Innsbruck, AT) were retrospectively acquired in anonymized form. All scans were taken with the patient lying supine and the arm adducted against the side of the body. Scans with insufficient resolution or pre-existing injuries, pathologies or extreme deformities were excluded from this analysis; no further in- or exclusion criteria were applied. The CT scans were then segmented (AMIRA; Thermo Fisher Scientific, Hillsboro, Oregon, USA), based on a threshold defining all points with tissue density  $\geq 200$  Hounsfield Units (hu) as bone. Segmentation was done at Synthes Innomedic GmbH (Rheinsheim, Germany). The segmentation results were manually checked and corrected where needed, Gaussian smoothing was applied and the surface was reconstructed using the marching cubes algorithm.<sup>13</sup> STL (stereolithography, a file format representing the surface of a 3D part as a mesh of triangles) files of clavicle and acromion of the same shoulder were then assembled in CAD files (CREO Parametric V3.0; PTC Inc., Needham, Massachusetts, USA), keeping their original relative position and orientation.

### References for measurements

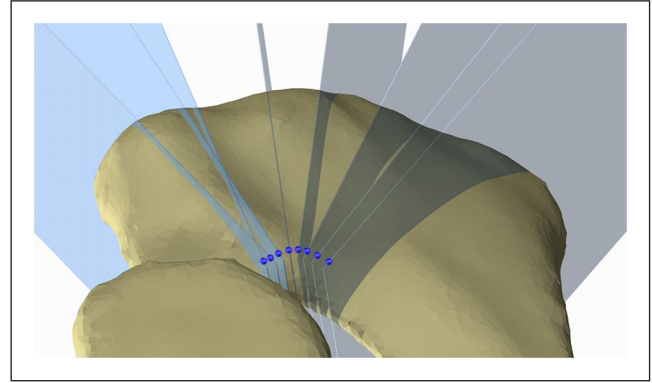
To provide a reference for the subsequent measurements, a coordinate system (CLS, clavicle lateral system) defined by three orthogonal planes was positioned on the lateral end of



**Figure 1.** Clavicle lateral system (CLS) defined by three orthogonal planes: clavicle superior plane (CSP in red), clavicle lateral axis plane (CLAP in green) and clavicle lateral plane (CLP in yellow).

the clavicle. The origin of the CLS was placed at the intersection of the clavicle superior plane (CSP), the clavicle lateral axis plane (CLAP) and the clavicle lateral plane (CLP), with the x-axis pointing medially along the intersection of the CSP and CLAP, the z-axis pointing posteriorly along the intersection of the CSP and CLP and the y-axis pointing either superiorly (for left shoulders) or inferiorly (for right shoulders) along the intersection of the CLAP and CLP (see Figure 1). The CSP was defined by three points on the superior, flat surface of the clavicle: the first point on the anterolateral corner, the second on the posterolateral corner and the third on the superior surface above the tip of the conoid tubercle. The CLAP was defined to be orthogonal to the CSP and coincident with the lateral clavicle axis, which is the line connecting the visually estimated centre of the ACJ articulating surface on the clavicle and the most inferior tip of the conoid tubercle. The CLP was specified to be orthogonal to the CSP and the CLAP and passing through the most lateral point of the clavicle. All reference points were chosen to allow for reproducible setting of the CLS according to anatomical landmarks.

Four to nine sections were defined on each acromion for a discrete measurement of the relevant parameters (see Figure 2). The exact number of sections for each shoulder was defined based on the individual anatomy dimensions and STL resolution. For each section, one point was placed on the medial edge of the acromion, facing the posterior gap between clavicle and acromion. The medial bone edge and the point were projected onto the CSP. A tangent to the projection of the medial edge of the acromion was placed at each projected point (see blue points in Figure 2). The projected points serve as origins for the sections. All sections coincide with their respective origin and are orthogonal to the tangent. Depending on the curvature of the medial edge of the acromion, the defined sections may intersect. The chosen method to define origins of the sections results in an offset of the planes in addition to the angular distribution; however, this offset is small in relation to the measured dimensions and was chosen to ensure inter-anatomical reproducibility.



**Figure 2.** Exemplary representation of the section planes (light blue to grey) for one anatomy. Each section coincides with an origin point (dark blue point) positioned on the projection of the medial edge of the acromion onto the clavicle superior plane. The section planes are orthogonal to the tangent to the projection of the medial edge of the acromion at their respective origin.

### Morphological parameters

Four parameters were used to characterize the acromion and lateral clavicle of each shoulder: torsional angle, inclination angle, acromion width and clavicle depth (see Figure 3).

**Torsional angle.** The torsional angle was defined as the AP angulation between the acromial section and the lateral clavicle. It was measured between the CLP and each section of each shoulder. From a clinical perspective, it would make sense to measure the torsional angle relative to the CLAP; however, to generate only positive values – and thereby facilitate the downstream optimizations – the CLP was chosen as a reference.

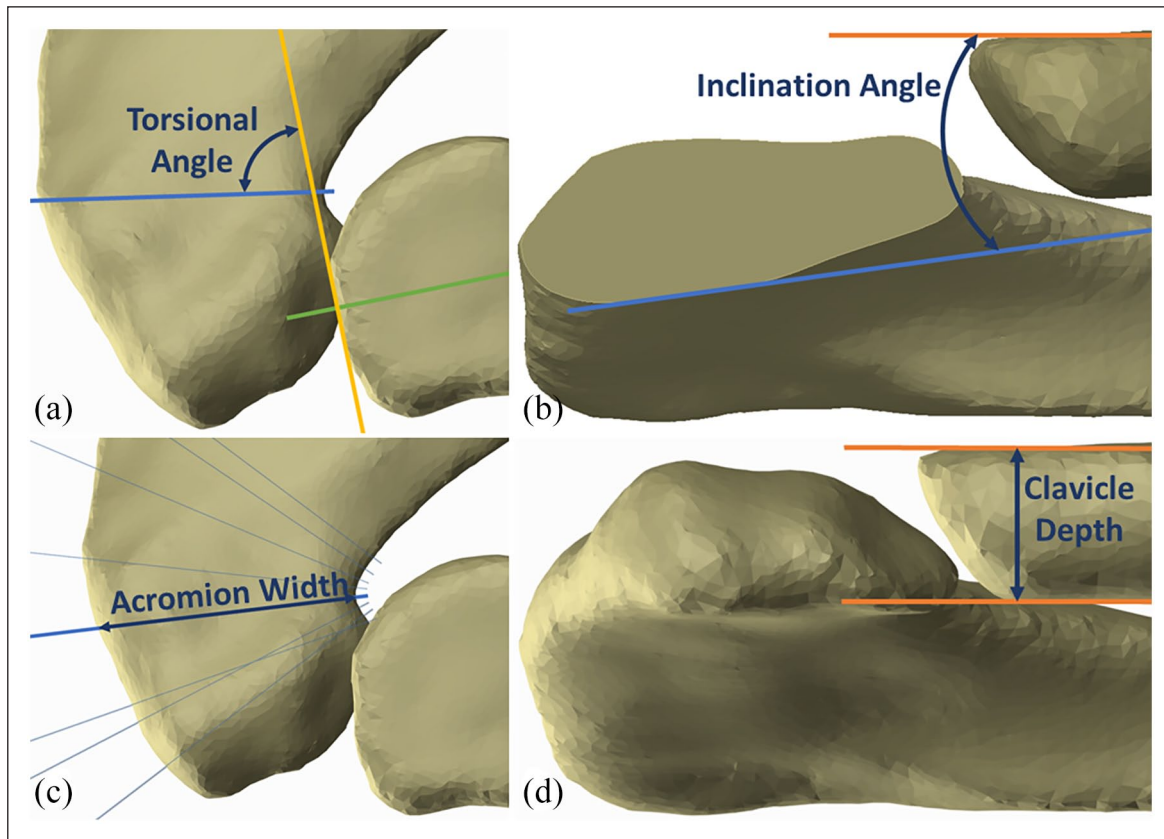
**Inclination angle.** The inclination angle was defined as the angulation between the most lateral intersection line on the inferior surface of the acromion and the CSP. This angle was measured for each section of each shoulder. Sections with negative inclination were recorded as inclination = 0° as a negative hook inclination of a subacromial support device would result in pin-point contact at the hook tip.

**Acromion width.** The acromion width was defined within each section as the distance between the most medial and the most lateral intersection points with the acromion. It was measured on a projection of the acromion onto the CSP.

**Clavicle depth.** The clavicle depth was defined as the distance from the CSP to a plane parallel to the CSP and tangential to the inferior surface of the lateral clavicle, ignoring any osteophytes.

### Parameter optimization

**Torsional and inclination angles.** A grid-search was performed within a defined angular range to identify the combination



**Figure 3.** Parameters used to characterize each acromioclavicular joint: torsional angle (a), inclination angle (b), acromion width (c) and clavicle depth (d). Blue lines represent section planes.

of torsional and inclination angles with the lowest expected interpatient variability (IPV). The evaluated grid ranged from  $0^\circ$  to  $180^\circ$  for the torsional angle and  $0^\circ$  to  $90^\circ$  for the inclination angle. Each integer combination of torsional and inclination angle within the grid represents one evaluation point. For each section within each shoulder, the squared difference (as defined in equation (1)) was calculated. The squared difference is the squared delta torsional angle plus the squared delta inclination angle. The delta torsional angle and the delta inclination angle were defined as the difference between the respective parameter value of the section and the evaluation point (see equations (2) and (3)). The values of the sections with minimal squared difference within each anatomy were summed up over all shoulders and the square root taken to obtain the IPV (see equation (4)). This was repeated for all evaluation points within the grid to identify the combination of torsional and inclination angles with minimal IPV.

$$d^2 = \Delta_{\text{torsional}}^2 + \Delta_{\text{inclination}}^2$$

*Equation (1): Squared difference defined as squared delta torsional angle plus squared delta inclination angle.*

$$\Delta_{\text{torsional}} = \text{torsional}_{\text{section}} - \text{torsional}_{\text{evaluation}}$$

*Equation (2): Delta torsional angle defined as AP angle of the respective section minus torsional angle of the evaluation point*

$$\Delta_{\text{inclination}} = \text{inclination}_{\text{section}} - \text{inclination}_{\text{evaluation}}$$

*Equation (3): Delta inclination angle defined as inclination angle of the respective section minus inclination angle of the evaluation point*

$$\text{IPV}(\text{torsional}, \text{inclination}) = \sqrt{\sum d_{\text{min}}^2}$$

*Equation (4): IPV defined as the square root of the sum of the squared minimal differences.*

The full data set, being representative of the addressed population, also contains outlying anatomies. These outliers increase the IPV and might affect the identified combination of torsional and inclination angles with the lowest IPV. The difference  $d$  (see equation (1)) was evaluated for the section closest to the evaluation point with the lowest IPV (see equation (4)) for all shoulders. Anatomies with a difference greater than  $12^\circ$  were labelled as outliers. The maximal value of  $12^\circ$  was defined according to the surgical technique guides

for existing clavicle hook plate systems on the market, which allow bending of the hook up to 10°–15°. The lower end of this range (10°) was used and an acceptable remaining mismatch of 2° was added, resulting in a maximally acceptable initial mismatch of 12°. The IPV was re-calculated on a subset of data sets excluding the outliers for all evaluation points within the previously defined grid. The combinations of torsional and inclination angles with the lowest IPV for the full data set and the subset without outlying anatomies were then compared to evaluate the influence of the outliers on the result. For comparison with a possible non-optimized hook plate, the number of outliers was calculated at the respective contact point of 90° torsion and 0° inclination. In addition, the number of outliers was evaluated at a torsion of 90° and at the corresponding average inclination, and at a torsion of 90° and at the corresponding inclination with the lowest IPV.

The grid-search for the combination of torsional and inclination angles with lowest IPV was repeated for various sub-datasets, to allow for a comparison of the results when grouped by side (left vs right), provider (Fukuyama vs Innsbruck vs Leuven) and gender (female vs male). Outliers as previously defined were included into this analysis to provide an analysis encompassing a large range of existing anatomies.

**Acromion width.** The width of the acromion was measured for each shoulder at the section which was the closest to the combination of torsional and inclination angles with the lowest IPV. For the full data set as well as each sub-dataset grouped by side, provider and gender, the mean value, the 5th and the 95th percentile were calculated.

**Clavicle depth.** For each shoulder, one measurement of the clavicle depth was performed according to the definition in Figure 3. A least mean square analysis on the measured clavicle depths was performed to categorize all analysed bones into groups. Each group was characterized by one clavicle group-depth and represents the hook depth of a device for subacromial support. To find the optimal set of group-depths (representing the hook depths) for a given number of groups (representing the number of hook depths available in one system), the minimal distance between the clavicle depth and the closest given group-depth was calculated for each shoulder scan. This was done for all possible group-depth combinations within the range from 6 to 22 mm and for sets containing one to eight different groups. The increments between the hook depths were chosen to be constant within a set. The squares of the minimal distances to the nearest group-depth were then averaged over all shoulders. The combination of group-depths with the lowest average squared minimal distance was the optimal set for a given number of groups.

### Statistical analysis

Statistical correlations between the parameters and to the patients' metadata were analysed. All statistical evaluations were performed using Minitab 18.1 (Minitab LLC, State

College, PA, USA). The measurement of the parameters on several discrete sections per data set yields a non-normal distribution of the corresponding values. Therefore, the Mann–Whitney U rank-sum test was chosen for all statistical comparisons within this study. Linear correlations were investigated with Pearson's test. A significance level of  $\alpha=0.05$  was used for all statistical comparisons.

### Intra- and inter-observer reliability

The consistency of the employed methodology was evaluated by repeating all measurements on a subset of 20 shoulders. The subset was randomly selected from the full database of 120 shoulders. The full workflow, including the placement of the CLS and the measurement of the anatomical parameters, was then repeated on these datasets by the original and one additional observer. The results of the second evaluation of the original observer were then compared to the results of the first evaluation for intra-observer and to the results of the additional observer for inter-observer reliability.

## Results

### Parameter optimization

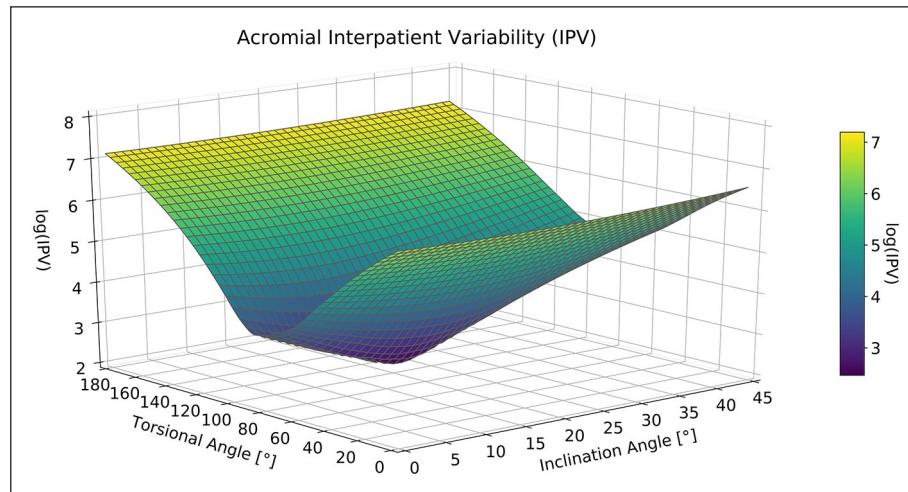
**Torsional and inclination angles.** The optimal combination of torsional and inclination angles, with the lowest IPV, was found at an optimal torsional angle of 80° and an optimal inclination angle of 16° (see Figure 4).

For the section of each shoulder closest to the optimal combination of torsional and inclination angles, the mean torsional angle is  $80.0^\circ \pm 6.1^\circ$  and the mean inclination angle is  $16.2^\circ \pm 7.2^\circ$  (see Table 2). A total of eight (6.6%) data sets with a negative inclination, noted as 0°, in their optimal section were identified.

No correlation of torsional and inclination angles was found when comparing the results for all sections (Pearson correlation coefficient=0.043,  $p=0.237$ ) as well as when comparing only the results for the optimal sections (Pearson correlation coefficient=0.131,  $p=0.153$ ).

The comparison of the optimized torsional and inclination angles of sub-datasets grouped by side, data provider and gender showed no relevant differences between the categories with one group (see Figure 5). The detailed results of this analysis including optimized torsional and inclination angles and their respective standard deviations for each group are listed in Table 2.

A total of 26 data sets (22%) were identified as outliers, that is their nearest section had a combined torsional and inclination difference greater than 12° to the evaluation point with the lowest IPV. However, no impact on the optimal torsional and inclination angles values resulted after the exclusion of these data sets. The identified outliers deviate uniformly in all directions around the point with lowest IPV (Figure 6). In consequence, the resulting optimal torsional and inclination angles for the analysis without outliers are



**Figure 4.** Calculated interpatient variability (IPV) for all torsional angles of 0°–180° and inclination angles of 0°–45°. The lowest IPV was found at 80° torsion and 16° inclination. The IPV is shown in logarithmic scale for improved visualization.

**Table 2.** Optimized hook torsional and inclination angles as well as acromion width at the optimal section and clavicle depth are reported for the full dataset and subsets of data grouped by gender, body side and data provider.

Parameter	Full data set	Data subset						
		Gender		Body side		Data provider		
		Female	Male	Left	Right	Fukuyama	Innsbruck	Leuven
Inclination (°)	16 ± 6	17 ± 5	15 ± 6	14 ± 5	18 ± 6	18 ± 6	18 ± 4	13 ± 6
Torsion (°)	80 ± 7	74 ± 7	81 ± 7	75 ± 8	76 ± 7	76 ± 7	82 ± 6	75 ± 9
Acromion width (mm)	27 ± 3	25 ± 2	29 ± 3	27 ± 3	27 ± 3	27 ± 3	28 ± 4	26 ± 2
Clavicle depth (mm)	11 ± 2	10 ± 2	12 ± 2	11 ± 2	11 ± 3	11 ± 2	11 ± 2	12 ± 1

Parameters are reported as average ± standard deviation and rounded for readability.

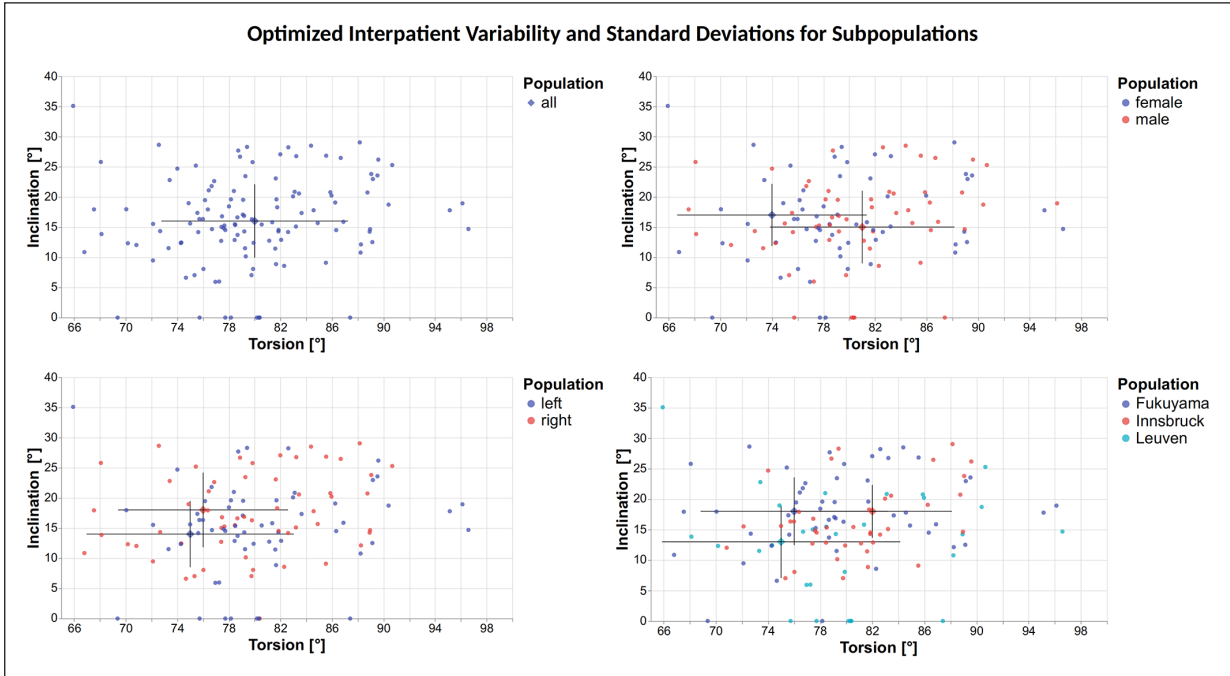
identical to the ones for the full data set, that is, 80° and 16°, respectively. As expected, the standard deviations for both parameters are reduced by removing the outliers from the analysis: from 7.2° to 5.1° for torsional and from 6.1° to 4.8° for inclination. For the evaluation at 90° torsion and 0° inclination, 79 outliers (66%) were found. The average inclination at 90° torsion is 17°, the lowest IPV is found at 14° inclination; for these evaluation points, 36 (30%) and 40 (33%) outliers were found, respectively.

**Acromion width.** The mean acromion width at the section closest to the optimal torsional angulation for each data set is 27.0 mm ± 3.3 mm. The 5th and 95th percentiles of an assumed normal distribution locate at 21.9 and 33.8 mm, respectively. Mean values and standard deviations for the analysed sub-datasets are listed in Table 2.

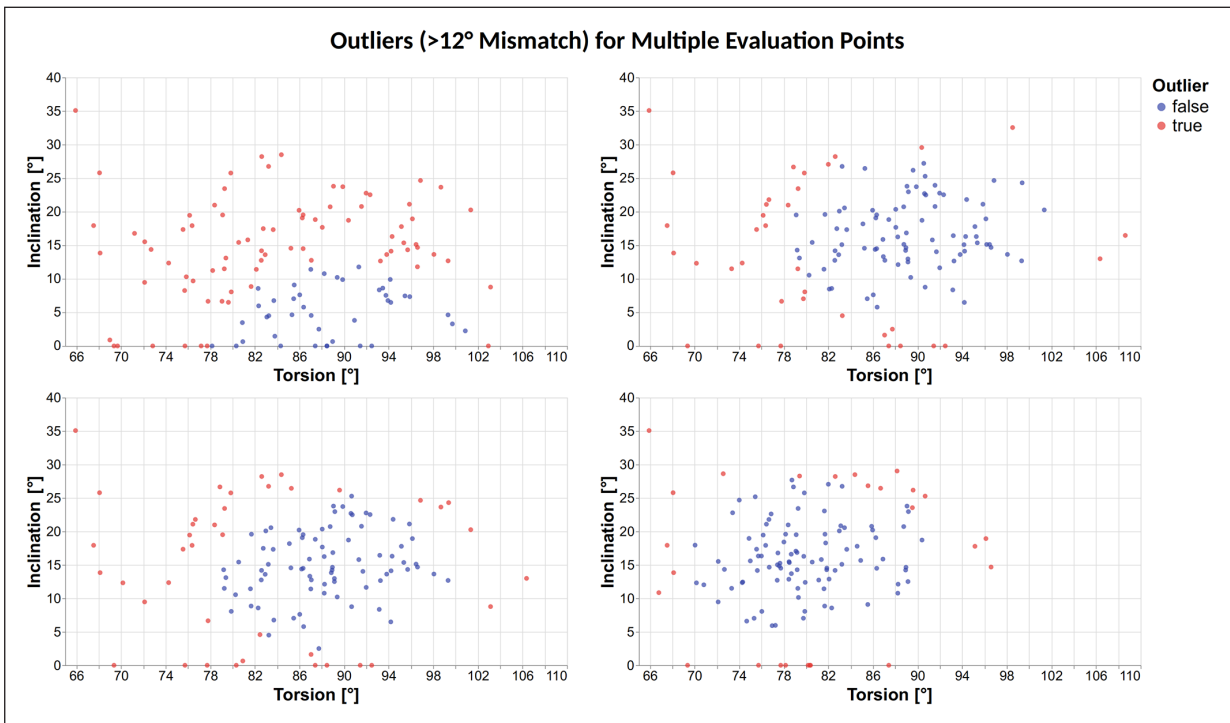
**Clavicle depth.** The mean clavicle depth for the full data set is 11.1 mm ± 2.0 mm. Mean values and standard deviations for the analysed sub-datasets are listed in Table 2. No statistically significant differences were found when comparing

the clavicle depth of all left versus all right data sets ( $p=0.668$ ) as well as when performing a paired comparison of the left and right clavicle depth for patients where both sides were available ( $p=0.130$ ). The optimal group-depth for one group is 11 mm with an average squared minimal distance of 21.6 mm<sup>2</sup>. As expected, the average squared minimal distance behaves inversely proportional to the number of depth groups within one set and decreases to 5.2 mm<sup>2</sup> for a set including eight different depth groups. For a set including three depth groups, the optimal set includes groups with 8/11/14 mm group-depth. However, three additional sets with very similar performance (<2% difference) were identified (see Table 3). The results of this evaluation represent the optimized hook depths to be available within a system of implants for subacromial support.

**Statistical correlations between parameters.** Moderate positive correlations were found between clavicle depth and acromion width (Pearson correlation coefficient=0.463,  $p<0.001$ ), clavicle depth and patient height (Pearson correlation coefficient=0.430,  $p<0.001$ ) and acromion width



**Figure 5.** Individual optimal section datapoints and optimized hook torsional and inclination angles (visible at the crossed error bars) for: the full data set (top, left), data grouped by gender (top, right), body side (bottom, left) and data provider (bottom, right). Error bars represent the standard deviation of the corresponding parameter at the optimal sections for each data set.



**Figure 6.** Inclination and torsional angles of the section closest to the respective evaluation point for each data set, grouped by in- and outliers. Outliers were defined as data sets where the nearest section had a combined torsional and inclination difference greater than 12° to the evaluation point. The following evaluation points were used. Top left: 90° torsion and 0° inclination (79 outliers) as contact point of an exemplary hook plate. Top right: 90° and 17° (36 outliers) as average inclination at 90° torsion. Bottom left: 90° and 14° (40 outliers) as lowest IPV at 90° torsion. Bottom right: 80° and 16° (26 outliers) as overall lowest IPV.

**Table 3.** Results of the least mean square analysis of all optimal group-depths for one to eight depth groups, based on the measured clavicle depths.

Number of groups per set	Optimal group depths (mm)								Min. distance <sup>2</sup> (mm <sup>2</sup> )
	1	2	3	4	5	6	7	8	
1	11								21.6
2	10	13							13.5
3	8	11	14						11.0
3 <sup>a</sup>	9	12	15						11.1
3 <sup>a</sup>	10	12	14						11.1
3 <sup>a</sup>	10	13	16						11.2
4	8	10	12	14					8.1
5	8	10	12	14	16				6.2
6	8	10	12	14	16	18			5.8
7	6	8	10	12	14	16	18		5.7
8	8	9	10	11	12	13	14	15	5.2

A lower average squared minimal distance corresponds to a better average characterisation of the anatomies contained within one group by the respective group-depth.

<sup>a</sup>For a set including three depth groups, three additional sets with very similar performance to the optimal set were identified.

and patient height (Pearson correlation coefficient=0.463,  $p < 0.001$ ). In addition, a weak negative correlation was found between optimal inclination and patient height (Pearson correlation coefficient=-0.184,  $p = 0.045$ ).

### Intra- and inter-observer reliability

The intra-observer comparison of the CLS showed a mean absolute error (MAE) and mean absolute deviation (MAD) for the translation of the origin of  $3.1 \text{ mm} \pm 2.1 \text{ mm}$  and rotations of  $4.8^\circ \pm 3.0^\circ$  (x-axis in XY plane),  $2.8^\circ \pm 2.1^\circ$  (x-axis in XZ plane) and  $2.1^\circ \pm 2.6^\circ$  (y-axis in YZ plane). The corresponding inter-observer evaluation yielded MAEs and MADs of  $2.5 \text{ mm} \pm 2.4 \text{ mm}$  for translation and  $4.8^\circ \pm 2.7^\circ$ ,  $2.1^\circ \pm 1.7^\circ$  and  $2.8^\circ \pm 2.4^\circ$  for the rotations.

The corresponding metrics for the anatomical parameters at the optimal section for the intra-observer comparison were  $12.6^\circ \pm 5.6^\circ$  for inclination,  $14.1^\circ \pm 7.5^\circ$  for torsion and  $2.2 \text{ mm} \pm 2.0 \text{ mm}$  for the width of the acromion. The results for the inter-observer evaluation were  $10.8^\circ \pm 7.7^\circ$  for inclination,  $13.5^\circ \pm 10.5^\circ$  for torsion and  $1.7 \text{ mm} \pm 1.9 \text{ mm}$  for width. The comparison of the measured depths of the clavicle yielded  $0.4 \text{ mm} \pm 0.3 \text{ mm}$  and  $0.7 \text{ mm} \pm 0.7 \text{ mm}$  for intra- and inter-observer, respectively.

### Discussion

There are many parameters in use to describe the complex morphology of the distal clavicle and the acromion, such as the height of the clavicle, the acromion width and the inclination of the acromion. The clinical relevance of these parameters is obvious, since they determine how the shape of a given hook plate will affect the acromion. There is evidence that hook plates do not match the anatomy of this region well.<sup>10,14-16</sup> The consequences are implant-related

pain and bony reactions of the under surface of the acromion, such as osteolysis and fractures.<sup>17,18</sup>

During this study, 120 CT-based shoulders were analysed, including both Caucasian and Asian-pacific specimens. These measurements show a mean clavicle depth of 11.1 mm, and a mean acromion width of 27 mm. These findings are in line with other published data.<sup>10,14,19,20</sup>

An important parameter seems to be the inclination of the acromion, since frequently its undersurface is not parallel to the upper surface of the distal clavicle. Comparability of the values reported for this parameter is not always given as there are several ways to measure the inclination of the acromion. Banas et al.<sup>21</sup> introduce the lateral acromion angle (LAA). This angle determines the inclination of the acromion in relation to the glenoid in the frontal plane. Using a frontal magnetic resonance imaging (MRI) sequence just posterior to the ACJ, this angle consists of two lines, one parallel to the under surface of the acromion and one parallel to the glenoid fossa. Within 100 patients, the authors measured a range of  $64^\circ$ – $99^\circ$ , in line with the variability reported by others.<sup>22,23</sup> While this definition of the subacromial inclination is helpful in understanding pathologies of the rotator cuff, it is not suitable to understand the relation between the distal clavicle and the acromion. In contrast to our study, Banas et al. also reported negative inclinations of the acromion ( $>90^\circ$ ), which is explained by the different goal of their analysis.

Our data reveal a mean inclination of the acromion of  $17^\circ$  posterior to the ACJ in line with the posterior aspect of the distal clavicle. The inclination of the acromion – even measured in a comparable way – has no consistent wording nor value in the recent literature. Kim et al. analysed 101 Asian-pacific shoulders using a CT scan at the level just posterior to the ACJ and referred to an ‘acromioclavicular (AC) angle’. With this definition, they measured an inclination of  $17.1^\circ \pm 10.5^\circ$ , which is confirmed by our data.<sup>19</sup> Yoon et al.



performed a CT-based analysis of 46 patients. They called the inclination ‘distal clavicle-acromion angle’ which was noted with a mean of  $24.6^\circ \pm 6.8^\circ$ .<sup>10</sup> By contrast, Wu et al. evaluated a ‘distal clavicle-acromion coronal angle’ as the angle between the upper surface of the distal clavicle and the under surface of the acromion on standardized true anteroposterior radiographs of 102 patients. They were able to categorize patients with different acromion inclinations into four groups. Group A, consisting of 56 patients, had a mean inclination of  $16.65^\circ \pm 1.8^\circ$ , whereas group B consists of 21 patients with a mean inclination of  $23.86^\circ \pm 2.1^\circ$ , group C, consisting of 16 patients, with a mean inclination of  $34.12^\circ \pm 2.5^\circ$  and group D, consisting of 9 patients, with a mean inclination of  $44.6^\circ$ , respectively.<sup>15</sup> This suggests that there is a high variability in morphologies. Thus, it is obvious that hook plates without a suitable inclination of the hook (e.g.  $0^\circ$  as in some implants) will cause in many cases a pointed contact of the hook tip with the acromion. Within our data, a  $0^\circ$ -inclination of a hook matches the anatomy of the acromion only in 34% of cases. This may explain the high number of reported implant-related side effects, such as pain, osteolysis and fractures of the acromion. A mean hook inclination of  $17^\circ$  reduces the mismatch drastically and matches the anatomy of the acromion in 70% of the analysed shoulders. This suggests that even with an optimized hook inclination, there is a need for frequent intraoperative hook adaptations – at least at this position within the subacromial space.

In order to evaluate whether the IPV can be further lowered, the inclination of the acromion was analysed at several positions along the medial border of the acromion. This approach considers that the under surface of the acromion changes in relation to its position. The posterior area of the acromion tilts into the scapular spine, whereas the more anterior areas flatten. To our best knowledge, this approach has not been used before. The analysed data show that the inclination depends not only on the individual, but also on the position where it is measured. Both the AP position and the medial-lateral position of the transection through the acromion influence the degree of inclination. A second parameter, the ‘torsional angle’, was introduced to correlate the position of the acromial transection with its inclination. This analysis demonstrates that the inclination of the acromion and the torsional angle do not correlate, reflecting the high variability in the shape of the acromion. However, a calculation of the lowest IPV suggests that the combination of a torsional angle of  $80^\circ$  and an inclination angle of  $16^\circ$  provides the best results within an average patient population. Using such a combination of parameters, a hook is likely to match the morphology of the acromion in 78% of the anatomies, which represents the best match within this optimization. Still, one has to be aware that there will be outliers which do not match the geometry of a hook with these parameters, requiring either bending the hook or rotating the plate – and therefore the hook itself – in order to achieve a better contact to the acromion.

## Limitations

Several limitations are implied by the design of this study. Due to the complex evaluation of the results, where measurements of the acromion are taken in several sections and only one of those sections is part of the final IPV evaluation, traditional sample size calculation is not applicable, and the power of this study remains unknown. In addition, the measurements for the inclination and torsional angle as well as for the acromion width were taken at discrete, visually selected sections along the acromion, which could slightly impact the outcome of the optimization of these parameters.

Soft tissues such as the capsule of the ACJ, subacromial bursa and the supraspinatus tendon were neglected during this study. However, depending on the individual patient’s anatomy as well as design and placement of a hook plate, these structures can influence the clinical performance of the device and should therefore be included in future analyses.

Furthermore, the results of our IPV optimization of the inclination and torsional angle, as well as of the least mean square analysis of the clavicle depths, only provide a relative comparison of the included options. The implications on the clinical performance of a device designed according to our findings, absolute and relative to currently existing devices remain open.

All CT scans were taken with the arm adducted against the side of the body, thereby excluding the kinematics of relative clavicle to acromion movement during abduction and elevation of the upper limb, and the corresponding changes of the measured torsional and inclination angles. In addition, the resolution of the CT scans used for this analysis differed between and within the three providers. Although all scans were checked for sufficient resolution, this could have an impact on the outcome of the analysis.

Our reliability investigation showed low variability of the CLS placement, acromial width and clavicle depth. However, the measurements of the torsional and inclination angles showed some intra- and inter-observer disagreement. This was allocated to the different placements of the sections and should be accounted for in future investigations by a stricter specification of this procedure step.

It is also important to note that even with an optimized hook plate design, adaptation of the hook’s inclination and torsional alignment may be necessary for outlying shoulder anatomies. To identify these anatomies, an intraoperative, standardized AP and transaxillary x-ray control of the ACJ is recommended.

## Conclusion

This study confirms a high variability of the lower surface of the acromion between anatomies. However, at an inclination angle of  $16^\circ$  and torsional angle of  $80^\circ$ , the IPV was shown to be minimized in an average patient population. With these angles, a subacromial support device would have the largest

average contact surface to the bone. A better contact may contribute to a lower number of tip-contact of the hook, therefore reducing the number of osseous reactions and sub-acromial impingements. This study demonstrates that there exists a region in the subacromial space (at 16° inclination and 80° torsional angulation), where a hook plate gives the best possible support for varying anatomies and thereby may lead to improved clinical outcomes.

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### Authors contributions

**Martin Zenker:** Responsible for research design, analysis and interpretation of data. Main authorship of methods & materials and results sections. Review and approval of the final submitted article.

**Javad Shamsollahi:** Responsible for analysis of data. Review and approval of the final submitted article.

**André Galm:** Review and approval of the final submitted article.

**Harry A. Hoyen:** Review and co-authorship of introduction. Review and approval of the final submitted article.

**Chunyan Jiang:** Review and approval of the final submitted article.

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**Martin Jaeger:** Responsible for research design, and interpretation of data. Main authorship of introduction and discussion sections. Review and approval of the final submitted article.

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This analysis is based on anonymized retrospective data. This study was approved by the ethical committee of the Innsbruck Medical University (EK Nr: 1011/2017).

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Informed consent was waived by the ethical committee and was not sought for the present study because this analysis is based on anonymized retrospective data.

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