The variance of clavicular surface morphology is predictable: an analysis of dependent and independent metadata variables

A R T I C L E   I N F O

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Clavicle anatomy
clavicle curvature
clavicle bow
3D reconstruction
implant fit
osteosynthesis

Level of evidence: Anatomic Study; Imaging

Background: The anatomy of the clavicle is specific and varied in reference to its topography and shape. These anatomic characteristics play an important role in the open treatment of clavicle fractures. The complex and variable topography creates challenges for implant placement, contouring, and position. Hardware prominence and irritation does influence the decision for secondary surgical intervention.

Methods: Computerized tomographic scans of 350 adult clavicles with the corresponding patients' metadata were acquired and digitized. Morphologic parameters determining the shape of the clavicle were defined and computed for each digitized bone. The extracted morphologic parameters were correlated with patient metadata to analyze the relationship between morphologic variability and patient characteristics.

Results: The morphologic parameters defining the shape, that is, the radius of the medial and lateral curves, the apparent clavicle height and width, and the clavicle bow position, correlate with the clavicle length. The clavicle length correlates with the patients' height. Gender differences in shape and form were dependent and related to individual height distribution and clavicle length. Asian populations showed a similarly predictable, but shifted, correlation between shape and clavicle length.

Conclusion: This anatomic analysis shows that the clavicle shape can be predicted through the clavicle length and patients' stature. Smaller patients have shorter and more curved clavicles, whereas taller patients have longer and less curved clavicles. This correlation will aid surgeons in fracture reduction, implant curvature selection, and in optimal adaptation of clavicle implants, and represents the basis for anatomically accurate solutions for clavicle osteosynthesis.

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The relationship between the bone morphometric parameters and patient demographics has been only partially described in the previous studies. The primary aim of this study was to describe, quantify, and correlate the shape and topographic morphology of the clavicle to individual metadata, such as height and ethnicity. The range of anatomic variability could then be related to different patient populations. This anatomic information may guide surgeons during fracture reduction and for appropriate implant selection and contouring.

Materials and methods

Computerized tomographic scans and patients’ metadata

Anonymized computerized tomographic (CT) scans of 350 clavicles with recorded gender, side, age, height, weight, country of origin, and ethnicity were used. A set of CT data (n = 303) was generated for reasons other than a clavicle fracture from 4 institutions: Fukuyma, Japan (n = 102), Innsbruck, Austria (n = 80), Jena, Germany (n = 89), and Leuven, Belgium (n = 32). Another data set of CT scans (n = 47) was acquired from the William Bass dry bone collection at the University of Tennessee, USA. Metadata were collected for each subject. This included gender, side, age, height, country of origin, ethnicity, and weight.

Digital reconstruction of the clavicles

The outer surface of the clavicle was digitized from the CT scans using AMIRA software (Visage Imaging GmbH, Berlin, Germany) by Synthes Innomedic GmbH (Germany) in a standardized protocol. The DICOM files were visually inspected for artifacts (ie, image distortion) and completeness of data (ie, integrity of the anatomy and the metadata) by accordingly trained persons. The segmentation of the clavicle surface was subsequently generated based on a predefined grayscale threshold of 200 Hounsfield units. This surface was then manually inspected and corrected if the surface of the bone was not captured correctly by the automated process. Eleven anatomic landmarks were defined on the segmented mesh to enable consistent alignment of each clavicle in its anatomic plane (see Fig. 1).

Morphologic parameters

Quantitative characterization of the morphologic parameters was performed for each bone with a custom script in MATLAB (R2015b; MathWorks, Natick, MA, USA). The STL file of the bone was oriented within a new coordinate system (COS) as defined by specific anatomic landmarks on the lateral end of clavicle (see Fig. 2). The first vector of the new COS was defined by the clavicle axis—that is, from the center of the lateral clavicle end to the center of the medial end—and was denoted by the vector $\mathbf{e}_x$. A lateral plane was then defined by 3 points: the center of the lateral end of the clavicle and 2 landmarks at the anterior and posterior edge of the clavicle. The second vector of the new COS was denoted as vector $\mathbf{e}_y$, and is defined as the vector orthogonal to the prior defined lateral plane. The third vector, $\mathbf{e}_z$, was subsequently defined as orthogonal to the previous 2 vectors.

The COS enabled the definition of parameters in 2 clinically relevant planes: the anterior view of the clavicle (coronal plane) and the superior view of the clavicle (horizontal plane). In these 2 planes, the outer contour of the clavicle and its centerline were computed. The centerline was defined as the point equidistant from the upper and lower line defining the clavicle outer contour. The apparent width is the width of the clavicle extracted from the projection of the superior plane, whereas the apparent height is the height of the clavicle extracted from the projection of the anterior plane. The quantified parameters are listed in Table I and shown diagrammatically in Figure 3.

| Parameter | Definition |
|-----------|------------|
| CL        | Length of the clavicle measured in its lateral-to-medial axis in millimeters |
| V         | Volume of the clavicle measured in cubic millimeters |
| $h_{50\%}$| Apparent height measured in the center of the clavicle (50% of clavicle length) |
| $h_{max}$ | Maximal apparent height measured across the clavicle length |
| $w_{50\%}$| Apparent width measured across the clavicle (50% of clavicle length) |
| $w_{max}$ | Maximal apparent width measured across the clavicle length |
| $d_{CT}$  | Conoid tubercle position measured from the lateral end of the clavicle |
| $d_{CT\ relative}$ | Conoid tubercle position measured from the lateral end of the clavicle divided by the clavicle length |
| $R_{lat}$ | Radius of lateral curvature in millimeters, measured at the centerline in the superior view |
| $R_{med}$ | Radius of medullary curvature in millimeters, measured at the centerline in the superior view |
| $d_{limb}$ | Distance between the center of lateral and medial circles in millimeters in the superior view |
| $\theta_{bow}$ | Bow angle measured at the centerline in the anterior view |
| $\delta_{bow}$ | Bow position measured at the centerline in the anterior view from lateral |
| $\theta_{bow\ sup}$ | Bow angle measured at the superior surface of the clavicle in the anterior view |
| $\delta_{bow\ sup}$ | Bow position measured at the superior surface of the clavicle in the anterior view |

Figure 1 Image of the surface identification during segmentation and the anatomic landmarks on the digitally reconstructed bone. CT, computed tomography.

Figure 2 Definition of the specific coordinate system to align all clavicles in the 2 clinically relevant plates: the anterior plane ($\mathbf{e}_x$ and $\mathbf{e}_y$) and the superior plane ($\mathbf{e}_x$ and $\mathbf{e}_z$).

Table I Definitions of the quantified morphologic parameters
The superior view. The position of the conoid tubercle center (at 50% of CL) are shown in the anterior view. Apparent width (between the circles (dbow_sup)) of a circle of best fit of the superior surface of the clavicle, and the bow angle (bow_sup) and position (dbow_sup) of the superior surface of the clavicle and the bow angle (bow) and position (dbow) at the centerline are shown in the anterior view.

Figure 3 Diagram to illustrate the definitions of the morphologic parameters. The axial clavicle length (CL), the lateral radius (Rmed), the medial radius (Rlat), the distance between the circles (dbow_sup) and the apparent width at 50% of CL (wbow_sup) are shown in the superior view. The position of the conoid tubercle center (dct), the apparent height at 50% of CL (htsup), the bow angle (bow_sup) and position (dbow_sup) of the superior surface of the clavicle, and the bow angle (bow) and position (dbow) at the centerline are shown in the anterior view.

Standard morphologic parameters were defined for comparison: CL, clavicle volume (V), apparent height (ht50 and hmax), and apparent width (w50 and wmax). Three parameters were defined to capture the curvature shape of the clavicle in the superior plane: the radius (Rsup) of a circle of best fit for the lateral clavicle, the radius (Rmed) of a circle of best fit for the medial clavicle, and the distance (dRmed) between the centers of these 2 circles. The shape of the clavicle in the anterior plane was quantified by the bow angle and bow position. These parameters were computed in 2 ways: (1) using the superior border of the clavicle (dSup and vSup) and (2) using the centerline of the clavicle (dMed and vMed).

Statistical analysis

The morphologic parameters were analyzed and compared in Minitab Statistical Software (Minitab 18; Minitab Inc., State College, PA, USA), and resulting distributions were tested with a 2-sample t-test: for normally distributed data, the Anderson-Darling test was applied, and for non-normal data, the Mann-Whitney U test was applied. A significance level of 0.05 and a confidence level of 0.95 were used. Linear correlation was tested with the Pearson method. Distribution values in the text are reported as average ± standard deviation.

Results

The countries of origin of the 350 clavicles were Japan (29%), Germany (25%), Austria (23%), Belgium (9%), and the United States (14%). Sixty-three percent of the specimens were male clavicles. Forty-eight percent of the specimens were right clavicles. The mean height of the subjects was 169 cm, ranging from 142 to 192 cm. The mean age of the subjects was 57 years, ranging from 17 to 83 years. The quality of the data gathered from hospitals was ensured with specific inclusion criteria for the CT scans and patients’ demographics, see Table II.

| Inclusion parameter | Inclusion criteria |
|---------------------|--------------------|
| Visible anatomies    | Visible shoulder girdle: AC-CC joint, clavicle, humerus, and scapula |
| Side                | Left and/or right sides |
| Ethnicity/region of origin | The data set must refer to a representative demography of institution’s situated region, that is, the origin of patients should match with institution’s location |
| Gender              | Male and female |
| Age                 | Between 22 and 75 yr |
| Year of birth       | After 1940 |
| Height              | Range from 145 to 190 cm |
| CT data requirements | Preferred slice thickness ≤ 1 mm. Available CT data should be examined for acceptable quality, if the slice thickness of existing data is greater than the preferred value |

CT, computed tomography; AC, acromioclavicular; CC, coracoclavicular.

Clavicle apparent width and height

The comparison of the apparent clavicle width and height within the presented data set is performed using the distance from the lateral end divided by the CL (see Fig. 4). The cross-section of the clavicle changes from wide and low height at the lateral end, more circular (ie, similar width and height) in the center, and then wide and higher height again at the medial end. The observed prominence at a point between 10% and 20% from the lateral end was found to be a consistent characteristic, resulting from the combination of a small depression often present on the superior surface of the clavicle lateral to the region of the inferior protrusion of the conoid tubercles. The maximal value of each parameter and the value at the center of the clavicle (ie, at 50% from the lateral end) are evaluated and reported in Table III.

Patients’ height and clavicle length

The distribution of the patients’ height (169 ± 11 cm) and CLs (143.7 ± 10.7 mm) is shown in Figure 5 for the entire population (n = 350). A strong correlation (Pearson’s coefficient = 0.968, P < .001) was found between the patients’ height and CL.

Asian patients were found to be statistically significantly smaller (P < .001) than Caucasian patients; however, Asian clavicles were not statistically different in length (P = .998) from Caucasian clavicles (see Fig. 6). In other words, Asian patients having the same CL as Caucasian patients were found to have a smaller height. The correlation of patients’ height and CL within the 2 ethnic groups showed a strong correlation (Pearson’s coefficients of 0.650 and 0.679 for Asian and Caucasian, respectively) with a clear shift between the 2 correlation lines, indicating that for both ethnic groups, smaller patients have shorter clavicles and taller patients have longer clavicles. The volume was also not statistically different (P = .480) between the 2 ethnic groups.

The effect of side and gender was investigated and is demonstrated in Figure 7, on the example of the parameter CL. No statistical difference was found between left and right clavicles for all 3 parameters: patients’ height (P = .555), CL (P = .511), and clavicle volume (P = .453). Considering gender, female and male clavicles
showed a significant difference \((P < .001)\) in all 3 parameters: patients’ height, CL, and volume.

**Curvature and bow**

All 3 parameters defining the curvature of the clavicle \((R_{\text{lat}}, R_{\text{med}}, \text{and } d_{R_{\text{med}}})\) correlated with the CL (Pearson’s coefficients are reported in Table III). This correlation is shown in Figure 8 as scatterplots for the entire population (in the left column) and for female and male populations (in the right column). A comparison of these results clearly demonstrates that differences between female and male populations are driven by the different distribution of their CLs (cf. Fig. 7). A similar variability (with the standard deviation being approximately 30% of the population mean) was

![Figure 4](image)

**Figure 4** Representative visualization of the clavicle superior and anterior plane (a) with the corresponding apparent clavicle width (b) and apparent clavicle height (c) parameters. Apparent width and height are shown over the relative clavicle length from lateral.

| Parameters | Mean | STD  | Minimum | Maximum | Correlation coefficient | Correlation P value |
|------------|------|------|---------|---------|------------------------|--------------------|
| CL (mm)    | 143.7| 10.7 | 112.8   | 171.9   | Reference              | Reference          |
| \(V\) (mm\(^3\)) | 30.18 | 8254 | 9289    | 51.995  | 0.603                  | <.001              |
| \(h_{\text{max}}\) (mm) | 11.1 | 1.8 | 6.2     | 16.1    | 0.385                  | <.001              |
| \(w_{\text{max}}\) (mm) | 26.5 | 3.7 | 13.3    | 35.4    | 0.392                  | <.001              |
| \(d_{\text{CT}}\) (cm) | 13.7 | 1.8 | 9.6     | 21.6    | 0.454                  | <.001              |
| \(R_{\text{med}}\) (mm) | 27.6 | 3.7 | 17.4    | 38.8    | 0.433                  | <.001              |
| \(d_{R_{\text{med}}}\) (mm) | 34.1 | 4.8 | 15.4    | 48.6    | 0.571                  | <.001              |
| \(d_{\text{CT}}\) relative (–) | 0.237 | 0.028 | 0.121 | 0.318 | 0.068 | .203 |
| \(R_{\text{lat}}\) (mm) | 54.0 | 17.6 | 28.7    | 138.1   | 0.276                  | <.001              |
| \(d_{\text{mid}}\) (mm) | 91.2 | 30.1 | 12.2    | 248.7   | 0.254                  | <.001              |
| \(w_{\text{max}}\) (mm) | 72.1 | 7.0 | 53.2    | 103.0   | 0.631                  | <.001              |
| \(d_{\text{bow}}\) (mm) | 10.0 | 5.7 | 5.1     | 28.1    | -0.006                 | .911               |
| \(d_{\text{bow sup}}\) (mm) | 77.1 | 23.1 | 7.1     | 154.9   | 0.201                  | <.001              |
| \(d_{\text{bow sup}}\) (mm) | 6.5  | 6.0 | -10.5   | 23.9    | 0.071                  | .184               |
| \(d_{\text{bow sup}}\) (mm) | 70.7 | 22.6 | 4.1     | 158.1   | 0.249                  | <.001              |

Pearson’s correlation of all parameters with the clavicle length (CL) was tested, and the corresponding correlation coefficient and P value are reported.
observed for the radii of both curvatures (ie, lateral and medial curvatures) and is also seen by the similar scatter in the plots in Figure 7.

The parameters defining the bow of the clavicle showed a statistically significant correlation with the CL for the bow position ($d_{bow}$ and $d_{bow,sup}$) but no correlation for the bow angle ($a_{bow}$ and $a_{bow,sup}$). The bow angle measured at the superior border of the clavicle ($a_{bow,sup}$) was significantly different from the bow angle measured at the centerline ($a_{bow}$). This difference is induced by the increase in the apparent height of the clavicle from lateral to medial, which increases the difference between the superior edge of the clavicle with respect to the centerline from lateral to medial. Parameters are reported in Table III.

Conoid tubercle

The position of the conoid tubercle is a relevant anatomic landmark used for the categorization of clavicle fractures and represents the region of the insertion of the coracoclavicular (CC) ligaments. The conoid tubercle was identified during the segmentation procedure and was defined as the apex of the protruding surface at the inferior posterior side of the clavicle in its lateral region. The position of the conoid tubercle was a mean of 34.1 mm from the lateral margin of the clavicle and strongly correlated with the length of the clavicle (Pearson’s coefficient = 0.563, $P < .001$), see Figure 9. The relative position of the conoid tubercle, that is, the position of the conoid tubercle as a proportion of the length of the clavicle, was consistently found to be $23.7\% \pm 2.8\%$ of the CL, from its lateral end.

Two sources of data have been used in this study. The first set of data was generated from CT scans of patients (ie, in vivo configuration), whereas the second set of data was acquired from CT scans of dry clavicles. The distribution of the CL parameter and of the relative conoid tubercle position ($d_{CT,relative}$) is shown in Figure 10 for both sources. Although the distribution in CL was slightly different ($P = .030$) for the 2 sources, due to their different population composition, the relative conoid tubercle position was not statistically different ($P = .122$).

Discussion

Morphologic parameters and patients’ metadata

The analyzed clavicles were selected by inclusion criteria based on phenotypic and genotypic variables in order to study a representative adult population. The resulting population was equivalent for side, included younger adult subjects, and comprised slightly more males (63%) than females. This study set therefore concorded with the higher fracture incidence reported in younger males.4,9,20

The mean patients’ height in this study was 159.8 cm in females and 174.1 cm in males. This is comparable to the anthropometric reference data of the United States,7 which report an overall average height of 162.1 cm in females and 175.9 cm in males of all racial and ethnic groups with a range from 156.6 to 177.4 cm. In the
anthropometric reference data, the smallest mean height was reported in Asian females (153.0 cm) and the highest mean height in Caucasian males (177.3 cm).

The mean CL (143.7 ± 10.7 mm) measured in this study is slightly lower than the overall mean length (145.0 ± 12.7 mm) reported by Huang et al\(^\text{10}\) based on 200 US clavicles, and also lower than the results (149.4 ± 10.3 mm) reported by Bernat et al\(^\text{3}\) on 68 Belgian clavicles. The Asian specimens (with CL 143.7 ± 9.1 mm) in this study were all from Japan. When comparing the distribution of the Asian mean CLs in this study with the results of Qiu et al\(^\text{18}\) on 104 Chinese clavicles (mean, 144.2 ± 12.0), no statistical difference was found in the overall distribution (\(P = .703\), summarized t-test).

In this study, the CL was shown to be significantly longer in male specimens (148.4 ± 9.1 mm) than in females (136.0 ± 8.3 mm). In a

Figure 6 Patients’ height (a) and clavicle length (b) distribution for Asian and Caucasian populations. A strong correlation (Pearson’s coefficient = 0.650 and 0.679) between these 2 parameters was found in both ethnic groups (c). CL, clavicle length.

Figure 7 Distribution of the clavicle length (CL) for clavicle side (a) and patients’ gender (b).
study by Kanur et al\textsuperscript{11} of 2000 Indian clavicles, the CL ranged from 134.5 ± 9.7 mm for females to 151.1 ± 8.7 mm for males. No statistical differences were found when comparing the lengths of left and right clavicles, a finding that is supported by other studies.\textsuperscript{2,4,5} Bernat et al\textsuperscript{3} identified that the left clavicle was 2.4 mm longer than the right clavicle, which is only 1.5\% difference in total CL.

The reported values of CLs and the identified differences suggest that the study population reported here is representative of a global experience. This analysis more importantly highlights that differences arising from gender and ethnicity are really related to the difference in CL and corresponding distribution of height between male and female patients, rather than the gender as the sole variable.

The correlation between the CL and patients’ height identified in this study has also been reported in literature.\textsuperscript{10,11} Kanur et al\textsuperscript{11} found a significant correlation in adults between the CL and the supine body length; however, when comparing different morphologic parameters, such as, for example, the lateral angle, the authors discuss these for ethnical and gender categories instead of the CL.
Clavicle variability

The variability in clavicle anatomies is well reported in literature and has also been investigated by means of principal component analysis. These analyses showed that the major source of variability (PC1: 70.5%-79%) is the CL. The large overall anatomic variability of the clavicle is also visible in the reported parameters of this study. In this study, the correlation between the CL and most of the other morphologic parameters—such as, for example, the clavicle radii—indicated that clavicles with different lengths have also different shapes. For example, as the length increases, the medial and lateral radii also increase so that a stable coefficient of length to radius exists (ie, 0.38 ± 0.12 for \( R_{\text{lat}} \) and 0.63 ± 0.21 for \( R_{\text{med}} \)). With the additional correlation between CL and patient height, it was shown that smaller patients have shorter clavicles that have smaller radii (ie, more curved shape). Conversely, taller patients have longer clavicles with larger radii (ie, less curved shape). The fact that the length of the clavicle defines the shape is important because most implants are currently designed with prefixed radii, independent of plate length. Future internal fixator systems should consider the relationship between length and shape. The clinical corollary is that, if operative fixation is chosen, fractures of shorter clavicles (in smaller patients) should be fixed using implants with smaller radii of curvature, whereas longer clavicles (in taller patients) should be fixed with implants having greater radii. If implants with different curvatures are not available, this relationship between CL and radii of curvature can assist during the contouring of the implant.

Conoid tubercle

The distribution of the relative position of the conoid tubercle was exceptionally narrow and clean for anatomic parameters. The center of the conoid tubercle was found to be 23.7% ± 2.8% from the lateral end of the clavicle. This result is in concordance with Rios et al., who found a constant ratio for the position of the medial edge of the conoid tuberosity independent of race and gender. They did identify different ratios for fresh/frozen samples (0.24 ± 0.03) with intact acromioclavicular and CC ligaments as compared with dry anatomies (0.31 ± 0.03). This difference might be related to the different landmarks available for the measurement between the 2 groups, where fresh/frozen samples were prepared with intact acromioclavicular and CC ligaments. The conoid tubercle represents the central position of the insertion of the conoid CC ligaments and is a relevant landmark for fracture classification. In our

![Figure 9](image)

(a) Correlation between the distance from lateral of the conoid tubercle center \( (d_{\text{CT}}) \) and the clavicle length (CL). (b) Distribution of the normalized conoid tubercle position \( (d_{\text{CT}} \text{ divided by CL}) \).

![Figure 10](image)

Distribution of the clavicle length (CL) (a) and of the relative conoid tubercle position (b) for the 2 sources of data within this study: from computed tomography (CT) scans of dry bones and in vivo bones.
study, the relative position of the conoid tubercle (0.24 ± 0.03) was not statistically significantly different for the 2 analyzed sources (ie, dry and in vivo).

Limitations

The semiautomated process of clavicle segmentation and the subsequent manual process of the definition of the anatomic landmarks bring some variability in the results, although detailed protocols were defined to standardize the process. If the anatomic landmarks are not positioned precisely, the definition of the new COS is affected and the position of the 2 anatomic planes (ie, anterior and superior planes) can be slightly rotated. The data set analyzed in this study has the limitation that the CT scans were acquired only from 5 different institutions. These institutions were specifically selected to contain the 2 ethnicities in focus for this study (ie, Asian and Caucasian) with high-quality scans. Intra-ethnic differences were not investigated and are not addressed in this study due to the limited number of countries included.

Conclusion

The overall correlation of the CL with other shape parameters confirms the hypothesis that clavicles of different lengths have different, but predictable, shapes. The height or stature of the individual relates to the length of the clavicle and the radii of the associated medial and lateral curves. Implants with higher curvatures should be selected for fractures in shorter clavicles or smaller patients, and less curved implants should be selected for fractures in longer clavicles or taller patients. If implants with different curvatures are not available, the relationship between clavicle curvatures and length can inform the implant contouring. The results of this study will aid surgeons in fracture reduction, implant selection, and the optimal adaptation of clavicle implants.

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