JSES International ■ (2020) 1–9

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

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

Arabella D. Fontana, PhD [a,*], Harry A. Hoyen, MD [b], Michael Blauth, MD, PhD [c,d], André Galm, Dipl-Ing [a], Marcel Schweizer, MS [a], Christoph Raas, MD, PhD [d], Martin Jaeger, MD [e], Chunyan Jiang, MD, PhD [f], Stefaan Nijs, MD, PhD [g], Simon Lambert, FRCSEd (Orth) [h]

[a] *R&D Department, DePuy Synthes, Zuchwil, Switzerland*
[b] *Department of Orthopaedic Surgery, MetroHealth Medical Center, Case Western Reserve University, Cleveland, OH, USA*
[c] *Clinical Medical Department, DePuy Synthes, Zuchwil, Switzerland*
[d] *Department for Trauma Surgery, Medical University Innsbruck, Innsbruck, Austria*
[e] *Department of Orthopedics and Trauma Surgery, Medical Center-Albert-Ludwigs-University of Freiburg, Freiburg, Germany*
[f] *Shoulder Service, Beijing Jishuitan Hospital, School of Medicine, Peking University, Beijing, China*
[g] *Department of Trauma Surgery, University Hospitals Leuven, Leuven, Belgium*
[h] *Department of Trauma and Orthopedic Surgery, University College London Hospital NHS Foundation Trust, London, UK*

ARTICLE INFO

Keywords:
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.

Clavicle fractures represent approximately 2%-5% of all fractures.[20] Surgical treatment of clavicle fractures is associated with improved functional outcome and is the increasingly preferred treatment option.[8,12] Different clavicle shapes in reference to curve, topography, and rotation are encountered during operative fixation procedures. Optimum surface area contact of the plate with the bone is desirable.[16] The morphologic variability of the clavicle makes it difficult to provide a precontoured implant that addresses the wide range of clavicular shapes.[22] Implant prominence and soft-tissue irritation can also influence the need for subsequent implant removal.[17,21] A number of morphometrical studies have been able to quantify the anatomic variability of clavicle shape and topography.[1–5,10,11,15,24] Shape characteristics include the clavicle length (CL), volume, medial and lateral curves, and clavicular bow.

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).

* Corresponding author: Arabella D. Fontana, PhD, R&D Department, DePuy Synthes, Luzernstrasse 21, Zuchwil 4582, Switzerland.

E-mail address: afonta14@its.jnj.com (A.D. Fontana).

https://doi.org/10.1016/j.jseint.2020.05.004

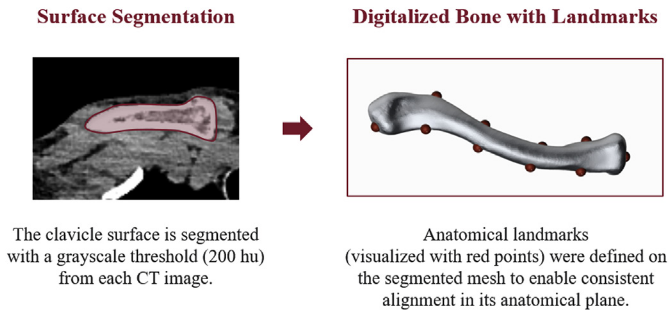

Figure 1 Image of the surface identification during segmentation and the anatomic landmarks on the digitally reconstructed bone. *CT*, computed tomography.

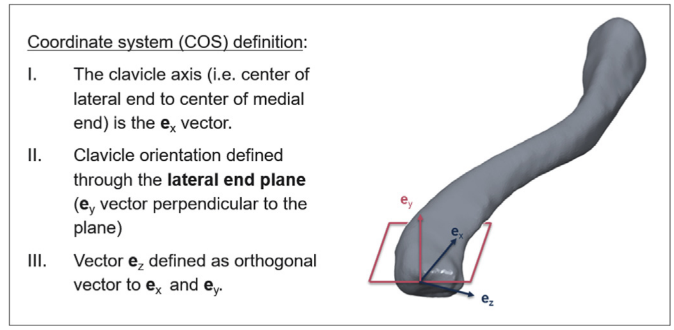

Figure 2 Definition of the specific coordinate system to align all clavicles in the 2 clinically relevant plates: the anterior plane ($\mathbf{e}_x$ and $\mathbf{e}_y$) and the superior plane ($\mathbf{e}_x$ and $\mathbf{e}_z$).

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: Fukuyama, 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.

Table I
Definitions of the quantified morphologic parameters

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 in the center of 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 medial curvature in millimeters, measured at the centerline in the superior view
d_{RmRl}	Distance between the center of lateral and medial circles in millimeters in the superior view
α_{bow}	Bow angle measured at the centerline in the anterior view
d_{bow}	Bow position measured at the centerline in the anterior view from lateral
α_{bow_sup}	Bow angle measured at the superior surface of the clavicle in the anterior view
d_{bow_sup}	Bow position measured at the superior surface of the clavicle in the anterior view

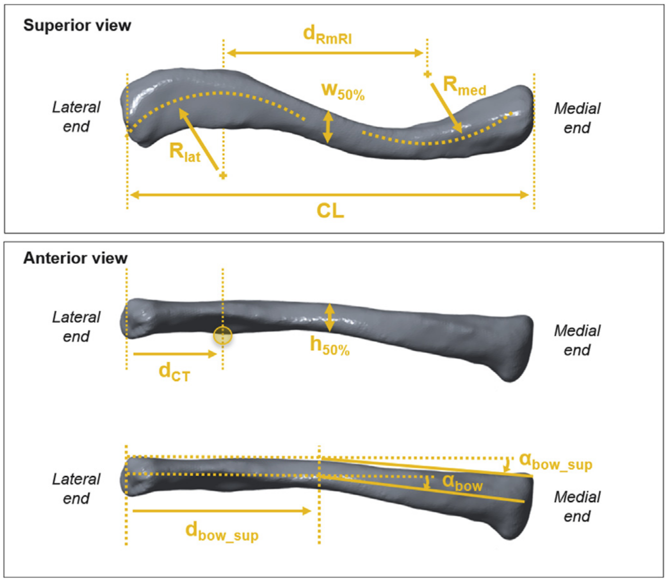

Figure 3 Diagram to illustrate the definitions of the morphologic parameters. The axial clavicle length (CL), the lateral radius (R_{lat}), the medial radius (R_{med}), the distance between the circles (d_{RmRl}), and the apparent width at 50% of CL ($w_{50\%}$) are shown in the superior view. The position of the conoid tubercle center (d_{CT}), the apparent height at 50% of CL ($h_{50\%}$), the bow angle (α_{bow_sup}) and position (d_{bow_sup}) of the superior surface of the clavicle, and the bow angle (α_{bow}) and position (d_{bow}) at the centerline are shown in the anterior view.

Standard morphologic parameters were defined for comparison: CL, clavicle volume (V), apparent height ($h_{50\%}$ and h_{max}), and apparent width ($w_{50\%}$ and w_{max}). Three parameters were defined to capture the curvature shape of the clavicle in the superior plane: the radius (R_{lat}) of a circle of best fit for the lateral clavicle, the radius (R_{med}) of a circle of best fit for the medial clavicle, and the distance (d_{RmRl}) 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 (α_{bow_sup} and d_{bow_sup}) and (2) using the centerline of the clavicle (α_{bow} and d_{bow}).

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 .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.

Table II
Overview of the inclusion criteria to ensure quality of the CT scans and patient's metadata

Inclusion parameter	Inclusion criteria
Visible anatomies	Visible shoulder girdle: AC-CC joint, clavicle, humerus, and scapula Only complete, intact bones, and joints: no present or previous bone fracture; no disrupted ligaments; and no bone deformations.
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 Increment ≤ thickness of slices Patient position: arms adjacent to the body, patient supine

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 ethnical 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

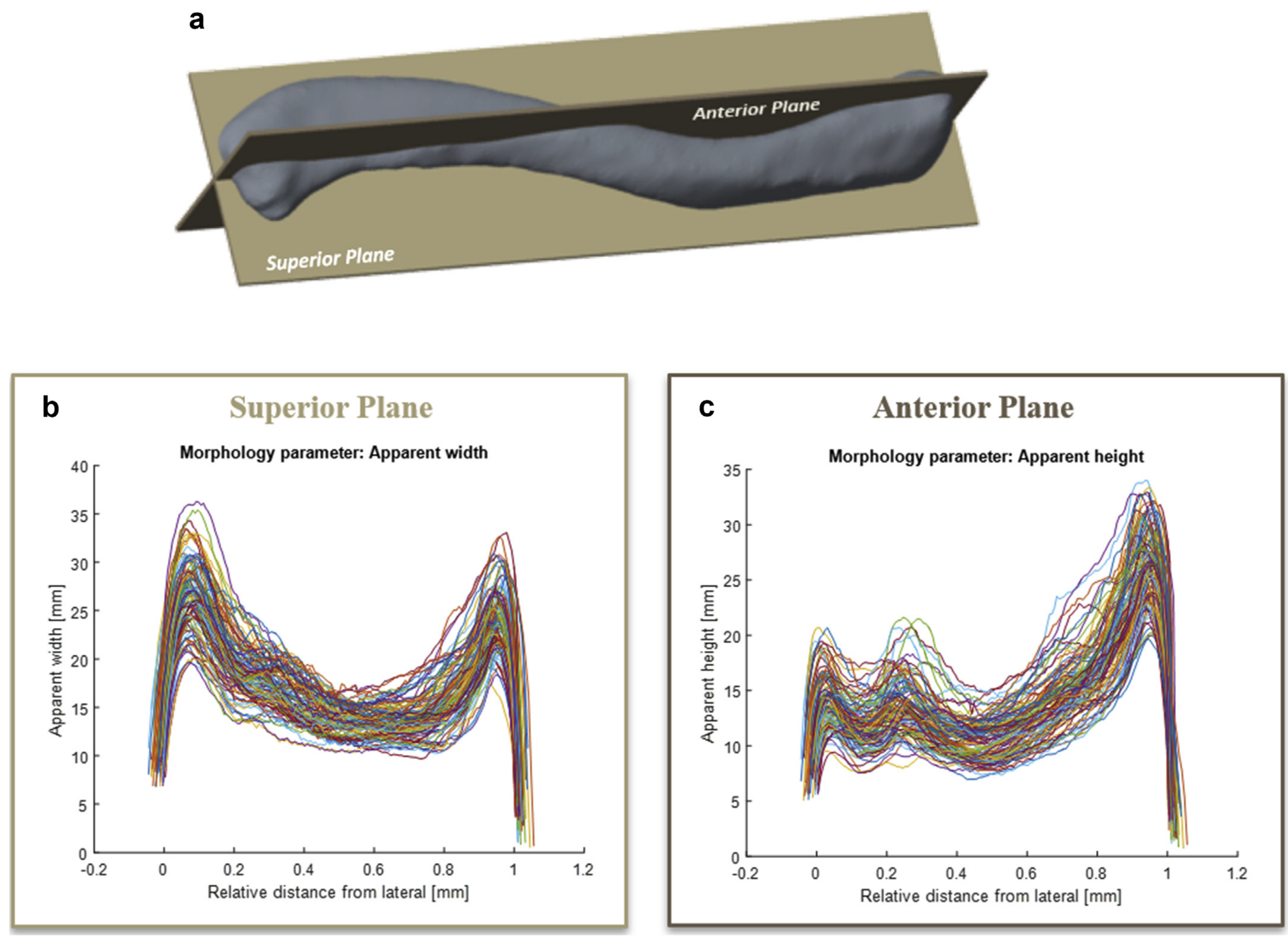

Figure 4 Representative visualization of the clavicle superior and anterior plane (**a**) with the corresponding apparent clavicle width (**b**) and apparent clavicle height (**c**) parameters. Apparent width and height are shown over the relative clavicle length from lateral.

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_{lat}, R_{med}, and d_{RmRl}) 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

Table III
Descriptive statistics of the morphologic parameters: mean, standard deviation (STD), and minimum and maximum values are reported for each parameter

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)	30,181	8254	9289	51,995	0.603	<.001
$h_{50\%}$ (mm)	11.1	1.8	6.2	16.1	0.385	<.001
h_{max} (mm)	26.5	3.7	15.3	35.4	0.392	<.001
$w_{50\%}$ (mm)	13.7	1.8	9.6	21.6	0.454	<.001
w_{max} (mm)	27.6	3.7	17.4	38.8	0.433	<.001
d_{CT} (cm)	34.1	4.8	15.4	48.6	0.571	<.001
d_{CT} relative (−)	0.237	0.028	0.121	0.318	0.068	.203
R_{lat} (mm)	54.0	17.6	28.7	138.1	0.276	<.001
R_{med} (mm)	91.2	30.1	12.2	248.7	0.254	<.001
d_{RmRl} (mm)	72.1	7.0	53.2	103.0	0.631	<.001
α_{bow} (°)	10.0	5.7	−5.1	28.1	−0.006	.911
d_{bow} (mm)	77.1	23.1	7.1	154.9	0.201	<.001
α_{bow_sup} (°)	6.5	6.0	−10.5	23.9	0.071	.184
d_{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.

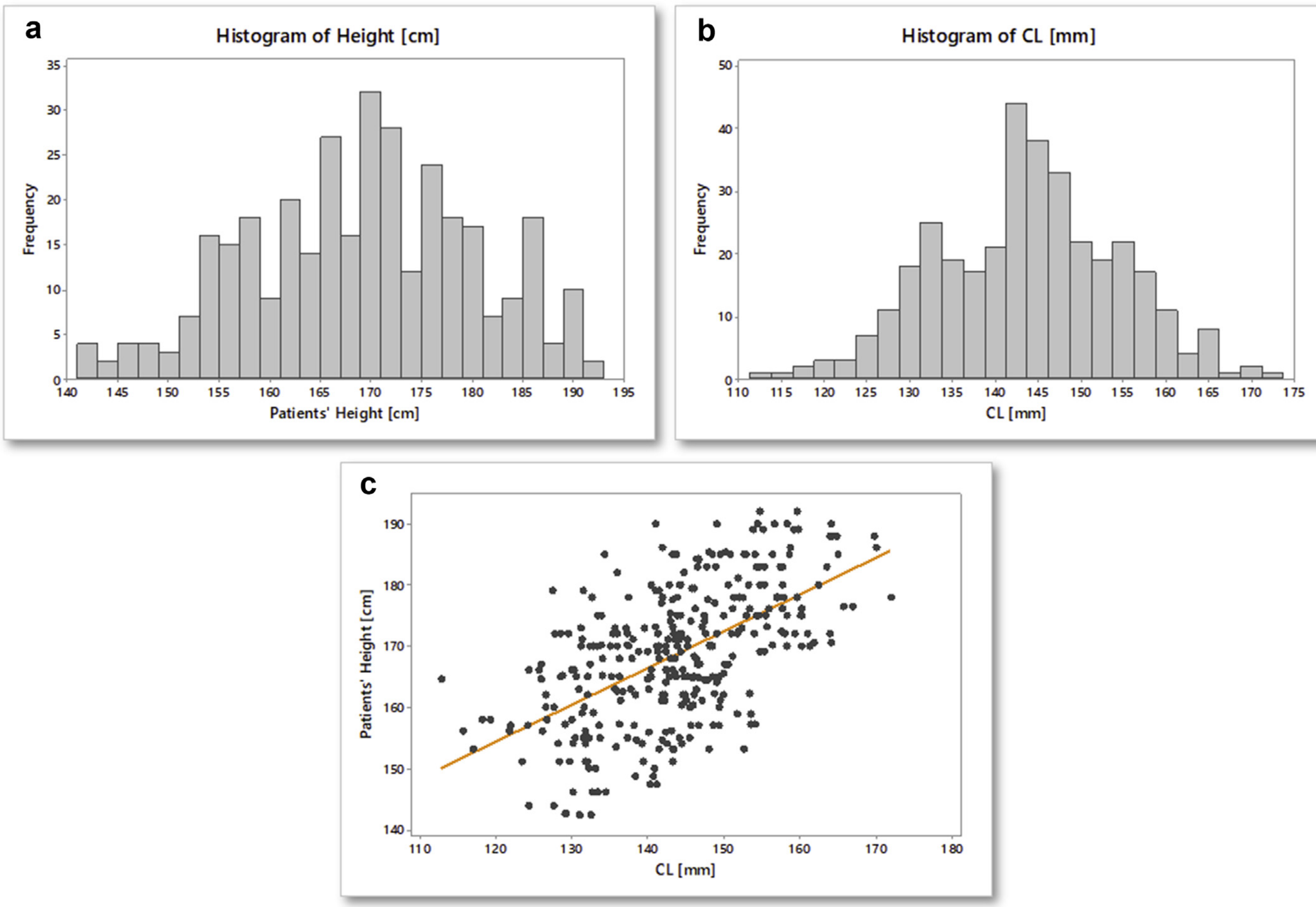

Figure 5 Distribution of the height of the patients included in this analysis (**a**) and the length of their clavicle (**b**). These 2 parameters show a strong correlation (Pearson's coefficient = 0.968, $P < .001$) (**c**). *CL*, clavicle length.

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 (α_{bow} and α_{bow_sup}). The bow angle measured at the superior border of the clavicle (α_{bow_sup}) was significantly different from the bow angle measured at the centerline (α_{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% ± 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

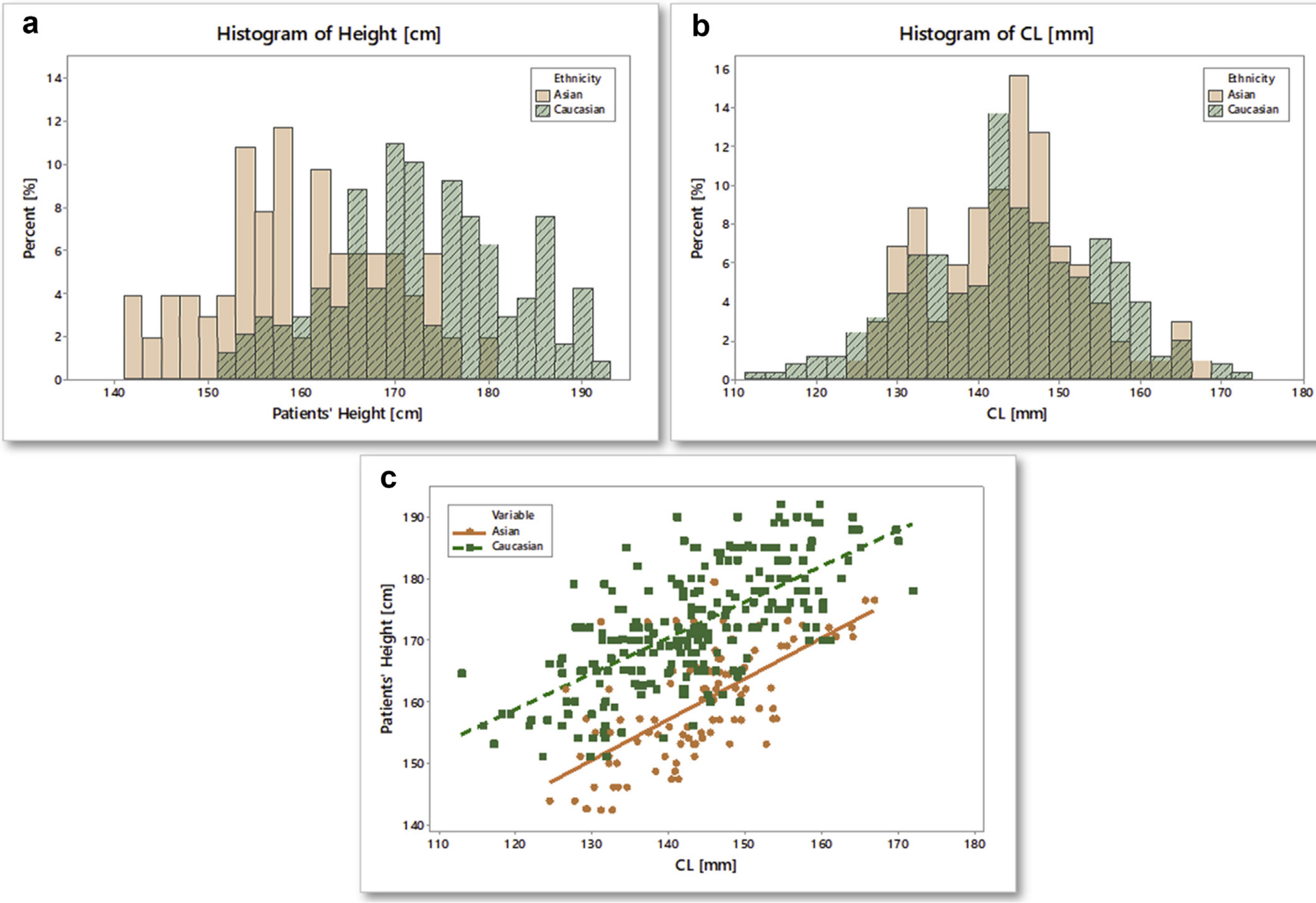

Figure 6 Patients' height (**a**) and clavicle length (**b**) distribution for Asian and Caucasian populations. A strong correlation (Pearson's coefficient = 0.650 and 0.679) between these 2 parameters was found in both ethnic groups (**c**). *CL*, clavicle length.

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[10] based on 200 US clavicles, and also lower than the results (149.4 ± 10.3 mm) reported by Bernat et al[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[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

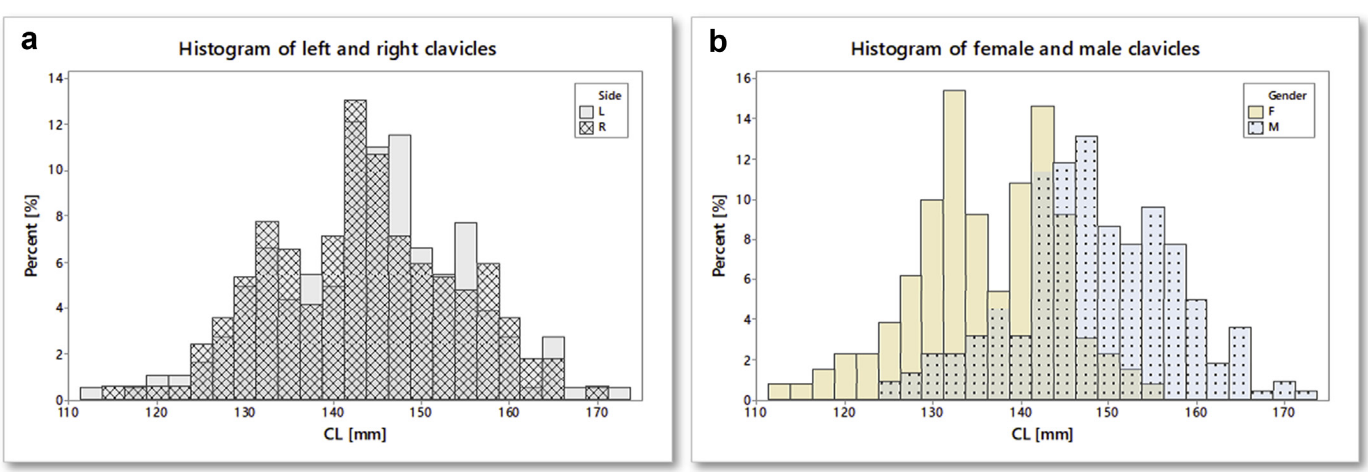

Figure 7 Distribution of the clavicle length (CL) for clavicle side (**a**) and patients' gender (**b**).

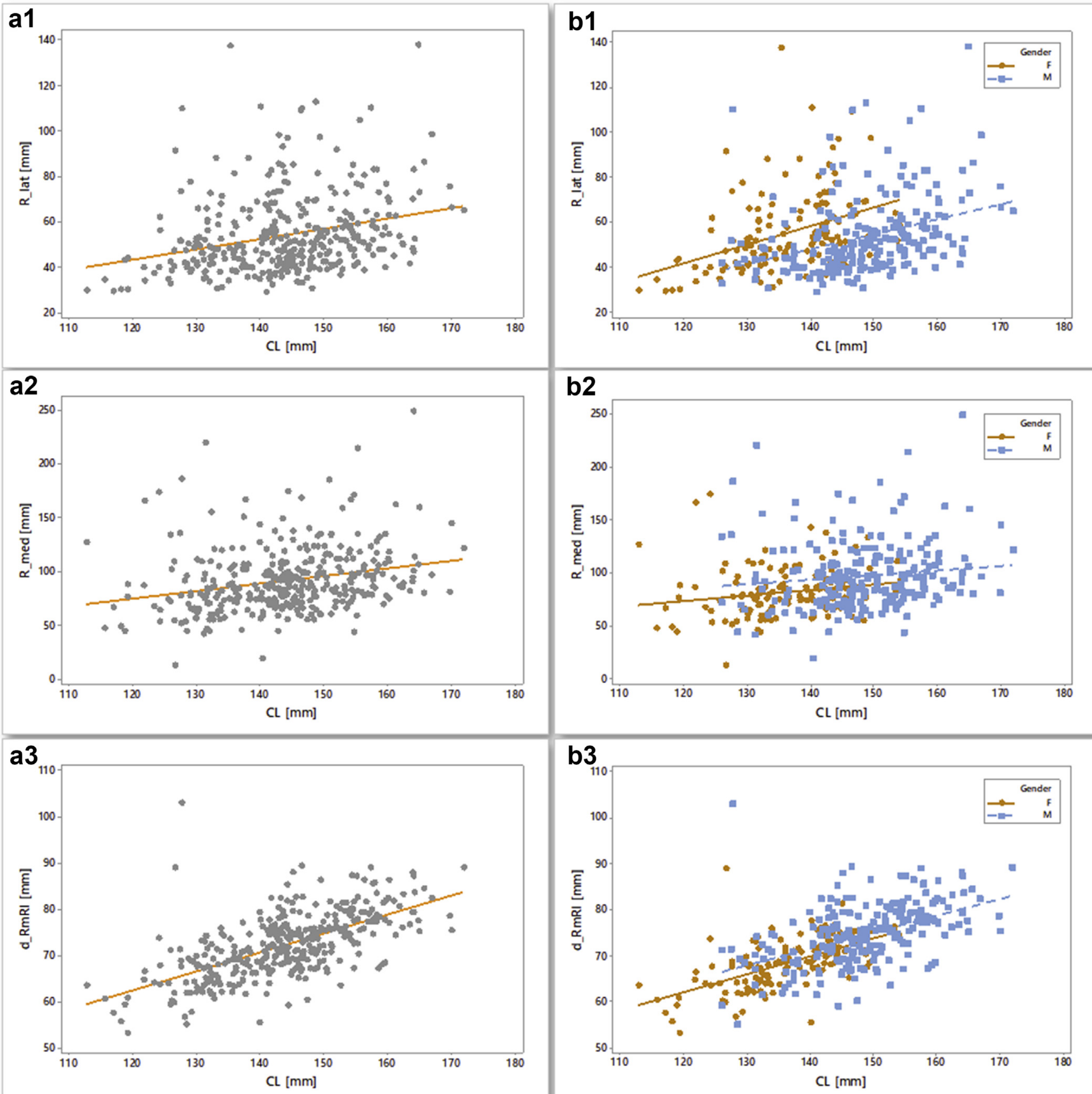

Figure 8 Scatterplots show the correlation of the clavicle curvature parameters (R_{lat}, R_{med}, and d_{RmRl}) with the clavicle length (CL) on the left (**a**, **1-3**). The same correlations for the male and female clavicles are shown on the right column (**b**, **1-3**), highlighting that the principal origin of the difference between female and male specimens is the difference in CL.

study by Kanur et al[11] of 2000 Indian clavicle, 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.[1,15] Bernat et al[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.[10,11] Kanur et al[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.

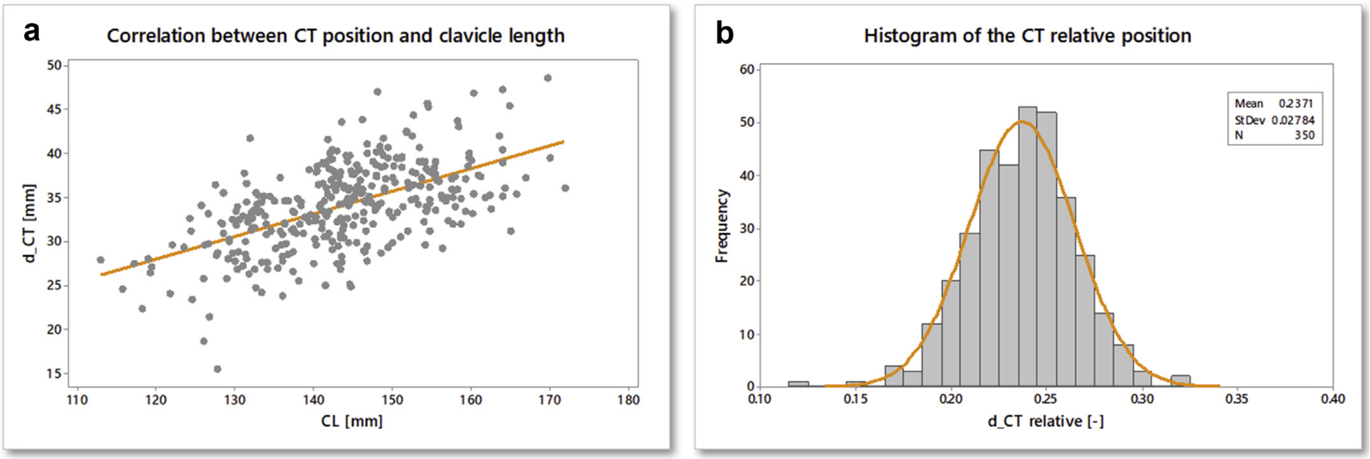

Figure 9 (**a**) Correlation between the distance from lateral of the conoid tubercle center (d_{CT}) and the clavicle length (CL). (**b**) Distribution of the normalized conoid tubercle position (ie, d_{CT} divided by CL).

Clavicle variability

The variability in clavicle anatomies is well reported in literature and has also been investigated by means of principal component analysis.[6,13,14,23] These analyses showed that the major source of variability (PC1: 70.5%[6]-79%[13]) 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_{lat} and 0.63 ± 0.21 for R_{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,[19] 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

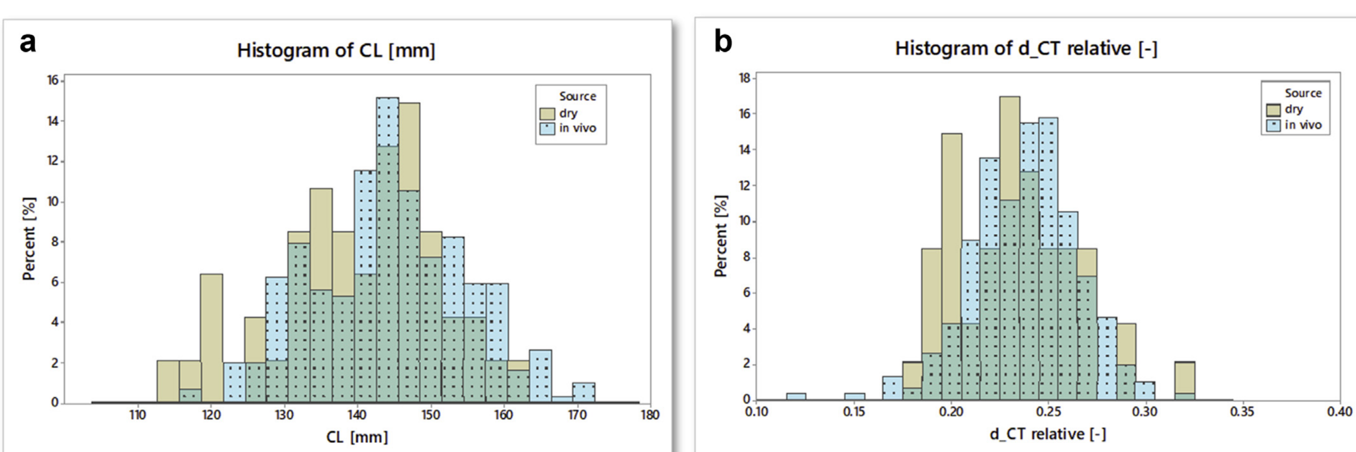

Figure 10 Distribution of the clavicle length (CL) (**a**) and of the relative conoid tubercle position (**b**) for the 2 sources of data within this study: from computed tomography (CT) scans of dry bones and in vivo bones.

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 semiautomatic 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-ethnical 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.

Acknowledgments

The authors wish to thank Fukuyama City Hospital, University Hospital Innsbruck, KU Leuven, and University Hospital Jena for the preparation of the CT data. For the coordination of the data acquisition, the authors thank Simge Tuna (DePuy Synthes, Switzerland) and Innomedic GmbH for the preparation and segmentation of the data. The authors gratefully acknowledge Marta Kerstan from the DePuy Synthes Clinical Research team and the Healthcare Compliance team for enabling and guiding the acquisition of the data and study coordination. They are also grateful to the AO Foundation, Switzerland for the support of this study.

Disclaimer

This study was funded through DePuy Synthes, a Johnson & Johnson Company.

Arabella D. Fontana, Marcel Schweizer, André Galm, and Michael Blauth are employees of DePuy Synthes, a Johnson & Johnson Company. As AO Technical Commission: All receive per diems for their work on behalf of the AOTC.

References

1. 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;35:2191–202. https://doi.org/10.1002/jor.23533.
2. Bachoura A, Deane AS, Wise JN, Kamineni S. Clavicle morphometry revisited: a 3-dimensional study with relevance to operative fixation. J Shoulder Elbow Surg 2013;22:e15–21. https://doi.org/10.1016/j.jse.2012.01.019.
3. Bernat A, Huysmans T, Van Glabbeek F, Sijbers J, Gielen J, Van Tongel A. The anatomy of the clavicle: a three-dimensional cadaveric study. Clin Anat 2014;27:712–23. https://doi.org/10.1002/ca.22288.
4. Chen W, Zhu Y, Liu S, Hou Z, Zhang X, Lv H, et al. Demographic and socioeconomic factors influencing the incidence of clavicle fractures, a national population-based survey of five hundred and twelve thousand, one hundred and eighty seven individuals. Int Orthop 2018;42:651–8. https://doi.org/10.1007/s00264-018-3815-0.
5. Daruwalla ZJ, Courtis P, Fitzpatrick C, Fitzpatrick D, Mullett H. Anatomic variation of the clavicle: a novel three-dimensional study. Clin Anat 2010;23:199–209. https://doi.org/10.1002/ca.20924.
6. Daruwalla ZJ, Courtis P, Fitzpatrick C, Fitzpatrick D, Mullett H. An application of principal component analysis to the clavicle and clavicle fixation devices. J Orthop Surg Res 2010;5:21. https://doi.org/10.1186/1749-799X-5-21.
7. Fryar CD, Gu Q, Ogden CL. Anthropometric reference data for children and adults: United States, 2007-2010. Vital Health Stat 2012;11:1–48.
8. Herteleer M, Hoekstra H, Nijs S. Diagnosis and treatment of clavicular fractures in Belgium between 2006 and 2015. J Shoulder Elbow Surg 2018;27:1512–8. https://doi.org/10.1016/j.jse.2018.01.016.
9. Herteleer M, Winckelmans T, Hoekstra H, Nijs S. Epidemiology of clavicle fractures in a level 1 trauma center in Belgium. Eur J Trauma Emerg Surg 2018;44:717–26. https://doi.org/10.1007/s00068-017-0858-7.
10. Huang JI, Toogood P, Chen MR, Wilber JH, Cooperman D. Clavicular anatomy and the applicability of precontoured plates. J Bone Joint Surg Am 2007;89:2260–5. https://doi.org/10.2106/JBJS.G.00111.
11. Kanur H, Harjeet SD, Jit I. Length and curves of the clavicle in Northwest Indians. J Anat Soc India 2002;51:199–209.
12. Kihlström C, Möller M, Lönn K, Wolf O. Clavicle fractures: epidemiology, classification and treatment of 2 422 fractures in the Swedish Fracture Register; an observational study. BMC Musculoskelet Disor 2017;18:82. https://doi.org/10.1186/s12891-017-1444-1.
13. Lambert S, Al-Hadithy N, Sewell MD, Hertel R, Südkamp N, Noser H, et al. Computerized tomography based 3D modeling of the clavicle. J Orthop Res 2016;34:1216–23. https://doi.org/10.1002/jor.23145.
14. Lu YC, Untaroiu CD. Statistical shape analysis of clavicular cortical bone with applications to the development of mean and boundary shape models. Comput Methods Programs Biomed 2013;111:613–28. https://doi.org/10.1016/j.cmpb.2013.05.017.
15. Mathieu PA, Marcheix PS, Hummel V, Valleix D, Mabit C. Anatomical study of the clavicle: endomedullary morphology. Surg Radiol Anat 2014;36:11–5. https://doi.org/10.1007/s00276-013-1140-2.
16. Perren SM. Evolution of the internal fixation of long bone fractures: the scientific basis of biological internal fixation: choosing a new balance between stability and biology. J Bone Joint Surg Br 2002;84:1093–110. https://doi.org/10.1302/0301-620x.84b8.13752.
17. Putnam M, Vanderkarr M, Nandwani P, Holy CE, Chitnis AS. Surgical treatment, complications, and reimbursement among patients with clavicle fracture and acromioclavicular dislocations: a US retrospective claims database analysis. J Med Econ 2019;22:901–8. https://doi.org/10.1080/13696998.2019.1620245.
18. Qiu XS, Wang XB, Zhang Y, Zhu YC, Guo X, Chen YX. Anatomical study of the clavicles in a Chinese population. Biomed Res Int 2016;2016. https://doi.org/10.1155/2016/6219761. 6219761.
19. Rios CG, Arciero RA, Mazzocca AD. Anatomy of the clavicle and coracoid process for reconstruction of the coracoclavicular ligaments. Am J Sports Med 2007;35:811–7. https://doi.org/10.1177/0363546506297536.
20. Robinson CM. Fractures of the clavicle in the adult: epidemiology and classification. J Bone Joint Surg Br 1998;80:476–84.
21. Ropars M, Thomazeau H, Huten D. Clavicle fractures. Orthop Traumatol Surg Res 2017;103:S53–9. https://doi.org/10.1016/j.otsr.2016.11.007.
22. VanBeek C, Boselli KJ, Cadet ER, Ahmad CS, Levine WN. Precontoured plating of clavicle fractures: decreased hardware-related complications? Clin Orthop Relat Res 2011;469:3337–43. https://doi.org/10.1007/s11999-011-1868-0.
23. Vancleef S, Herteleer M, Carette Y, Herijgers P, Duflou JR, Nijs S, et al. Why off-the-shelf clavicle plates rarely fit: anatomic analysis of the clavicle through statistical shape modeling. J Shoulder Elbow Surg 2019;28:631–8. https://doi.org/10.1016/j.jse.2018.09.018.
24. Walters J, Solomons M, Roche S. A morphometric study of the clavicle. SA Orthop J 2010;9:47–52.