J Shoulder Elbow Surg (2019) 28, 631–638

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Why off-the-shelf clavicle plates rarely fit: anatomic analysis of the clavicle through statistical shape modeling

Sanne Vancleef, MSc[a,*,1], Michiel Herteleer, MD[b,c,1], Yannick Carette, MSc[d,2], Paul Herijgers, MD, PhD[e], Joost R. Duflou, PhD[d,2], Stefaan Nijs, MD, PhD[c,f], Jos Vander Sloten, PhD[a]

[a]*Biomechanics Section, KU Leuven, Leuven, Belgium*
[b]*Organ Systems, KU Leuven, Leuven, Belgium*
[c]*Department of Traumatology, Universitaire Ziekenhuizen (UZ) Leuven, Leuven, Belgium*
[d]*Department of Mechanical Engineering, KU Leuven, Leuven, Belgium*
[e]*Anatomy Skills Center, KU Leuven, Leuven, Belgium*
[f]*Department of Development and Regeneration, KU Leuven, Leuven, Belgium*

Background: The clavicle presents a large variability in its characterizing sigmoid shape. Prominent and nonproperly fitting fixation plates (FP) cause soft tissue irritation and lead to hardware removal. It is therefore key in FP design to account for shape variations. Statistical shape models (SSMs) have been built to analyze a cluster of complex shapes. The goal of this study was to describe the anatomic variation of the clavicle using SSMs.
Methods: Two different SSMs of the clavicle were created, and their modes of variation were described. One model contained 120 left male and female clavicles. The other model consisted of 76 left and corresponding right clavicles, 41 originating from men and 35 from women.
Results: The model of 120 left clavicles showed that 10 modes of variation are necessary to explain 95% of the variation. The most important modes of variation are the clavicle length, inferior-superior bow, and medial and lateral curvature. Statistically significant differences between male and female clavicles were seen in length, sigmoid shape, and medial curvature. Comparison in men between left and right revealed significant differences in length and medial curvature. For women, a statistically significant difference between left and right was only seen in the length.
Conclusions: Although the operative treatment of displaced midshaft clavicular fractures has clear benefits, the variable anatomy of the clavicle often makes it challenging for the surgeon to make the plate fit adequately. Based on the identified variability in the clavicle's anatomy, it seems unlikely that a clavicle plating system can fit the entire population.

The Commissie Medische Ethiek van de Universitaire Ziekenhuizen KU Leuven approved this study (S58565).

*Reprint requests: Sanne Vancleef, MSc, Biomechanics Section, Katholieke Universiteit (KU) Leuven, Celestijnenlaan 300C, 3001 Heverlee, Belgium.

E-mail address: sanne.vancleef@kuleuven.be (S. Vancleef).
[1]These authors contributed equally to the performed research.
[2]Member Flanders Make.

https://doi.org/10.1016/j.jse.2018.09.018

Level of evidence: Anatomy Study; Imaging

Keywords: Clavicle anatomy; clavicular fractures; statistical shape modeling; principal component analysis; anatomic parameters; fixation plate design

Clavicular fractures are common injuries with an incidence of up to 71 per 100,000 persons per year,[14] The middle third of the clavicle is where 65% to 71% of these fractures occur.[15,20] In the past, these midshaft fractures were mostly treated conservatively.[25] However, recent high-quality evidence supports the practice of operative treatment for displaced midshaft clavicular fractures.[34] Fixation plates or intramedullary nails can be used for the operative treatment of midshaft clavicular fractures.[4,13]

Both techniques have advantages and disadvantages, but the most common complication of plate osteosynthesis is soft tissue irritation, typically resulting in implant removal. Large retrospective studies show that these removal rates are between 15% and 18.8%, and some authors even report removal rates up to 53%.[22,26,33] Naimark et al[26] also demonstrated that this hardware removal is associated with worse long-term clinical outcomes. Several authors have suggested positioning the clavicle plate anteroinferior to reduce implant related complications.[7,12,17,27] Although the scientific evidence suggests that an anteroinferior position could be associated with a decreasing incidence of symptomatic hardware removal, it is associated with a more extensive muscle dissection, and most available plates are designed for a superior position.[17]

The renewed interest in midshaft clavicular fracture fixation has led to several anatomic studies that have focused on how current plates fit the clavicle.[6,16,24] All of these studies investigated the fitting of superiorly positioned plates and showed that the current plates poorly fit the clavicle, which might be a contributing factor to the high hardware removal rates.

Several authors used advanced 3-dimensional analysis methods to study the clavicle's anatomy to improve implant design and reduce hardware related complications.[5,16,24] These studies demonstrate that the shape of the clavicle is highly variable and that current plates only have an optimal fit for a limited part of the population. However, the currently available studies do not systematically describe the statistical variations of the anatomic shape or identify relationships that exist between features of the anatomic shapes.

A statistical shape model (SSM) is a model that represents the mean shape of a population and its modes of variation. These SSMs have been used to describe shape variations in the population.[10,28,29,31] Principal component (PC) analysis (PCA) is used to create these models. This mathematic technique separates interrelated variables into a set of linearly independent variables or modes of variation and therefore allows related geometries within one component to be shown.[19] Few studies have used SSMs to describe the shape variations of the clavicle, and these studies used only a limited set of samples.[10,23]

Therefore, the primary goal of this study was to describe the variability in the shape of the clavicle through SSM. The secondary goal was to describe differences between men and women, and left and right clavicles.

Materials and methods

Data

A database with clavicles was set up, and 100 anonymized forensic CT scans were obtained and screened by a medical doctor (M.H.) for abnormalities in the clavicle. No pathologic signs were seen on the CT scans for 82 left and 81 right clavicles. From the University Hospital Leuven, we obtained 13 additional anonymized CT scans from the thorax and shoulder containing left clavicles and in which no clavicle pathologies were present.

The CT scans were segmented in Mimics 19 software (Mimics Innovation Suite; Materialise, Leuven, Belgium) and exported as STL (stereolithography) files. Twenty-five left historically available dry clavicles were obtained from the Anatomy Skills Center (KU Leuven, Leuven, Belgium) and laser scanned (LC60Dx; Nikon Metrology, Leuven, Belgium). The resulting point clouds were then meshed to the STL format using 3-Matic 12 (Mimics Innovation Suite) and added to the group of 95, resulting in 120 left clavicles. These were first manually aligned and then automatically aligned using a best fit algorithm in 3-Matic.

SSM technique

An SSM describes the geometric variations or modes of variation of a set of shapes, such as a set of clavicles. To create such an SSM, a 1-on-1 mesh correspondence between all bones was first obtained by a nonrigid surface registration algorithm. During this process, a selected source clavicle mesh was registered to all other clavicle meshes in the data set. The registration algorithm was based on Danckaers et al[9] and was implemented in MATLAB (MathWorks, Natick, MA, USA). Secondly, a Procrustes analysis[8] was performed to align the registered clavicles with the source. Finally, an SSM was generated using PCA. In PCA, the mean clavicle shape and its modes of variation or PCs were calculated. An important property of these PCs is that they are independent from each other. Each clavicle can then be described by the SSM using formula (1), in which y is a random clavicle mesh, $\bar{x}$ is the mean clavicle mesh, w corresponds to a weighting factor and p denotes the mode of variation or PC.

$$y = \bar{x} + \sum_{i=1}^{n} w_i p_i \tag{1}$$

Two SSMs were built: a model consisting of all left clavicles (n = 120) and a model consisting of 152 clavicles. The latter consisted of 76 left and their corresponding right clavicles, of which 41 clavicles came from men and 35 from women.

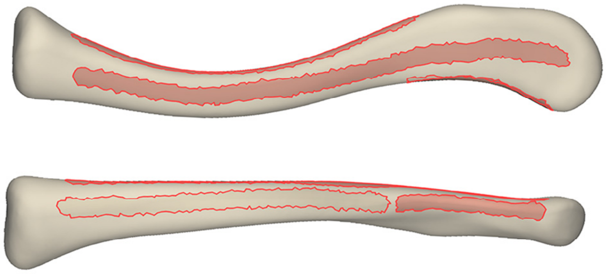

Figure 1 Superior and anterior view on the mean clavicle of the statistical shape model with the marked medial, lateral, and superior region of interest.

Description of the PCs

The anatomic description was done for the first 5 PCs. Firstly, the standard deviation (SD) of the weighting factors was calculated for each component. Secondly, to visualize the influence of one particular PC on the mean clavicle, point clouds were generated from the SSM for which only that particular PC was given a weighting factor of –3 SDs and +3 SDs. To describe the PCs, several anatomic parameters were measured using MATLAB. These parameters are length, medial, lateral, and superior radius from a specific region of interest, as shown in Fig. 1. The measurements were performed in a semiautomated way to improve the reliability and repeatability. The length was measured by first calculating the inertia axis of each clavicle.[30] Then, the clavicle and its inertia axes were aligned with the world coordinate system, and the difference between the maximal and minimal value along the longitudinal axis was used as the length of the clavicle. The medial, lateral, and superior curvature regions were first marked on the average clavicle of each SSM.

Because meshes built with the SSM are 1-on-1 corresponding, coordinate indices of the regions of interest of the mean clavicles correspond to the same region in any other mesh resulting from that SSM. Therefore, a MATLAB script (Supplementary Appendix S1) was used to automatically select the regions of interest in each point cloud of the first 5 modes of variation (–3 SD to +3 SD) and to fit a sphere in each region.[18] This sphere was then used to describe the radius of each region (Fig. 2).

Evaluation of the SSMs

Evaluation of the SSMs was performed by assessing the model compactness and generalization. The model compactness is a measure of the model's efficiency and corresponds to the number of PCs required to describe a fixed preset percentage of variation.[35] Generalization is a measure of how well a random clavicle can be described by the model.[23] The latter was performed by a leave-one-out reconstruction and measuring the average distance between the reconstructed and original clavicle. Reconstruction was performed using an increasing number of PCs.

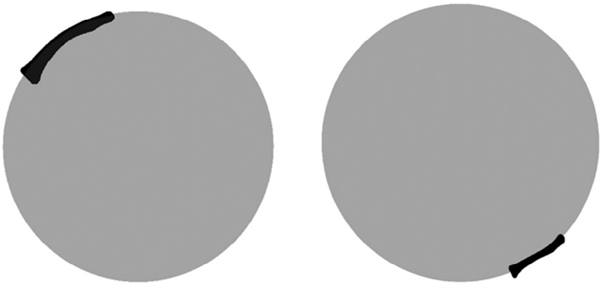

Figure 2 Fitted sphere in second principal component −3 standard deviations (left) and +3 standard deviations (right).

Evaluation of the variation in anatomy

To evaluate the variation in anatomy, the model consisting of 152 clavicles was used. In addition to the measurements to describe the principal components, 2 generalization graphs were plotted: the first containing the mean geometric error of female left, female right, male left, and male right reconstructed clavicles, and the second containing the mean geometric error of male, female, left, and right reconstructed clavicles. Paired and unpaired *t* tests were performed in MATLAB to test for significant differences ($P < .05$) in weighting factors of the PCs between side and sex, respectively.

Results

Variation of the clavicle anatomy (120 left clavicles)

Evaluation of the statistical shape model

Fig. 3 shows the compactness and generalization graphs of the SSM that included 120 left clavicles. The compactness graph shows that 10 PCs are required to explain 95% of the variation. The first 5 PCs explain, respectively, 78.5%, 6%, 3.6%, 2.6%, and 1.5% of the total variation. Adding these numbers gives 92.2% of the total variation being described. The generalization graph shows that a random clavicle can be reconstructed with an average accuracy of 0.33 mm.

Description of the PCs

The mean length was 150.8 mm, the mean radius of the medial curvature was 79.5 mm, and the mean radius of the lateral curvature was 42.9 mm. The effect of the PCs on the mean clavicle can be seen in Fig. 4.

In the first PC, the length variation of the clavicle is most prominent and varied between 184.1 mm (–3 SD) and 117.9 mm (+3 SD). Within the first PC, the medial and lateral curvature changed in function of the length. Larger clavicles had larger medial and lateral curvatures, and smaller clavicles had smaller medial and lateral curvatures (Table I).

In the second PC, the anatomic parameter that mainly varied was the inferior-superior bending of the clavicle. It varied between a strongly superiorly bowed clavicle (red clavicle in Fig. 4), where the fitted sphere was positioned on the inferior side of the clavicle and had a radius of 193 mm (–3 SD), and a lesser inferiorly bowed clavicle (blue clavicle in Fig. 4), where the sphere was fitted on the superior side of the clavicle and had a radius of 324 mm (+3 SD; Fig. 2).

In the third PC, the variation is seen in the volume of the clavicle. This is related to the medial and lateral curvature in which clavicles with a smaller volume have a lesser bowed

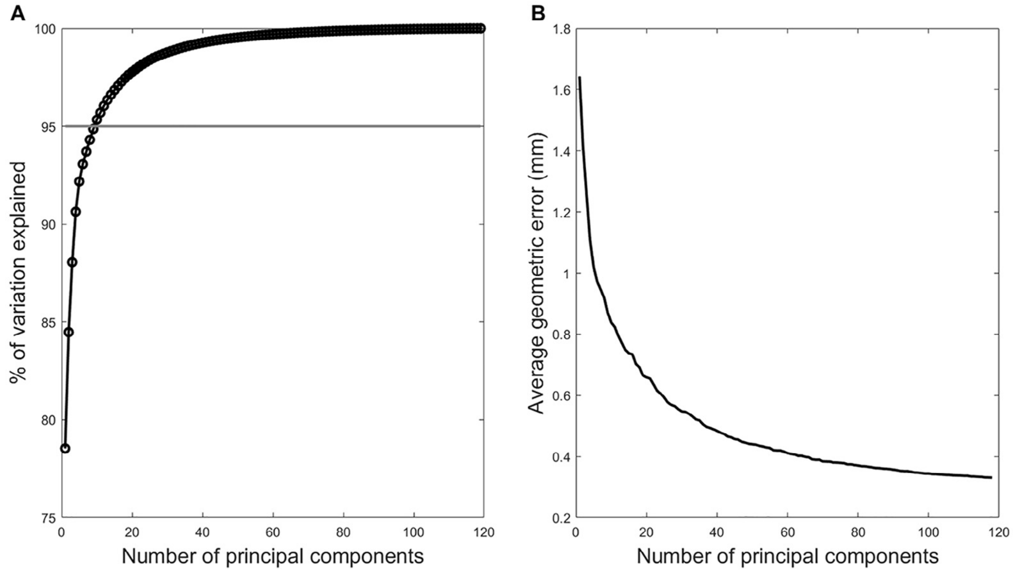

Figure 3 Evaluation of the statistical shape model containing 120 left clavicles. (**A**) Compactness of the statistical shape model showing that 10 principal components explain 95% of the total variation. (**B**) Generalization graph. Our model allows a random clavicle to be reconstructed with an average accuracy of 0.33 mm.

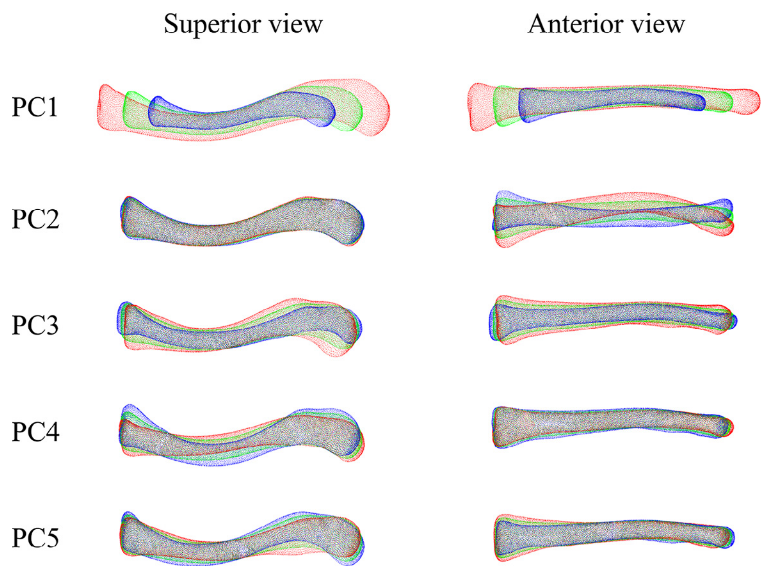

Figure 4 Shape variations of the statistical shape model consisting of 120 left clavicles. The *green clavicle* is the mean clavicle and is the same in all images. The *red clavicles* correspond with –3 standard deviations, and the *blue clavicles* correspond with +3 standard deviations of the respective principal component.

medial (94.2 mm [+3 SD] vs. 68.5 mm [–3 SD]) and lateral curvature (46.8 mm [+3 SD] vs. 34.8 mm [–3 SD]).

In the fourth PC, the largest variation is present in the medial curvature of the clavicle (114.0 mm [–3 SD] vs. 62.0 mm [+3 SD]). The radius of the lateral curvature also changes, but less prominently (49.7 mm [+3 SD] vs. 35.8 mm [+3 SD].

In the fifth PC, the main variation is found in the lateral curvature (55.2 mm [–3 SD] vs. 31.4 mm [+3 SD]). In this component, a larger volume of the sternal part of the clavicle is related to a straight shaped acromial side of the clavicle.

The detailed measurements of the described principal components are provided in Table I.

Variation between men and women, left and right (152 clavicles)

Evaluation of the SSM

In the SSM consisting of 152 clavicles, 9 components explain 95% of the variation. The first 5 components explain, respectively, 78.7%, 6.3%, 3.1%, 2.7%, and 1.5% of the variation. The generalization graphs in Fig. 5 show that the

Table I Description of the regions of interest of the statistical shape model that consists of 120 left clavicles

Variable	SD	Medial radius (mm)	Lateral radius (mm)	Superior radius* (mm)	Length (mm)
Mean		79.5	42.9	–	150.8
PC 1	−3	94.3	52.1	–	184.1
	+3	65.9	33.6	–	117.9
PC 2	−3	81.0	44.2	193	151.7
	+3	77.6	42.7	324	151.4
PC 3	−3	68.5	34.8	–	147.8
	+3	94.2	46.8	–	155.2
PC 4	−3	114.0	49.7	–	152.4
	+3	62.0	35.8	–	150.6
PC 5	−3	90.6	55.2	–	150.5
	+3	71.0	31.4	–	151.7

SD, standard deviation; *PC*, principal component.

* The superior curvature is only given for PC 2 because the inferior/superior bow of the clavicle only changed in this component. Note that the 193-mm radius corresponds with the superior bowed (red) clavicle in Fig. 4 and the 324-mm radius corresponds with the inferior bowed (blue) clavicle in Fig. 4

variation between male left and right is similar, whereas there is more variation in female right than in female left. In addition, Fig. 5 shows that there is more variation in male than female clavicles and that the variation between left and right clavicles is similar. Overall, a random clavicle can be reconstructed with an average geometric error of 0.24 mm.

Description of the PCs

As can be seen in Fig. 6, PC 1 corresponds to a scaling factor in length and thickness of the clavicle, and PC 2 corresponds to the inferior-superior bow. The overall sigmoid shape and diameter of the clavicle is visible in PC 3. In PC 4, variation in the medial curvature is present, whereas in PC 5, variation in the lateral curvature is present. Absolute values can be found in Table II.

Evaluation of sex and side differences

Looking at the weighting factors of each clavicle for the first 5 PCs reveals a statistically significant difference between male left and right for PC 1 ($P = .0322$) and PC 4 ($P = .00071$). Between women left and right, only a statistically significant difference is seen in the weighting factor of the PC 1 ($P = .0072$). Comparison between the left clavicle of men and women revealed statistically significant differences in the weighting factor of the PC 1 ($P = 6.00 \times 10^{-9}$) and PC 4 ($P = .0065$). The same weighting factors differed significantly between men right ($P = 1.35 \times 10^{-8}$) and women right ($P = 3.95 \times 10^{-4}$). An unpaired *t* test between male and female clavicles showed statistically significant differences in weighting factors of PC 1 ($P = 2.91 \times 10^{-16}$), PC 3 ($P = .0292$), and PC 4 ($P = 9.59 \times 10^{-6}$). The mean clavicle length was 157.3 mm in men and 144.4 mm in women. A paired *t* test between left and right showed statistically significant differences in weighting factors of PC 1 ($P = .0011$), PC 2 ($P = .0152$) and PC 4 ($P = 3.48 \times 10^{-4}$). The mean left clavicle has a longitudinal length of 152 mm, and the mean right clavicle measures 150.7 mm.

Discussion

In this study we created 2 SSMs of the clavicle, the first to describe the variation in the clavicle, the second to compare male and female, left and right clavicles. The created SSMs had excellent performances regarding their compactness and generalization. The most important finding was that the medial and lateral curvature varied largely in 4 of the first 5 PCs. This means that a clavicle's sigmoid shape is not only related

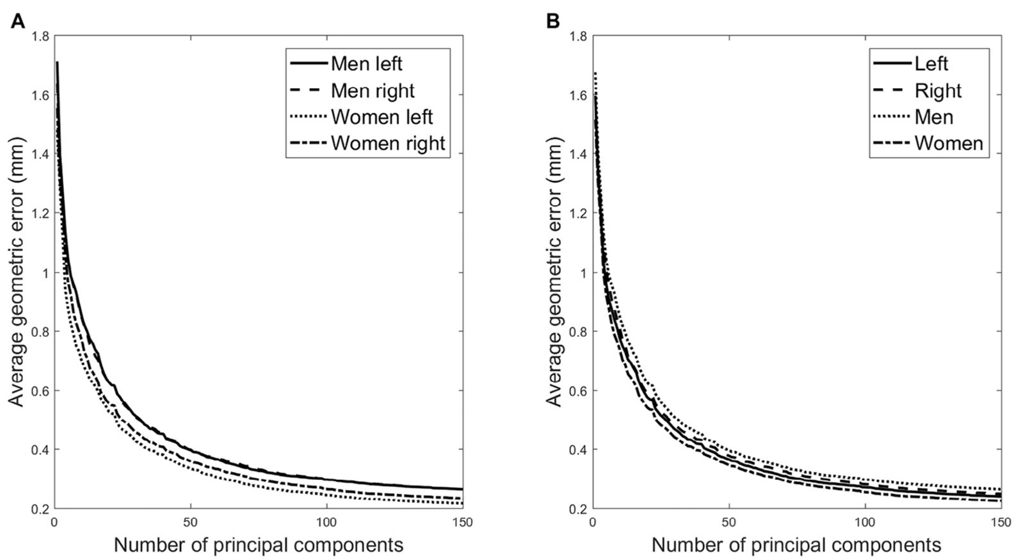

Figure 5 Generalization graph of (**A**) men left, men right, women left and women right and (**B**) left, right, men and women.

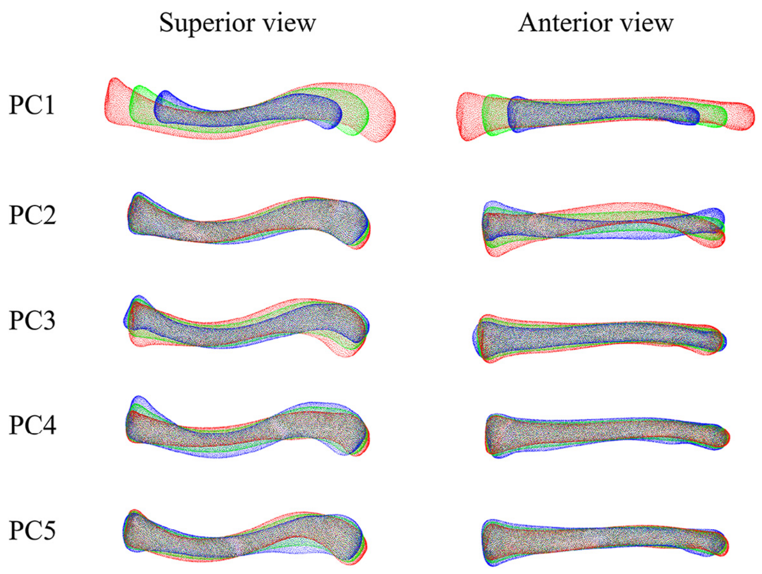

Figure 6 Shape variations of the statistical shape model consisting of 152 clavicles. The *green clavicle* is the mean clavicle and is the same in all images. The *red clavicles* correspond with –3 standard deviations, and the *blue clavicles* correspond with +3 standard deviations of the respective principal component.

Table II Description of the regions of interest of the statistical shape model containing 152 clavicles

Variable	SD	Medial radius (mm)	Lateral radius (mm)	Superior radius* (mm)	Length (mm)
Mean		74.7	47.5	–	150
PC 1	–3	90.7	53.8	–	182.4
	+3	58.6	40.4	–	117.7
PC 2	–3	78.9	56.5	136	150.4
	+3	70.8	40.4	365	150
PC 3	–3	74.4	39	–	147.9
	+3	74.1	56.5	–	153.7
PC 4	–3	109.6	59	–	151.7
	+3	57.7	34.4	–	148.3
PC 5	–3	65.3	33.3	–	151.5
	+3	87.6	50.9	–	149

SD, standard deviation; *PC*, principal component.
* The superior curvature is only given for PC 2 as the inferior /superior bow of the clavicle only changed in this component.

to its length but that it is also an independent variable. Analysis of the side- and sex-specific models showed significant differences in the weighting factors for the modes of variation between male and female and left and right clavicles.

Our models contained 120 left clavicles and 152 left and corresponding right clavicles, which is a larger number than other studies that used PCA to evaluate the shape of the clavicle (Daruwalla et al,[10] 21 clavicles; Lu and Untaroiu,[23] 20 clavicles). When looking at the quality of our SSMs by evaluating the generalization and compactness graphs (Fig. 3), we see that Lu and Untaroiu[23] had a geometric error of 2 mm compared with only 0.33 mm in our study. This indicates that a random clavicle can be more accurately described by our SSM than by earlier described models. Lambert et al[21] did not report any data about the generalization of their model. When looking at the compactness graph of our 120 left clavicle model (Fig. 3), the first PC accounted for 78.5% of variation. The SSMs of Daruwalla et al[10] and Lu and Untaroiu[23] showed that the first PC explained 70.5% and only 31.9%, respectively. We believe that these differences are mainly explained by the small number of clavicles they included.

In the first PC the largest shape variation is seen in the clavicle's length, which is in accordance with the results of previous studies.[10,21,23] The second PC of our analysis shows a large variation in the inferior and superior bending of the clavicle. Although this bending is briefly mentioned in the articles by Daruwalla et al[10] and Lambert et al,[21] its variation is not described. Aira et al[2] also described a large variation in the inferior bending of the clavicle.

PCs 3, 4, and 5 of our study show varying medial and lateral curvatures independent of the clavicle's length. This is the most important finding of our study because it implies that the curved shape of the clavicle is not only determined by its length but is also highly variable. These findings are reported visually in the studies by Lu and Untaroiu[23] and Daruwalla et al,[10] but are not quantified. However, as mentioned before, these 2 studies only included a small number of clavicles (20 and 21 clavicles, respectively).[10,23] The only study, to our knowledge, that used PCA to describe the variation in clavicle anatomy and that included a large number of clavicles (174 clavicles from 95 individuals) is the study by Lambert et al.[21] However, their SSM was based on a region of interest on the anterosuperior aspect of the clavicle and not on the entire clavicle. They state in their conclusion that the largest variation in clavicle anatomy is explained by the length of the bone, which is in accordance to our and other authors' results.[10,21,23] However, they also state that because the second and third PCs contribute less to the compactness of the model, the shape variations in these components are less important for implant design. This assumption is, however, contradicted by our results.

The SSM containing 152 clavicles consisting of 76 left and corresponding 76 right clavicles, was created with the purpose to detect sex and side differences. From the comparison between male and female clavicles, it can be concluded that the average female clavicle is smaller than the male clavicle, which other authors[1,3,11] have also reported. In addition, significant differences were found between male and female clavicles in PC 1, PC 3, and PC 4. These differences might be explained by differences in the muscle strength of men compared with women, as hypothesized by Fatah et al.[1] The comparison between left and right revealed statistically significant differences in length, inferior/superior bow, and medial curvature. This is in contradiction with the study of Daruwalla et al,[10] in which no significant differences were observed. This can, however, be explained by the small subject group. Andermahr et al[3] also reported on significant side differences in medial curvature, which is in accordance with our results. In addition, a larger variation is observed between men and women than between left and right. We therefore advise that it is more important to include male and female clavicles than to include left and right clavicles in the SSM to describe the anatomic variation.

Furthermore, the percentage of explained variation is similar in both models. The average geometric error from the generalization graph was 0.24 mm in case of the second model (Fig. 5). At first sight, this model performs better than the model of 120 left clavicles, but we should pay attention while interpreting these results. Fig. 5 was obtained by a leave-one-out experiment. Because the model contained a left and right clavicle from the same patient, information about the right side of the patient is still present in the model when describing the left side of this patient. Although significant side differences were identified, the presence of the corresponding side in the model might induce a certain bias.

The identified variation in the clavicle raises the question how implants should be designed to assure a better fit and thus to make sure less intraoperative contouring is necessary. First, most clavicle fixation plates only possess the sigmoid shape, but as indicated by the second PC, the bow in the coronal plane also has an important contribution to the variation. Plating systems should therefore also at least take this variation into account. In addition, because the medial and lateral radius vary independently from each other, the sigmoid shape will not fit each clavicle. Moreover, no sex-specific plates currently exist, although there is a difference of 13 mm between the average male and female clavicle. In a plating system designed to take into account 3 sizes of each component, 3 to the power of 5 combinations would be possible, resulting in 243 plates. Therefore, the use of patient-specific implants to reduce hardware irritation could be the solution to avoid this complication.[32]

Our study has some limitations that need to be addressed. We chose to focus on the surface morphology because this will determine the fit of a plate and did not provide any information about the intramedullary canal or the cortical thickness. Due to the anonymized patient data, we could not relate any of the information regarding the shape to other patient's characteristics, such as length, ethnicity, age, or hand dominance.

One of the strengths of our study was the new methodology that was used to describe the morphologic parameters of the different PCs. Several authors have used different methods to describe the morphologic characteristics of the clavicle.[2] We believe that because of the clavicle's complex individual geometry, aligning and orientating a group of clavicles in a repeatable and methodologically correct way would be very difficult. Computer-assisted measurement methods allow researchers to make reliable and repeatable measurements.

Conclusion

Although there are clear benefits for the operative treatment of displaced midshaft clavicular fractures, the variable anatomy of the clavicle often makes it challenging for the surgeon to make the plate fit adequately. Based on the identified variability in the clavicle's anatomy, it seems unlikely that a clavicle plating system can fit the entire population. Our results encourage research to focus on the improvement of implant design that could lead to less hardware-related removal. Although patient-specific solutions could be beneficial from an anatomic point of view, its clinical impact remains unknown.

Acknowledgments

The authors thank KU Leuven for providing funding through the BioMeTIOm IDO project and the Materialise Chair for image-based patient-specific biomechanics for access to Mimics and 3-Matic. The authors also thank Walter Coudyzer of the radiology department of the University Hospital Leuven for providing us with the CT scans from which the clavicles were segmented.

Disclaimer

This research was funded by the internal funds of KU Leuven through the BioMeTIOm project. The authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jse.2018.09.018.

References

1. Abdel Fatah EE, Shirley NR, Mahfouz MR, Auerbach BM. A three-dimensional analysis of bilateral directional asymmetry in the human clavicle. Am J Phys Anthropol 2012;149:547-59. http://dx.doi.org/10.1002/ajpa.22156
2. Aira JR, Simon P, Gutierrez S, Santoni BG, Frankle MA. Morphometry of the human clavicle and intramedullary canal: a 3D, geometry-based quantification. J Orthop Res 2017;http://dx.doi.org/10.1002/jor.23533
3. Andermahr J, Jubel A, Elsner A, Johann J, Prokop A, Rehm KE, et al. Anatomy of the clavicle and the intramedullary nailing of midclavicular fractures. Clin Anat 2007;20:48-56. http://dx.doi.org/10.1002/ca.20269
4. Andrade-Silva FB, Kojima KE, Joeris A, Santos Silva J, Mattar R. Single, superiorly placed reconstruction plate compared with flexible intramedullary nailing for midshaft clavicular fracture. J Bone Joint Surg Am 2015;97:620-6. http://dx.doi.org/10.2106/JBJS.O.00118
5. Bachoura A, Deane AS, Kamineni S. Clavicle anatomy and the applicability of intramedullary midshaft fracture fixation. J Shoulder Elbow Surg 2012;21:1384-90. http://dx.doi.org/10.1016/j.jse.2011.10.032
6. 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. http://dx.doi.org/10.1016/j.jse.2012.01.019
7. Baltes TP, Donders JC, Kloen P. What is the hardware removal rate after anteroinferior plating of the clavicle? A retrospective cohort study. J Shoulder Elbow Surg 2017;26:1838-43. http://dx.doi.org/10.1016/j.jse.2017.03.011
8. Bookstein FL. Morphometric tools for landmark data. Cambridge: Cambridge University Press; 1991.
9. Danckaers F, Huysmans T, Lacko D, Ledda A, Verwulgen S, Van Dongen S, et al. Correspondence preserving elastic surface registration with shape model prior. Paper presented at: 22nd International Conference on Pattern Recognition (ICPR), Stockholm, Sweden, August 24-28, 2014. p. 2143-8. http://dx.doi.org/10.1109/ICPR.2014.373.
10. 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. http://dx.doi.org/10.1186/1749-799X-5-21
11. 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. http://dx.doi.org/10.1002/ca.20924
12. Galdi B, Yoon RS, Choung EW, Reilly MC, Sirkin M, Smith WR, et al. Anteroinferior 2.7-mm versus 3.5-mm plating for AO/OTA type B clavicle fractures: a comparative cohort clinical outcomes study. J Orthop Trauma 2013;27:121-5. http://dx.doi.org/10.1097/BOT.0b013e3182693f32
13. Groh GI. Clavicle fractures: pins, plates, and drilling down. J Bone Joint Surg Am 2015;97:e38, 1-2. http://dx.doi.org/10.2106/JBJS.O.00118.
14. 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. http://dx.doi.org/10.1016/j.jse.2018.01.016
15. 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 2017;1-10. http://dx.doi.org/10.1007/s00068-017-0858-7
16. Huang JI, Toogood P, Chen MR, Wilber JH, Cooperman DR. Clavicular anatomy and the applicability of precontoured plates. J Bone Joint Surg Am 2007;89:2260-5. http://dx.doi.org/10.2106/JBJS.G.00111
17. Hulsmans MH, van Heijl M, Houwert RM, Timmers TK, van Olden G, Verleisdonk EJ. Anteroinferior versus superior plating of clavicular fractures. J Shoulder Elbow Surg 2016;25:448-54. http://dx.doi.org/10.1016/j.jse.2015.09.005
18. Jennings A. Sphere fit. MATLAB Central File Exchange. <https://www.mathworks.com/matlabcentral/fileexchange/34129-sphere-fit-least-squared> 2011, accessed August 25, 2017.
19. Jolliffe IT, Cadima J. Principal component analysis: a review and recent developments. Philos Trans A Math Phys Eng Sci 2016;374:20150202. http://dx.doi.org/10.1098/rsta.2015.0202
20. 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 Disord 2017;18:82. http://dx.doi.org/10.1186/s12891-017-1444-1
21. Lambert S, Al-Hadithy N, Sewell MD, Hertel R, Sudkamp N, Noser H, et al. Computerized tomography based 3D modeling of the clavicle. J Orthop Res 2016;34:1216-23. http://dx.doi.org/10.1002/jor.23145
22. Leroux T, Wasserstein D, Henry P, Khoshbin A, Dwyer T, Ogilvie-Harris D, et al. Rate of and risk factors for reoperations after open reduction and internal fixation of midshaft clavicle fractures: a population-based study in Ontario, Canada. J Bone Joint Surg Am 2014;96:1119-25. http://dx.doi.org/10.2106/JBJS.M.00607
23. 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. http://dx.doi.org/10.1016/j.cmpb.2013.05.017
24. Malhas AM, Skarparis YG, Sripada S, Soames RW, Jariwala AC. How well do contoured superior midshaft clavicle plates fit the clavicle? A cadaveric study. J Shoulder Elbow Surg 2016;25:954-9. http://dx.doi.org/10.1016/j.jse.2015.10.020
25. Micev AJ, Hsu D, Edwards SL, Marra G, Saltzman MD. The rising incidence of operative fixation of acute mid-shaft clavicle fractures. J Shoulder Elbow Surg 2014;23:e237. http://dx.doi.org/10.1016/j.jse.2014.06.018
26. Naimark M, Dufka FL, Han R, Sing DC, Toogood P, Ma CB, et al. Plate fixation of midshaft clavicular fractures: patient-reported outcomes and hardware-related complications. J Shoulder Elbow Surg 2016;25:739-46. http://dx.doi.org/10.1016/j.jse.2015.09.029
27. Nourian A, Dhaliwal S, Vangala S, Vezeridis PS. Midshaft fractures of the clavicle. J Orthop Trauma 2017;31:461-7. http://dx.doi.org/10.1097/BOT.0000000000000936
28. Plessers K, Vanden Berghe P, Van Dijck C, Wirix-Speetjens R, Debeer P, Jonkers I, et al. Virtual reconstruction of glenoid bone defects using a statistical shape model. J Shoulder Elbow Surg 2017;27:160-6. http://dx.doi.org/10.1016/j.jse.2017.07.026
29. Poltaretskyi S, Chaoui J, Mayya M, Hamitouche C, Bercik MJ, Boileau P, et al. Prediction of the pre-morbid 3D anatomy of the proximal humerus based on statistical shape modelling. Bone Joint J 2017;99B:927-33. http://dx.doi.org/10.1302/0301-620X.99B7.BJJ-2017-0014
30. Small Satellites. Moments of inertia, center of mass. <https://nl.mathworks.com/matlabcentral/fileexchange/39371-moments-of-inertia-center-of-mass?focused=3776583&tab=function>; 2012, accessed March 19, 2018.
31. Vanden Berghe P, Demol J, Gelaude F, Vander Sloten J. Virtual anatomical reconstruction of large acetabular bone defects using a statistical shape model. Comput Methods Biomech Biomed Engin 2017;20:577-86. http://dx.doi.org/10.1080/10255842.2016.1265110
32. Vanhove H, Carette Y, Vancleef S, Duflou JR. Production of thin shell clavicle implants through single point incremental forming. Procedia Engineer 2017;183:174-79. http://dx.doi.org/10.1016/j.proeng.2017.04.058
33. Wijdicks FJ, Van Der Meijden OA, Millett PJ, Verleisdonk EJ, Houwert RM. Systematic review of the complications of plate fixation of clavicle fractures. Arch Orthop Trauma Surg 2012;132:617-25. http://dx.doi.org/10.1007/s00402-011-1456-5
34. Woltz S, Krijnen P, Schipper IB. Plate fixation versus nonoperative treatment for displaced midshaft clavicular fractures. J Bone Joint Surg 2017;99:1051-7. http://dx.doi.org/10.2106/JBJS.16.01068
35. Zhang J, Malcolm D, Hislop-Jambrich J, Thomas CD, Nielsen PM. An anatomical region-based statistical shape model of the human femur. Comput Methods Biomech Biomed Eng Imaging Vis 2014;2:176-85. http://dx.doi.org/10.1080/21681163.2013.878668