Clinical Anatomy 27:712–723 (2014)

ORIGINAL COMMUNICATION

The Anatomy of the Clavicle: A Three-dimensional Cadaveric Study

AMIT BERNAT,[1*] TOON HUYSMANS,[2] FRANCIS VAN GLABBEEK,[1] JAN SIJBERS,[2] JAN GIELEN,[3] AND ALEXANDER VAN TONGEL[4]

[1]*Department of Orthopedic Surgery and Traumatology, University Hospital of Antwerp, Antwerp, Belgium*
[2]*iMinds-Vision Lab, Department of physics, University of Antwerp, Antwerp, Belgium*
[3]*Department of Radiology, University Hospital of Antwerp, Antwerp, Belgium*
[4]*Department of Orthopedic Surgery and Traumatology, University Hospital of Ghent, Ghent, Belgium*

The clavicle has a complex osteologic structure that makes morphological analysis extremely difficult. A three-dimensional study was conducted to examine the anatomical variations and characteristics of the bone. Sixty-eight human cadaver clavicles were dissected, CAT-scanned, and reconstructed. An automated parameterization and correspondence shape analysis system was developed. A new length, designated as centerline (CL) length, was defined and measured. This length represents the true length of the clavicle. The endpoint length was measured as the distance between two endpoints. The width and curvature were measured in the axial (AX) and frontal (FR) plane and defined along the CL. Next gender and side characteristics and variations were examined. The mean CL length was 159.0 ± 11.0 mm. The mean endpoint length was 149.4 ± 10.3 mm, which was statistically significantly shorter than the CL. The male clavicle was significantly longer (166.8 ± 7.3 mm vs. 151.0 ± 8.2 mm), wider (14.6 ± 1.5 mm vs. 12.7 ± 1.3 mm lateral FR plane, 25.9 ± 4.1 mm vs. 23.5 ± 3.0 mm lateral AX plane and 24.7 ± 2.8 mm vs. 22.8 ± 2.8 mm medial AX plane), and more curved (10.8 ± 2.8 mm vs. 8.6 ± 2.3 mm medial and 10.5 ± 3.3 mm vs. 9.1 ± 2.5 mm lateral) than the female one. Left clavicles were significant longer (159.8 ± 10.9 mm vs. 158.0 ± 11.2 mm) than right clavicles. A novel three-dimensional system was developed, used and tested in order to explore the anatomical variations and characteristics of the human clavicle. This information, together with the automated system, can be applied to future clavicle populations and to the design of fixation plates for clavicle fractures. Clin. Anat. 27:712–723, 2014.

Key words: clavicle anatomy; three-dimensional analysis; true length; width; curvature

INTRODUCTION

The clavicle serves as the sole bone structure connecting the axial skeleton to the shoulder girdle through the sternoclavicular joint medially and the acromioclavicular joint laterally. It is a complex structure that plays an important role in the stability, movement, and cosmetic aspect of the shoulder girdle. The close relationship between the clavicle, its shape, the muscles and ligaments forms the basic platform for the full range of motion of the shoulder (Lazarus and Seon, 2006).

*Correspondence to: Amit Bernat, M.D., Department of Orthopedic Surgery and Traumatology, University Hospital of Antwerp, Wilrijkstraat 10, 2650 Edegem, Belgium. E-mail: bernat.amit@gmail.com

Received 28 June 2012; Revised 3 June 2013; Accepted 5 June 2013

Published online 21 October 2013 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ca.22288

Clavicular morphology has developed in recent years a great interest among researchers. Archeologists use the clavicle to explain evolutionary processes (Voisin, 2006, 2008), anatomic and forensic pathology use the clavicle for explaining handedness, gender, bone and muscle development (McCormick et al., 1991; Mays et al., 1999; Auerbach and Raxter, 2008; Danforth and Thompson, 2008; Ludewig et al., 2009).

Orthopedic surgeons research the clavicle for better treatment of fractures and complications (Nowak et al., 2004; Andermahr et al., 2007; Huang et al., 2007; VanBeek et al., 2011; Hillen et al., 2012).

Clavicle fractures account for 2.6%–12% of all fractures and for 44–66% of fractures about the shoulder. Middle-third fractures account for 80% of all clavicular fractures; whereas, fractures of the lateral and medial third of the clavicle account for 15% and 5%, respectively (Egol et al., 2010).

Injuries at the diaphysis of the clavicle are more likely to be displaced as compared with medial- and lateral third fractures. Recent evidence suggests these specific subsets of patients may be at high risk for nonunion, shoulder dysfunction, or residual pain after nonsurgical management (Altamimi and McKee, 2008; McKee et al., 2006). In these patients, acute surgical intervention may minimize suboptimal outcomes (Canadian Orthopaedic Trauma Society, 2007; Althausen et al., 2013).

Altamimi and McKee (2008) have advocated the use of anatomical precontoured plates for the decrease in soft tissue irritation and increase in patient satisfaction. VanBeek et al. (2011) have compared the outcome after precontoured and noncontoured superior plating of the clavicle and showed a significant decrease of hardware prominence and 50% less reoperation rate for hardware removal in the precontoured group.

Several studies have been conducted to define its complex shape and variability of this double-curved bone structure. Most of these studies used a two-dimensional (2D) analysis (Parsons, 1916; Olivier 1951–1956; McCormick et al., 1991; Jit and Singh, 1996; Mays et al., 1999; Andermahr et al., 2007; Huang et al., 2007; Auerbach and Raxter, 2008; Danforth and Thompson, 2008; Voisin, 2008).

Recently, it has been described that 3D morphometric analysis can provide more exact, correct, and consistent results (Fitzpatrick et al., 2007). Daruwalla et al. (2010a,b) were the first to measure the length and width of the clavicle using 3D reconstruction. However, their study had several weaknesses. First, only 27 clavicles were evaluated, which is too small a number taking the high variability of the bone into account. Secondly, the population was not balanced (9 men and 18 women, 15 left and 12 right). These can influence the average length, width, and curvature results. Thirdly, a coordinate system was created based on axes that were defined on each individual clavicle with a user interface. This process was done manually on each clavicle. One of the axes was based on the selection of two end points. As the variation rate at the edges of the clavicle is high, selecting these points can give a false representative evaluation.

In the present study, we used a newly developed technique for the mathematical evaluation of 3D-reconstructed material to evaluate the length (defined as the line which crosses through the center of the clavicle and as the line between two extremity points), width, and curvature (in the frontal and axial plane). All the measurements were repeated for the comparison between sides and gender.

These anatomical characteristics will provide a better understanding of the complexity of the clavicle and act as a steppingstone in the creation and development of an anatomical precontoured plate.

MATERIAL AND METHODS

Study Population

In this study, 68 human clavicles (34 pairs) from human Caucasian cadavers were dissected and investigated. This set of clavicles represented 17 male and 17 female specimens with a mean age of 77 years (range: 43–99 years). The population consisted of 34 (17 males, 17 females) right and 34 (17 males, 17 females) left clavicles.

Data Acquisition

Preparation of the clavicles was done in the anatomy lab at the University of Antwerp. After resection of the clavicles, the soft-tissue envelope was completely removed.

All clavicles were scanned with a GE LightSpeed Volume CT (GE Medical Systems, Milwaukee WI) with a spatial resolution of $500 \times 500 \times 600\,\mu m^3$ at the University Hospital of Antwerp. The scans were performed by placing the clavicles in a standardized fashion with their flat superior surface of the lateral end facing down to prevent movement of the bone during the scan.

Surface Generation

The computed tomography (CT) reconstructions from the GE Lightspeed Volume CT system were automatically segmented by morphological image-processing operations. Where necessary, manual corrections were made using Avizo (Visualization Sciences Group, Burlington MA). From the obtained segmented images, the outer boundary surface of each clavicle was extracted using the marching cubes algorithm (Lorensen and Cline, 1987).

For each clavicle surface, a point on both the sternal and acromial end was selected using custom-made manual annotation software. Then, each surface was punctured at the selected ends, effectively converting it to cylindrical topology, which is a necessary step in our analysis procedure (Fig. 1). Repeating this step twice by two orthopedic surgeons in 10 selected clavicles at random tested inter- and intra-observer discrepancy.

Finally, all left clavicles were mirrored with respect to the sagittal plane, and thereby brought into the coordinate space of the right clavicle. This allowed us to compare the geometry of all clavicles

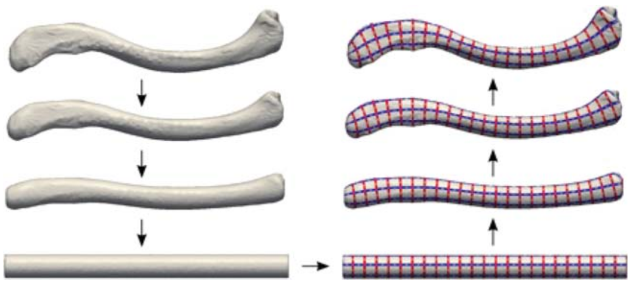

Fig. 1. Parameterization of a clavicle to the cylinder. Left: gradual deformation of the clavicle into a cylinder of optimal length and with minimal deformation. Right: the blue axial lines of the cylinder are mapped by the parameterization to curves along the clavicle and the red circumferential lines are mapped to cross-sections of the clavicle.

in the population, both left and right, in a meaningful way.

Surface Parameterization (The Process of Transforming the Clavicle into the Cylinder)

Each clavicle in the population was parameterized onto the cylinder. This allowed us to calculate the centerline (CL) of each clavicle and to construct a correspondence between the surfaces of the clavicles.

The parameterization defined a mapping from each point on the surface of the clavicle onto the cylinder, much like a cylindrical map projection in cartography where the surface of the earth is projected on the surface of a cylinder. We used the cylindrical parameterization technique of Huysmans et al. (2005), which provides a map between the clavicle surface and the cylinder that introduces the least deformation, i.e. areas and angles are preserved as much as possible.

Secondly, it automatically estimates the optimal length of the cylinder so as to introduce the least possible deformation with the mapping. This technique also guarantees that the mapping is one-to-one, i.e. each point of the clavicle surface exactly corresponds to one point on the cylinder and vice versa (Fig. 1).

The parameterization of a clavicle can be visualized on the surface of the clavicle using a texture. The axial lines of the cylinder were mapped to blue curves along the clavicle and the circumferential lines of the cylinder were mapped to red cross-sections of the clavicle (Fig. 1). Based on the parameterization of

Fig. 2. Visualization of some (23) circumferential lines of the parameterization on the cylinder together with the CL that connects the centers of the circumferential lines.

Fig. 3. Transparent overlay of all 68 clavicles. Both spatial alignment (position and orientation) and parameterization alignment (blue axial and red circumferential lines) has been achieved.

the clavicle, by averaging the points on each circumferential line of the parameterized clavicle the central point can be calculated, called the center points.

Next, these center points were connected into a curve, called the CL (Fig. 2). As a final step in the parameterization, we modified the parameterization such that an equal distance measured along the CL separated the positions of the centers of the circumferential lines. In this way, the circumferential lines divided the clavicle in 100 equal parts.

Correspondence Construction

To compare the geometry of the clavicles in the population with each other, a correspondence was defined. Such a correspondence (a) spatially aligns

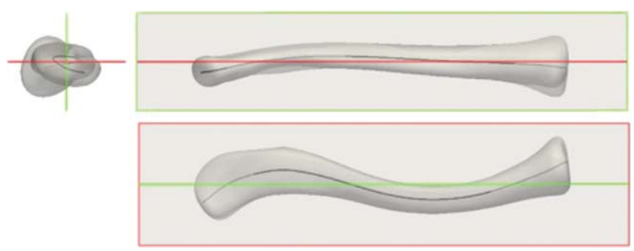

Fig. 4. The FR (green)–AX (red) coordinate system for the evaluation of width and curvature. The average CL is shown in black and the average clavicle is shown in gray.

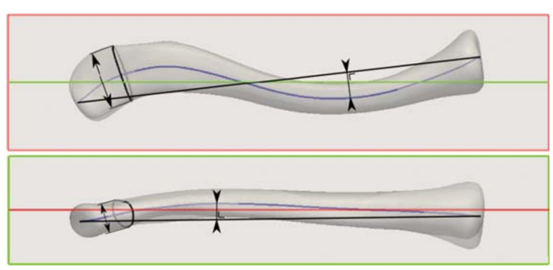

Fig. 5. Visualization of the feature measurement: CL (blue curved line) and EP (black straight line). A cross-section at the acromial end, viewed in the AX and FR plane. The curvature measured by perpendicular lines viewed in the AX and FR plane.

TABLE 1. Mean Centerline Length and Mean End-Point Length and Comparison of the End-Point Length With the Literature Data

	Centerline length[a]	End-point length[a]	Parson et al.	Andermahr et al.	Huang et al.	Darwalla et al.
All	159.0 ± 11.0 (139.9–182.5)[b]	149.4 ± 10.3 (130.7–171.9)[b]	146	151 ± 11	145 ± 12.7	
Right	158.0 ± 11.2 (139.9–181.4)[c]	148.4 ± 10.5 (130.7–169.4)[d]	145	149 ± 11		143.24
Left	159.8 ± 10.9 (139.9–182.5)[c]	150.3 ± 10.1 (132.8–171.9)[d]	146	152 ± 11		145.21
Females	151.0 ± 8.2 (139.9–169.5)[b]	142.9 ± 8.4 (130.7–161.8)[b]	138	146 ± 10	152.6 ± 10,2	140.34
Male	166.8 ± 7.3 (151.8–182.5)[b]	155.8 ± 7.6 (140.7–171.9)[b]	152	156 ± 10	137.3 ± 10,2	152.33
Female right	150.4 ± 8.7 (139.9–169.0)	142.3 ± 9.2 (130.7–160.2)	138			139.27
Female left	151.7 ± 7.9 (139.9–169.5)	143.5 ± 7.9 (132.8–161.8)	139			141.1
Male right	165.7 ± 7.7 (151.8–181.4)	154.6 ± 8.1 (140.7–169.4)[e]	152			151.19
Male left	167.8 ± 6.8 (155.2–182.5)	157 ± 7.2 (142–171.9)[e]	154			153.2

[a]Mean ± SD (min length–max length)/mm
[b]$P < 0.0001$
[c]$P = 0.02$ (paired *T*-test)
[d]$P = 0.015$ (paired *T*-test)
[e]$P = 0.03$ (paired *T*-test)

the clavicles with each other bringing them in a standard position, and (b) aligns the parameterizations with each other such that the axial and circumferential parameterization lines of different clavicles line up as much as possible (Fig. 3).

To obtain such a correspondence, we followed the approach of Huysmans et al. (2010), which determines the optimal values for the position and orientation of each clavicle and the optimal rotation of the parameterization for each clavicle (Huysmans et al., 2010). The method finds the optimal values for these degrees of freedom by minimizing the variance for corresponding points.

Reference Coordinate System

To consistently measure and compare the geometric features of the clavicle, we used the obtained correspondence and introduced a standard reference coordinate system. This coordinate system provided us with two perpendicular planes, in which the width and curvature of the clavicles will be reported.

The orientation of the coordinate system was derived from the 3D-averaged CL of all clavicles using principal component analysis (Fig. 4) (Pearson, 1901): (1) the origin of the coordinate system is located at the centroid (average of all center points) of the average CL; (2) the first axis is oriented in the direction that yields the largest variance of the CL points projected on this direction; (3) the second axis is oriented perpendicular on the first axis and again in the direction that yields the largest variance of the projected CL points. The first and the second axes form the axial plane, also known as the transversal plane (AX); (4) the third axis is perpendicular to both the first and the second axis. The first and the third axis form the frontal plane, also known as the coronal plane (FR).

Feature Measurement

As specified above, connecting all the center points created a CL. The length of this CL, running through the center of the outer cortical surface, represents the true length of the clavicle. Also, the distance between the two endpoints was measured and was called the length of the endpoint line (EP) (Fig. 5). A correlation

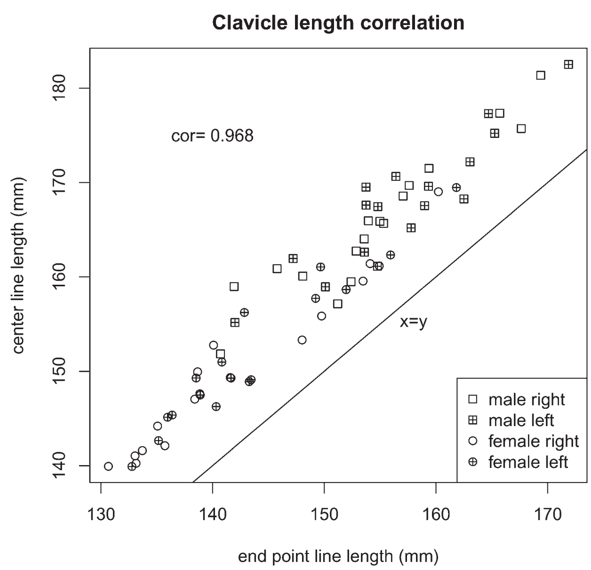

Fig. 6. Correlation between the CL and EP length.

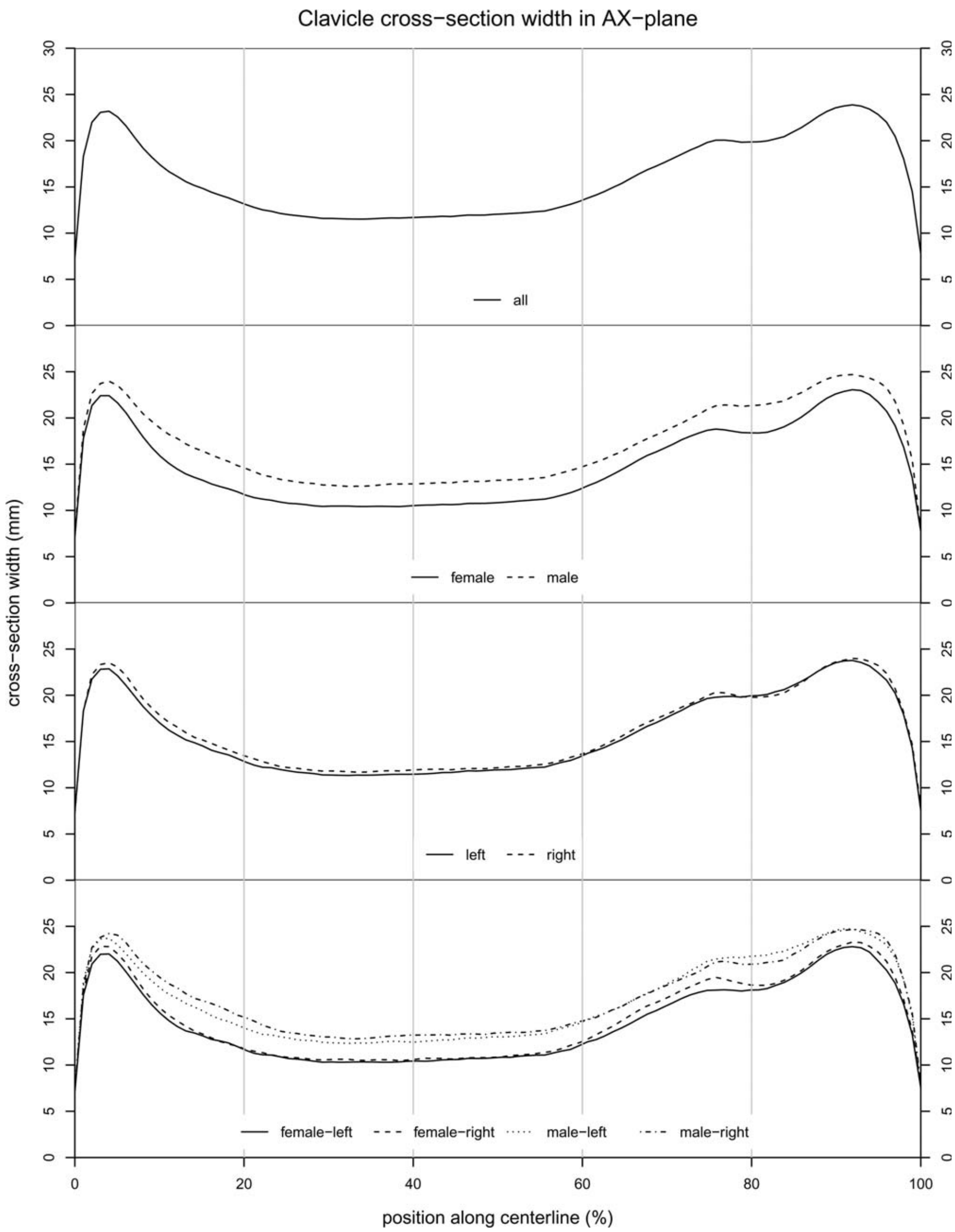

Fig. 7. Mean width as a function of the length, starting at the sternal end in the AX plane.

between the CL and EP was examined. The clavicle cross-section width in the AX and FR plane was measured as the diameter of the cross-section in both planes. The largest diameter at the sternal end and at the acromial end in both planes was evaluated. The smallest diameter of the clavicle in both planes was also measured. The location of these diameters was measured and defined as a percentage of the CL length of the clavicle starting at the sternal end (Fig. 5). The curvature at each cross-section center was measured as the distance to the closest point on the EP and was described as depth. This was performed in the two planes, resulting in an AX curvature and an FR curvature. The depth was described as positive if going anterior and negative if going posterior in the AX plane, and positive if going superior and negative if going inferior in the FR plane. Also, the inflection point (point on a curve at which the convexity or concavity changes sign) in the AX plane was measured.

All the measurements were done in five groups: average, male, female, left, and right. A comparison was made between the male–female group and the left–right group.

Hypothesis testing was performed using the unpaired two-sample Student *t*-test. For the left–right analysis a paired Student *T*-test was used. Results

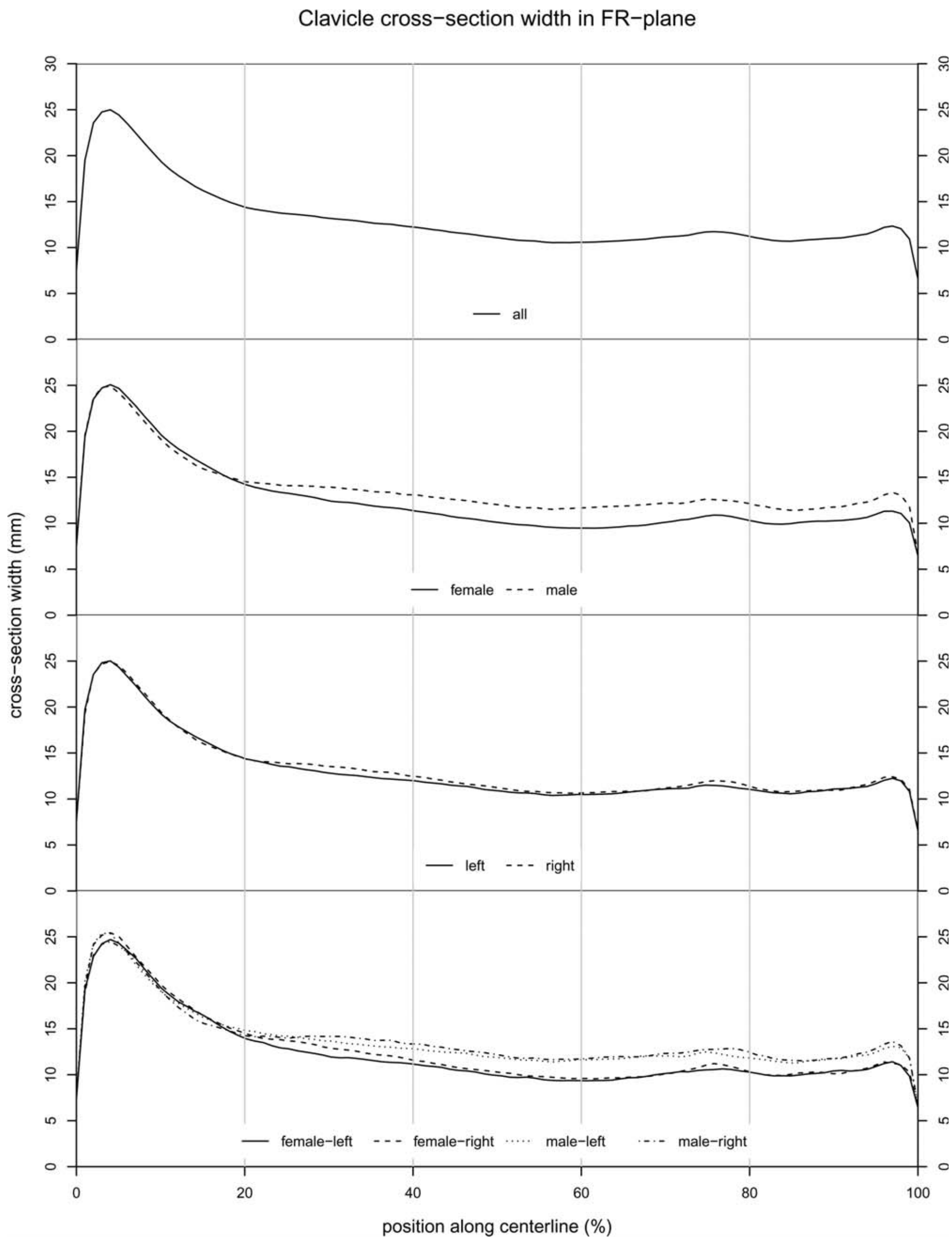

Fig. 8. Mean width as a function of the length, starting at the sternal end in the FR plane.

with a *P*-value less or equal than 0.05 were considered to be significant.

RESULTS

Interclass Correlation

The EP length interobserver difference mean was 0.25 ± 0.37 mm for the first observer and 0.47 ± 0.75 mm for the second observer. The CL length interobserver difference mean was 0.26 ± 0.25 mm for the first observer and 0.29 ± 0.34 mm for the second observer. The intraobserver difference mean was 0.47 ± 0.58 mm for the EP length and 0.42 ± 0.33 mm for the CL length. The two-way Intraclass Correlation (ICC) consistency was 0.9998 for the EP and 0.9996 for the CL length and the standardized error of measurement was 0.15 mm for the EP length and 0.21 mm for the CL length, which can be consider as excellent.

Length Centerline = True Length Clavicle

The mean CL length of the clavicles was 159.0 ± 11.0 mm (139.9–182.5) for the general population

TABLE 2. Thickest Width at the Lateral and Medial End in the AX and FR Plane

	AX plane lateral		FR plane lateral		AX plane medial		FR plane medial	
	Width[a]	Position[b]	Width[a]	Position[b]	Width[a]	Position[b]	Width[a]	Position[b]
All	24.7 ± 3.8	91.4 ± 5.3	13.6 ± 1.7	84.6 ± 14.5	23.8 ± 3.0	4.8 ± 1.4	25.6 ± 3.1	4.9 ± 1.3
Right	24.8 ± 3.7	91.5 ± 5.9	13.9 ± 1.8	83.0 ± 16.2	24.3 ± 3.0	5.0 ± 1.4	25.6 ± 2.9	5.0 ± 1.3
Left	24.7 ± 3.9	91.3 ± 4.7	13.4 ± 1.7	86.2 ± 12.7	23.2 ± 2.8	4.7 ± 1.5	25.5 ± 3.5	4.8 ± 1.3
Female	23.5 ± 3.0[c]	91.9 ± 4.8	12.7 ± 1.3[d]	86.2 ± 13.6	22.8 ± 2.8[c]	4.6 ± 0.9	25.4 ± 3.0	5.0 ± 1.1
Male	25.9 ± 4.1[c]	90.8 ± 5.6	14.6 ± 1.5[d]	83.0 ± 15.4	24.7 ± 2.8[c]	5.0 ± 1.8	25.7 ± 3.7	4.8 ± 1.5

[a]Mean ± SD/mm
[b]Position in % from the sternal end
[c]$P = 0.007$
[d]$P < 0.0001$

(Table 1). The mean CL length of the male clavicles was significantly larger (15.8 mm) than that of the female clavicles ($P < 0.0001$). The mean of the CL length of the left clavicles was 1.8 mm larger than the length of the right clavicles ($P = 0.02$). The mean CL length of the left male clavicle was 1.9 mm larger than the right CL length ($P = 0.09$). Also, the mean CL length of the left female clavicle was 1.3 mm larger than the right CL length ($P = 0.11$).

Length "Endpoints"

The mean EP length of the clavicles was 149.4 ± 10.3 mm (130.7–171.9) for the general population (Table 1). The mean EP length of the male clavicles was significantly larger (12.9 mm) than that of the female clavicles ($P < 0.0001$). Again the mean EP length of the left clavicles was significant larger (1.9 mm) than the length of the right clavicle ($P = 0.015$). The mean EP length of the left male clavicle was significant larger (2.4 mm) than the right EP length ($P = 0.03$). Also, the mean EP length of the left female clavicle was 1.2 mm larger than the right EP length ($P = 0.25$).

CL Length vs EP Length

The mean CL length was statistically significantly ($P < 0.0001$) larger than the mean EP length, 9.6 mm respectively (Table 1) (Fig. 6).

Correlation between the CL and EP length is seen in Figure 6. Parson correlation coefficient is 0.968, which indicates a strong correlation. Straight clavicles situated on the line, curved clavicles have a longer CL length and therefore placed at the upper side of the graph.

Width AX–FR Plane

The thickest mean width at the sternal end and at the acromial end was located in the AX and FR plane (Figs. 7 and 8) (Tables 2 and 3) at the same position (Table 2). At the lateral end, the thickest mean width was significantly smaller in female than in male clavicles in the FR plane ($P < 0.0001$) and in the AX plane ($P = 0.007$). In contrast, at the medial end, the mean thickest width was significantly smaller in female than in male clavicles in the AX plane ($P = 0.007$) but not in the FR plane ($P = 0.7$).

In the FR plane medially, the thickest width in the female right clavicle is larger than the female left one, however in the male left clavicle this width is larger than in the male right one. These results were also seen in the AX plane laterally. In the AX plane medially and in the FR plane laterally the thickest width in the right clavicle is larger than the left one (both sexes). No significant difference between genders was found when measuring the location of the thickest width in the FR and AX plane, nor was there a significant difference between the sides when measuring the thickest width and its locations in the AX and FR plane (Figs. 7 and 8).

The smallest mean width was 10.9 ± 1.5 mm in the AX plane and was located at 38.4 ± 9.7% of length. In the FR plane, the smallest mean diameter was 9.5 ± 1.3 mm at the 71.5 ± 13.7% (Table 3). The smallest mean diameter was significantly thinner in female than in male specimens ($P < 0.0001$). No significant difference between the sides was found when measuring the smallest width and its locations in the AX and FR plane.

TABLE 3. Smallest Width at the Lateral and Medial End in the AX and FR Plane

	AX plane		FR plane	
	Width[a]	Position[b]	Width[a]	Position[b]
All	10.9 ± 1.5	38.4 ± 9.7	9.5 ± 1.3	71.5 ± 13.7
Right	10.9 ± 1.6	39.5 ± 10.0	9.4 ± 1.3	69.4 ± 13.3
Left	10.8 ± 1.5	37.4 ± 9.5	9.5 ± 1.3	73.6 ± 14.0
Female	9.8 ± 1.0[c]	39.9 ± 10.3	8.7 ± 0.9[c]	71.1 ± 12.6
Male	11.9 ± 1.3[c]	37.0 ± 9.0	10.2 ± 1.2[c]	71.9 ± 14.8

[a]Mean ± SD/mm
[b]Position in % from the sternal end
[c]$P < 0.0001$

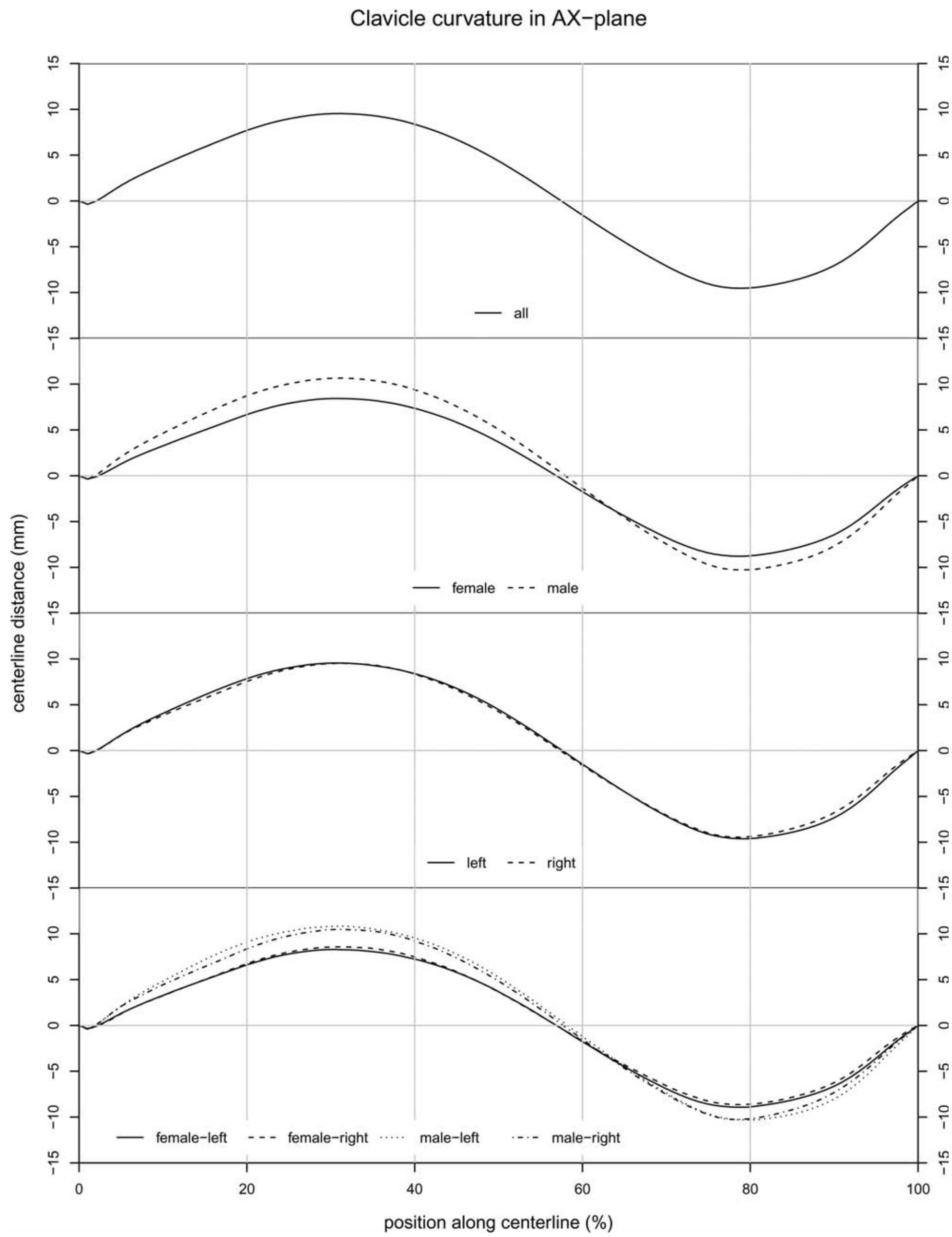

Fig. 9. Mean curvature as a function of the length, starting at the sternal end in the AX plane.

Curvature AX–FR plane

In the AX plane, the clavicle showed an S-shaped configuration with a short length of curvature laterally and a longer length medially (Figs. 9 and 10) (Table 4). The mean medial and lateral depth of the curvature was 9.7 ± 2.8 mm and −9.8 ± 3.0 mm, respectively. In the FR plane, a convex curvature was present and the largest depth of the curvature was located at 63.7 ± 11.5% and measured 6.6 ± 3.2 mm. The inflection point in the AX plane was located at 60.9 ± 5.7%.

In the AX plane, the mean depth of the lateral ($P = 0.05$) and medial ($P = 0.007$) curvature was significantly greater in male than in female specimens, but there was no significant difference when the location of the deepest points was evaluated. In contrast, in the FR plane, the mean depth and location of the curvature was not significantly different between genders. In the AX plane, female left medial curvature is more pronounced than female right curvature and male right medial curvature is more pronounced than the male left one. The exact opposite results are seen in the lateral curvature (Fig. 9). In the FR plane, both the male left

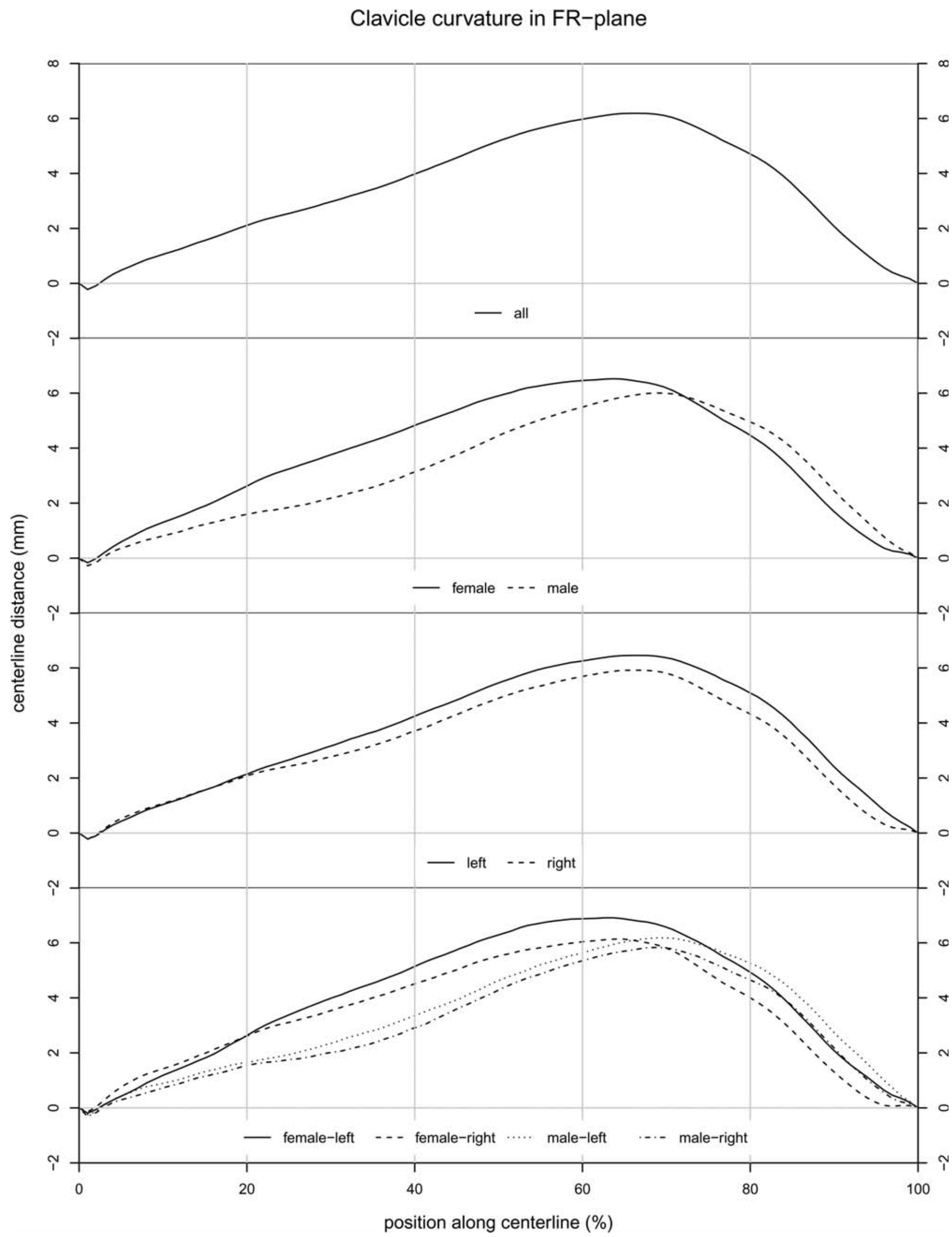

Fig. 10. Mean curvature as a function of the length, starting at the sternal end in the FR plane.

and the female left curvatures are more pronounced compared to the right ones (Fig. 10). No significant difference was found between the two sides concerning the curvature in the AX and FR plane. There was no significant difference between genders and sides when the location of the inflection point was evaluated.

DISCUSSION

Anatomical research on the human clavicle has been a long and difficult endeavor. This is mainly due to the complexity of the clavicle and the lack of a good, reproducible and fast measurement technique. The importance of clavicular morphology has increased greatly in recent decades. Anatomy scholars try to unravel whether gender-specific morphology and left–right differences can be identified (Mays et al., 1999; Danforth and Thompson, 2008). Forensic pathologists study the morphology to increase the existing knowledge and to identify new elements which would help forensic science, such as the ability to characterize a person with the use of only the clavicle. Orthopedic surgeons, who use this knowledge to treat and cure fractures and other

TABLE 4. Deepest Curvature Position and Depth in the AX and FR Plane and the Inflection Point in the AX Plane

	FR		AX				
	Depth[a]	Position[b]	Med depth[a]	Med position[b]	Inflexion position[b]	Lat depth[a]	Lat position[b]
All	6.6 ± 3.2	63.7 ± 11.5	9.7 ± 2.8	31.6 ± 3.4	60.9 ± 5.7	−9.8 ± 3.0	79.4 ± 3.3
Right	6.4 ± 3.6	62.5 ± 14.7	9.7 ± 2.9	32.1 ± 2.9	60.8 ± 6.0	−9.7 ± 2.6	79.1 ± 2.8
Left	6.8 ± 2.8	62.5 ± 7.0	9.7 ± 2.7	31.1 ± 3.7	60.4 ± 5.5	−9.9 ± 3.4	79.7 ± 3.8
Female	6.8 ± 3.7	61.4 ± 9.8	8.6 ± 2.3[c]	31.7 ± 3.6	61.1 ± 5.3	−9.1 ± 2.5[d]	79.3 ± 3.8
Male	6.4 ± 2.6	66.0 ± 12.7	10.8 ± 2.8[c]	31.4 ± 3.2	60.0 ± 6.1	−10.5 ± 3.3[d]	79.5 ± 2.8

[a]Mean ± SD/mm
[b]Position in % from the sternal end
[c]$P = 0.007$
[d]$P = 0.05$

bone disorders, have taken the greatest interest in the morphology, specifically in the last few years, with the increased use of anatomical osteosynthesis hardware (Huang et al., 2007; Partal et al., 2010). It must be noted that while intramedullary and plate fixation are accepted and widely used methods of treatment for fractures of the clavicle, current clavicular implants overlook the variations in geometry of the bone (Daruwalla et al., 2010b).

To our knowledge, our study represents the largest population of fresh frozen cadaver clavicles that were scanned, computed, and analyzed. Furthermore, our correspondence technique provided us with a single global coordinate system in which all clavicles were aligned and measured. The coordinate system, together with the AX and FR planes, was derived from the population average CL. Taking into account information of all the clavicles in the construction of the coordinate system increases the robustness and consistency of the measurements. The measurement process was also highly automated, requiring only two points to be selected for each clavicle. Extending it to larger populations of clavicles requires minimal effort. Also, the cross-sections in our measurement technique were perpendicular to the CL, providing a more physiological evaluation of the width and the curvature of the clavicle compared to axis-aligned cross-sections.

Length

Our technique enabled us to not only measure the true length of the clavicle (CL), but also the endpoint length, which was compared with the literature data.

Hillen et al. (2012) showed significant orientation changes with clavicle shortening. These changes were progressive with the amount of shortening. The scapula was changed into a more "winging" position, the sternoclavicular and acromiclavicular joint was more protracted and axially rotated. Restoration of clavicular length is considered a determining factor for the optimal restoration of function after a clavicle fracture (Hill et al., 1997; Andermahr et al., 2006). Until now, the true length of the clavicle has not yet been described. In all studies, the length of the clavicle was measured as the length between two extremity points (end-point length) and not as the true length (Parsons, 1916; Mays et al., 1999; Andermahr et al., 2007; Daruwalla et al., 2010a). The EP length is an underestimation of the true length of the clavicle.

We defined the true length of the clavicle as the length of the line connecting the center of the cross-sections of the clavicle. As already mentioned, a significant difference was found between CL length and EP length. The mean true length was 9.6 mm larger than the mean EP length.

The average EP length in our population was 149.9 mm, which is consistent with previous findings by Andermahr et al. (2007) (Table 1). Huang et al. (2007) and Parsons (1916) reported different lengths in their population. Two reasons may account for these differences. A first explanation may be the variation in demographics and evolution (Garcia and Quintana-Domeque, 2007). Our study was based on a Caucasian population from the 20th century. This corresponds with the population described by Andermahr et al. (2007). Parsons (1916) and Huang et al. (2007) used a collection of bones from the previous century and another geographic location. Second, the definition and determination of length also vary between studies.

As was reported in previous literature (Parsons, 1916; Andermahr et al., 2007; Haung et al., 2007; Daruwalla et al., 2010a), the male clavicle is longer than the female one. We found significant differences in length for both the EP and CL length (12.9 and 15.8 mm, respectively).

As described in literature (Parsons, 1916; Mays et al., 1999; Andermahr et al., 2007; Auerbach and Raxter, 2008; Danforth and Thompson, 2008; Daruwalla et al., 2010a), we found a difference between sides. This was found significant for both the EP and the CL length (1.8 and 1.9 mm, respectively). Most authors found the mean left clavicle to be larger than the right one, but only two authors reported a significant difference (Mays et al., 1999; Auerbach and Raxter, 2008). The other authors either did not perform this measurement or did not find a significant difference. When evaluating the length in both genders there was only a statistical difference in the male EP length.

On the basis of our data, a new set of anatomical plates can be developed that take into account clavicular center length, though allowing for correct anatomical reconstruction and fit, which may be associated with better clinical result. In regard to curvature and other morphometric elements, the use of the CL can help to restore the correct length and alignment of the fractured clavicle.

Width

Anatomically, the lungs and vascular structures are in close proximity to the clavicle. Placing a screw longer than required can damage these structures. Knowing the thickness in each parts of the clavicle can be helpful to assess the screw length when anteroposterior or superoinferior plate and screw fixation is used.

Width was measured in two planes, FR and AX. Several different measurement protocols have been described. Mays et al. (1999) and Danforth et al. (2008) measured the width only at the midshaft. Andermahr et al. (2007) measured the diameter in three locations and Parsons in five locations. Daruwalla et al. (2010a) measured the width at 10% intervals of the length. We were the first to measure the diameter at 100 different cross-sections. In this way, a graph could be constructed to describe the width along the clavicle. The thickest width both in the AX as in the FR plane is located at the same position. Females have a significantly lees wide clavicle than males, but only in the FR plane laterally and in the AX plane medially. In females the thinnest width is again smaller compared to male clavicles in both planes. The location of the thinnest width in males is significantly more lateral than in females. There were no significant differences between sides regarding the width of the clavicle.

Mays et al. (1999) and Auerbach and Raxter (2008) have used the diameter at the midshaft to study the asymmetry and handedness of the clavicle. With our results the width can be measured in each point and directly applied for the further research of asymmetry.

Curvature

The curvature of the clavicle is extremely difficult to describe and different methods have been used to this end. Parsons (1916) was the first to measure the curvature with the description of angles but his method had a low interobserver reliability. Several other authors measured the depth of the curvature by measuring the distance between the outer surface and the EP line (Mays et al., 1999; Andermahr et al., 2007; Huang et al., 2007; Daruwalla et al., 2010a). In the present study, the curvature was measured as the depth between the CL and the EP line in the FR and AX plane at all cross-sections. In our opinion, this provides a more physiological representation of the curvature medially, laterally, and inferiorly in the two planes. As far as we know, this is the first representation of the curvature in the frontal plane in this configuration.

In the FR plane, the clavicle was found to have a superior curvature with the largest depth at 63.7% of the clavicle. This is more medial than what Huang et al. (2007) described, namely a mean location at 75% of the clavicle. Specimens from Caucasians donors also had a bow apex that was significantly more medial compared with those from donors of African ancestry and a trend toward a larger bow magnitude that was not statistically significant (Huang et al., 2007). Our population consisted only of white Caucasian specimens. We found a significant difference between male and female clavicles in both curvatures. This was also the first time the location of the inflection point was described. The location was found not to change between sides and genders. The findings relating to the curvature in both planes and the location of the inflection point in both genders can be important in the design of new anatomical clavicular plates. A clear S-shaped curvature is present in the AX plane and has already been applied in the current anatomical clavicular plate. As previously reported by Voisin (2006, 2008) and Olivier (1951), we observed a second inferior curvature in the FR plane, which is not compensated for in the current commercially available plates. Altamimi and McKee (2008) have advocated to fit the plate perfectly on the clavicle to avoid soft tissue irritation and patient dissatisfaction, we believe that the inferior curvature is one of the missing pieces in achieving a perfect fit.

Limitations

Our study has some limitations. Firstly, our population consisted of only 64 samples but was optimally balanced (34 right vs. 34 left).

Secondly, because the body length of the cadavers was not known, the ratio between body length and clavicular length could not be evaluated. Also, data on the handedness in the samples were unavailable. Such information could have been useful for the left–right analysis.

CONCLUSION

The goal of this study was to examine the 3D anatomical characteristics and variations of the human clavicle, using a fully automated 3D analysis. This technique allowed the true length of the clavicle to be measured for the first time. Also, the curvature in the AX and FR plane was described more accurately. A significant difference between genders in length, width, and curvature and the length between the sides was found.

ACKNOWLEDGMENTS

This work was partially financially supported by iMinds (Interdisciplinary Institute for Technology, a research institute founded by the Flemish Government). Authors thank Iris Wojtowicz, Department of Orthopedic Surgery and Traumatology, Ghent University Hospital, for her linguistic support and our colleagues at the anatomy lab, Department of Anatomy and Embryology, Antwerp University, for their help with the preparation of the clavicles. Last, authors would like to thank the donors and their families.

REFERENCES

Altamimi SA, McKee MD. 2008. Nonoperative treatment compare with plate fixation of displaced midshaft clavicular fractures: Surgical technique. J Bone Joint Surg Am 90:1–8.

Althausen PL, Shannon S, Lu M, O'Mara TJ, Bray TJ. 2013. Clinical and financial comparison of operative and nonoperative treatment of displaced clavicle fractures. J Shoulder Elbow Surg 22:608–611.
Andermahr J, Jubel A, Elsner A, Prokop A, Tsikaras P, Jupiter J, Koebke J. 2006. Malunion of the clavicle causes significant glenoid malposition: A quantitative anatomic investigation. Surg Radiol Anat 28:447–456.
Andermahr J, Jubel A, Elsner A, Johann J, Prokop A, Rehm KE, Koebke J. 2007. Anatomy of the clavicle and the intramedullary nailing of midclavicular fractures. Clin Anat 20:48–56.
Auerbach BM, Raxter MH. 2008. Patterns of clavicular bilateral asymmetry in relation to the humerus: Variation among humans. J Hum Evol 54:663–674.
Canadian Orthopaedic Trauma Society. 2007. Nonoperative treatment compared with plate fixation of displaced midshaft clavicular fractures. a multicenter, randomized clinical trial. J Bone Joint Surg Am 89:1–10.
Danforth ME, Thompson A. 2008. An evaluation of determination of handedness using standard osteological measurements. J Forensic Sci 53:777–781.
Daruwalla ZJ, Courtis P, Fitzpatrick C, Fitzpatrick D, Mullett H. 2010a. Anatomic variation of the clavicle: A novel three-dimensional study. Clin Anat 23:199–209.
Daruwalla ZJ, Courtis P, Fitzpatrick C, Fitzpatrick D, Mullett H. 2010b. An application of principal component analysis to the clavicle and clavicle fixation devices. J Orthop Surg Res 5:21.
Egol KA, Koval KJ, Zuckerman JD. 2010. Handbook of fractures. 4th Ed. Philadelphia: Lippincott, Williams & Wilkins. p 141–149. ISBN: 978–1605477602.
Fitzpatrick C, FitzPatrick D, Auger D, Lee J. 2007. A tibial-based coordinate system for three-dimensional data. Knee 14:133–137.
Garcia J, Quintana-Domeque C. 2007. The evolution of adult height in Europe: A brief note. Econ Hum Biol 5:340–349.
Hill JM, McGuire MH, Crosby LA. 1997. Closed treatment of displaced middle-third fractures of the clavicle gives poor results. J Bone Joint Surg Br 79:537–539.
Hillen RJ, Burger BJ, Pöll RG, van Dijk CN, Veeger DH. 2012. The effect of experimental shortening of the clavicle on shoulder kinematics. Clin Biomech (Bristol, Avon) 27:777–781.
Huang JI, Toogood P, Chen MR, Wilber JH, Cooperman DR. 2007. Clavicular anatomy and the applicability of precontoured plates. J Bone Joint Surg Am 89:2260–2265.
Huysmans T, Sijbers J, Verdonk B. 2005. Parameterization of tubular surfaces on the cylinder. J Winter School Comput Graph 13: 97–104. (ISSN No. 1213–6964).
Huysmans T, Sijbers J, Verdonk B. 2010. Automatic construction of correspondences for tubular surfaces. IEEE Trans Pattern Anal Mach Intell 32:636–651.
Jit I, Singh S. 1996. The sexing of the adult clavicles. Indian J Med Res 54:551–571.
Lazarus M, Seon C. 2006. In: Bucholz R, Heckman J, Court-Brown C, editors. Chapter 32: Fractures of the Clavicle. 6th Ed. Philidephia: Lippincott Williams Wilkins. p 1212–1213. (ISBN No. 978–0781746366).
Lorensen WE, Cline HE. 1987. Marching cubes: A high resolution 3D surface construction algorithm. SIGGRAPH Comput Graph 21: 163–169.
Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. 2009. Motion of the shoulder complex during multiplanar humeral elevation. J Bone Joint Surg Am 91:378–389.
Mays S, Steele J, Ford M. 1999. Directional asymmetry in the human clavicle. Int J Osteoarchaeol 9:18–28.
McCormick WF, Stewart JH, Greene H. 1991. Sexing of human clavicles using length and circumference measurements. Am J Forensic Med Pathol 12:175–181.
McKee MD, Pedersen EM, Jones C, Stephen DJ, Kreder HJ, Schemitsch EH. 2006. Deficits following nonoperative treatment of displaced midshaft clavicular fractures. J Bone Joint Surg Am 88:35–40.
Nowak J, Holgersson M, Larsson S. 2004. Can we predict long-term sequelae after fractures of the clavicle based on initial finding? A prospective study with nine to ten years of follow-up. J shoulder Elbow Surg 13:479–486.
Olivier G. (1951–1956). Anthropologie de la clavicule. Bull Mem Soc Anthropolo Paris Série 10:47–56 (VII), 67–99 (I), 144–153 (VIII), 269–279 (IV), 282–289 (IX), 290–302 (X), 553–561 (V).
Parsons FG. 1916. On the proportions and characteristics of the modern english clavicle. J Anat 51(Part 1):71–93.
Partal G, Meyers KN, Sama N, Pagenkopf E, Lewis PB, Goldman A, Wright TM, Helfet DL. 2010. Superior versus anteroinferior plating of the clavicle revisited: A mechanical study. J Orthop Trauma 24:420–425.
Pearson K. 1901. On lines and planes of closest fit to systems of points in space. Philos Mag 2:559–572.
VanBeek C, Boselli KJ, Cadet ER, Ahmad CS, Levine WN. 2011. Precontoured plating of clavicle fractures: Decreased hardware-related complications? Clin Orthop Relat Res 469:3337–3343.
Voisin JL. 2006. Clavicle, a neglected bone: Morphology and relation to arm movements and shoulder architecture in primates. Anat Rec A Discov Mol Cell Evol Biol 288:944–953.
Voisin JL. 2008. The Omo I hominin clavicle: Archaic or modern? J Hum Evol 55:438–443.