CraMs, an application for craniometric analysis using 3D skull models

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Abstract

Craniometric analysis plays an important role in anthropology studies and forensics. This paper presents CraMs, an application using a new craniometric approach based on 3D models of the skull. The main objective is to obtain, through a process supervised by anthropologists, the main points of interest used to compute craniometric measurements. The novelty is that the process is aided by the application that analyses the skull geometry and automatically provides points of interest. Other points are semi-automatically detected: user provide an initial guess that might be refined based on the curvature of the skull. The application also allows the manual selection of any other points of interest. Moreover, results comparing measurements obtained with CraMs and traditional craniometry methods on eight skulls suggest that the application provides comparable craniometric measurements and lower inter-observer variability. This approach also presents other advantages such as an easier access to skulls with no risk of bone damage and the possibility to define new measurements based on morphology or other characteristics of the skulls, which are not possible using traditional methods.

Keywords

Craniometry, Morphology, 3D Models, Feature Detection.

1. INTRODUCTION

In anthropological analysis, the skull plays an extremely important role since it is one of the most informative bone pieces. Through its analysis, sex, ancestry, age at death, and variations among populations can be assessed [Oxnard74]. Furthermore, the skull is the bone structure base of the face, allowing reconstruction of the individual's face, a relevant aspect in the analysis of historically relevant skeletons (such as kings) and of great importance in identifying victims in forensic cases.

In traditional craniometry anthropologists perform direct measurements on the skulls, a technique suffering from several drawbacks: poor repeatability (intra- and inter-observer), impossibility to be performed on fragments, inadequacy to describe complex shapes, and the need for actual contact with the skulls, which may damage the bones since these are very delicate structures [Stephens00]. Therefore, the development of robust methods to support craniometric studies, even using fragmented skulls, is of the utmost importance. Considering application scenarios such as forensic practice, where the results of anthropological analysis can serve as evidence in court, the robustness and reliability of the gathered results is crucial.

2. CRAMS

In this context, a software application called CraMs (Craniometric Measurements) was developed to perform craniometric analysis using 3D replicas of skulls acquired with a 3D scanning system. The idea came from discussions with two anthropologists (CC and MTF) who were interested in performing the analysis of 11 specimens discovered outside the modern and medieval walls of the city of Lagos, in Portugal [Neves11]. The anthropologists, involved from the very beginning, were particularly concerned in avoiding degradation of the specimens (dating from between the 15th and 17th centuries) and in developing tools to reduce the poor repeatability of analysis performed by traditional methods. It was clear, from the onset, that the application should not be fully automatic but rather an auxiliary for the experts, who see the software application as a tool to ease and improve their analysis.

CraMs provides measurements defined between characteristic points (see Figure 1), as in traditional craniometry. At this stage, eight craniometric points can be detected automatically after a skull alignment procedure. The application can also assist anthropologists in the identification of fifteen additional points of interest by using their input as an initial estimation. Automation of parts of the process yields a more systematic approach to the craniometric analysis and preliminary results show evidence that it reduces intra- and inter-observer variability.

3. 3D MODEL ACQUISITION

The acquisition of the 3D skulls is performed with a Breuckmann smartSCAN Scanner[1]. A team of specialists including a 3D technician (HS) and an anthropologist (CC) were involved in the process. A typical final 3D model is composed of 1.5 million points with an error below 30µm. More information about the skull acquisition procedure can be found in [Dias13].

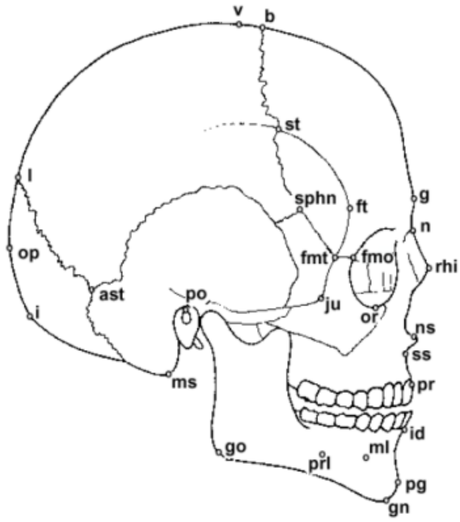

Figure 1: Lateral view of a skull with some craniometric points annotated (adapted from [Pereira79]).

4. APPLICATION DESIGN

The application CraMs (Craniometric Measurements) was developed in C++ using VTK for visualization and 3D processing, and Qt for the user interface. The application provides skull alignment features and several automatic and semi-automatic methods for the detection of craniometric points. It also allows the anthropologist to manually select additional points of interest.

4.1 Skull alignment

The acquisition process does not guarantee any kind of alignment of the models. However, alignment with a specific set of planes is essential since it provides important information about the location of points of interest. Furthermore, many measurements are related to maximal distances in a given axis and are easy to compute once the model is aligned.

CraMs features two methods to align the skull, manually and semi-automatically. The manual method requires the user to pick seven reference points which allow a computation of the skull orientation. The semi-automatic method uses a pre-aligned reference skull and the well-known Iterative Closest Point (ICP) [Besl92] algorithm to compute the rigid body transformation which minimizes the Euclidean distance between the two point clouds. However, since ICP might fall into misaligned skulls (corresponding to local minima), the user can rotate the skull under study in all three axis to provide a good initial guess when the correct transformation is not computed automatically. The alignment is used to define three reference planes (Sagittal, Coronal and Frankfurt) used by the anthropologists (Figure 2).

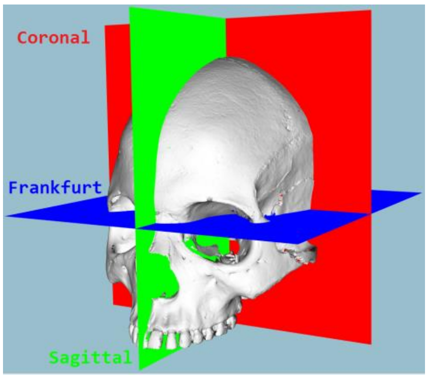

Figure 2: skull aligned with standard orthogonal craniometric reference planes: sagittal, coronal and Frankfurt (axial).

4.2 Craniometric point detection and measures

Based on the aligned skulls, it is possible to automatically detect multiple points using maximum/minimum criteria and surface curvature analysis. These points allow the computation of several craniometric measures. Interactive methods are used to help detect additional points allowing the computation of other relevant measures.

4.2.1 Automatic and semi-automatic points detection

Based on the aligned skulls, it is possible to automatically identify eight points of interest: left and right *Zygion(zy)*, left and right *Eurion(eu)*, *Basion(ba)*, *Bregma(b)*, *Vertex(v)* and *Opsitokranion(op)* (see Figure 3). These points correspond to minima/maxima for a given axis on a certain region of the skull. Other techniques that might help to detect additional points of interest were investigated. After presenting the anthropologists with visual mappings of different surface properties onto the models' surface (e.g., normal, surface principal and Gaussian curvatures), Gaussian curvature [Colombo06] seemed promising to detect peaks and valleys corresponding to features of interest. A semi-automatic selection method was devised. The expert is asked for a rough estimate of the point of interest, in a convex or concave region. Then, the Gaussian curvature is used, in its neighbourhood, to determine the highest or lowest point in the region which is used as the craniometric feature point of interest. This procedure allows the detection of ten additional points: *Nasion(n)*, *Glabella(g)*, *Prosthion(pr)*, right and left *Ectomalar(ekm)*, right and left *Auricular(po)*, *Nasoespinal(ns)* and right and left *Frontomalar-Temporalle(fmt)*. It is possible to obtain ten measures based on the above mentioned points.

[1]http://aicon3d.com/

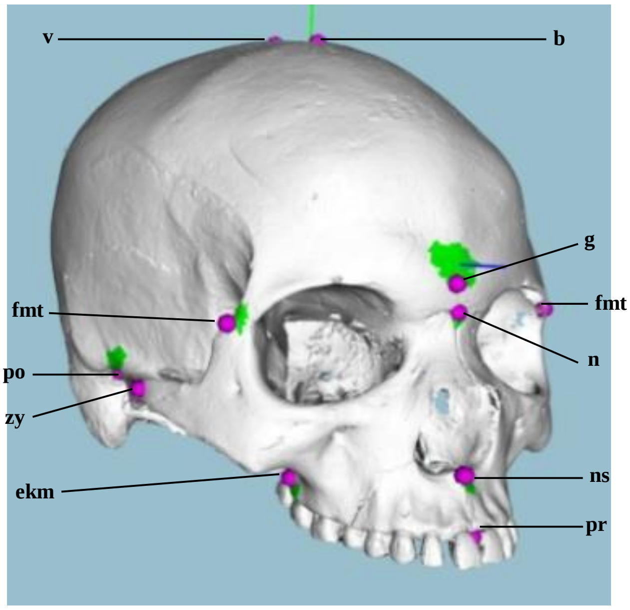

Figure 3: Standard craniometrics points determined using the CraMs application (in green, neighbourhood for curvature analysis)

4.2.2 Measures using projection

Some measures required by the anthropologists need to be obtained by computing the distance from a point to a specific plane. This has also been implemented in CraMs, as depicted in Figure 4. The user interactively selects a point to define a new plane parallel to a reference plane. Note that this is, as remarked by the anthropologists, a very difficult and error prone measurement to perform using the traditional method. Using this technique, two additional measures can be obtained: the maxilla-alveolar length (MAL) and the height of the mastoid process (MDH). Figure 4 presents the traditional and assisted methods (with CraMs) to obtain MDH defined as the distance between the Frankfurt plane and the nadir point of the Mastoid process

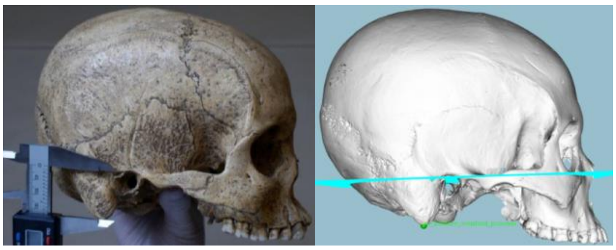

Figure 4: Measure MDH obtained with traditional methods (left) [Coelho12] and with the CraMs application (right).

4.2.3 Orbit detection

Anthropologists were also very interested in the analysis of notable structures in the skull. Our first focus was on the orbits (bone cavities in which the eyeballs reside) with the goal of retrieving two additional measures (orbital breadth- OBB and orbital height-OBH). The rationale was to detect the sharp edge and use it to extract the orbit's contour. For the identification of these points, we used the method proposed by Vieira and Shimada [Vieira05].

Initially, (1) is applied to each vertex x_i in the model to determine the neighbourhood size by calculating the average length of the edges connected to it.

$$l_{avg,i} = \frac{1}{N} \sum_{j \in N(i)} \|x_j - x_i\| \qquad (1)$$

Where N(i) are the vertices under analysis in the neighbourhood of vertex x_i. A vertex x_i is considered as being a part of a sharp edge if it satisfies expression (2).

$$\frac{1}{|k_i|} < \lambda \cdot l_{avg,i} \qquad (2)$$

Here $\frac{1}{|k_i|}$ is the minimum curvature radius for vertex x_i and k_i is the curvature value for that vertex. The value of λ should be adjusted according to the resolution of the model and the precision required for the results. It was selected empirically to fit the complexity of the available skulls.

The final algorithm is semi-automatic: a number of reference points (between 2 to 30) are picked sequentially by the user to guide the detection algorithm, which defines a structure section (composed by sharp edges) between two reference points at a time. These sections can be deleted and redefined by the user. The detection process is finalized by closing the structure (connecting the first and last reference point). Figure 5 shows two examples of detected structures using three and seven reference points (represented in green).

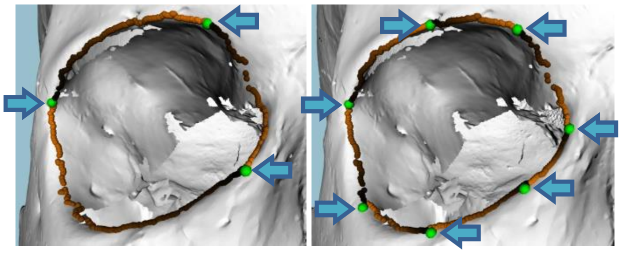

Figure 5: Orbit structure detected using three (left) and seven (right) user-defined reference points.

After defining the structure, the plane that best fits the whole set of points is computed and the points are projected in 2D. Finally, the 2D ellipse that best fits the whole set of points is computed (see Figure 6). The blue spheres are the projected points; the red spheres are the ellipse points. The two line segments represent the ellipse axes used to define the OBB and OBH measures. These two measures are especially difficult to obtain using traditional methods since their definition implies that they have to be perpendicular to each other (see Figure 7).

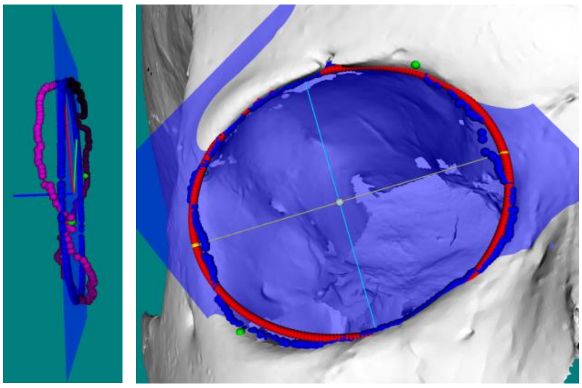

Figure 6: 2D fitting of orbit points to a planar ellipse and adjusted 2D ellipse inserted within the original orbit in the skull.

Figure 7: Demonstration of how the measures OBB (left) and OBH (right) are obtained using traditional methods [Coelho12].

4.2.4 Manual selection

The anthropologist can manually select any additional points and perform other measures deemed important for a complete analysis and classification of the skulls with CraMs. This feature, although simple, supports three important aspects: 1) anthropologists are able to perform important measures, that are still not supported by CraMs, which would, otherwise, force them to analyse the real skull to complete the classification; 2) the skulls can be freely explored, by the anthropologists, not necessarily using the standard measures, to test research ideas; 3) allows us to gather additional insight and knowledge on how to extend and improve the number of points that can be detected automatically.

5. RESULTS AND DISCUSSION

The 24 craniometric measures supported by CraMs were measured by two anthropologists using the application (App) and traditional craniometry (Antr). As representative examples, the measures obtained for two specimens (#25 and #67), of the eight used on this study, are shown in Table 1. A few measurements could not be performed due to bone fragmentations.

The difference in percentage of the total length of each measure taken by both specialists, using CraMs and Traditional methods, were calculated for each measure on the 8 skulls under study. In Figure 8, the averages are represented as squares, the maximum and minimum values are represented as the limits of the vertical lines. These graphics suggest that, for automatic measures taken with CraMs, the average differences and variations decrease in comparison with the ones taken using traditional methods; it seems that semi-automatic measures also show lower variations using CraMs. Manual measures show a larger discrepancy due to the fact that they solely depend on points the user picked with no aid from the application

Table 1: Measures (mm) obtained using CraMs (App) and traditional methods (Antr) in two specimens.

		Skull #25				Skull #67			
		User #1		User #2		User #1		User #2	
		App	Antr	App	Antr	App	Antr	App	Antr
Automatic	1-ZYB	136,7	136	136,7	137	126,5	126	126,5	126
	2-BBH	142,7	142	142,7	143	131	131	131	130
	3-XCB	135	131	135	131	131,5	122	131,5	126
Semi-Automatic	4-GOL	182,1	181	182,1	181	182	182	182	173
	5-BNL	105,3	106	105,3	107	104,6	104	104,6	105
	6-FRC	116,6	114	116,6	115	109,6	107	109,6	108
	7-BPL	102,8	103	102,8	104	100	94	100,7	102
	8-UFHT	64,6	62	64,8	64	63,4	64	65,6	66
	9-MAB	65,3	66	65,7	65	60,1	61	59,1	61
	10-AUB	116,9	110	114,6	108	110,4	107	107,7	107
	11-NLH	48,5	47	48,5	46	49,6	49	49,2	49
	12-UFBR	106,7	106	106,7	109	105,2	106	105,3	108
	13-PAC	115,3	115	114,7	116	105,5	106	105,9	105
	14-FOL	40	39	40,8	38	33,3	32	33,6	32
	15-MAL	54,3	56	53	58	54	57	53,6	59
	16-MDH	31,5	31	28,8	32	25,8	27	23,5	25
	17-OBB	44,1	47	42,6	43	46,5	43	46,6	42
	18-OBH	35,3	35	34,9	33	33,8	34	34,2	32
Manual	19-WFB	99,7	101	98,5	101	93,6	96	92,7	95
	20-NLB	27,6	28	28,8	27	26,4	26	27,2	25
	21-EKB	102,4	100	98,9	100	100,8	99	100,5	98
	22-DKB	-	-	-	-	-	27	-	26
	23-OCC	93,6	94	93,5	96	96,7	97	96,3	97
	24-FOB	28,9	29	31,7	29	31,6	30	33,4	30

To obtain an overall quantification of the precision attained using CraMs and how it compares to the traditional measuring methods, the precision index TEM (Technical Error of Measurements), a common way to express the error margin in anthropometry [Perini05], was computed . The TEM value is calculated by applying expression (3) followed by expression (4).

$$Absolute\ TEM = \sqrt{\frac{\sum d_i^2}{2n}} \qquad (3)$$

$$Relative\ TEM = \frac{\text{Absolute}\ TEM}{VAV} * 100 \qquad (4)$$

In which d_i is the deviation on measure i and n the number of measures. Relative TEM is the technical error expressed in percentage and VAV is the average value (average between all the observations, for each measure). TEM values may vary in a scale of 0 to 100%. Typically, a value above 10% means the measurements are not acceptable corresponding to a significant difference in inter observer measurements. Analysing the TEM values (Table 2)**Error! Reference source not found.** for CraMs (App) suggests that the more automated the process of selection is the better the results are. Through the comparison of the TEM, it is clear that the application has potential to be more reliable than the traditional methods for taking measures in terms of repeatability.

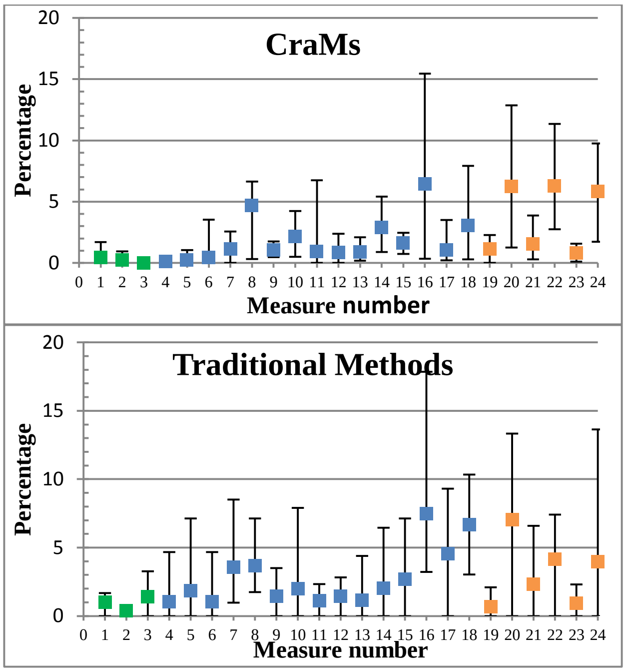

Figure 8: Difference percentages for each measure taken on the eight specimens using the application (top) and traditional methods (1-3 manual (green) , 4-18 semi-automatic (blue). 19-24 manual (orange)).

Table 2: Relative TEM values obtained for the three types of measure using both methods on eight specimens.

Type	App (%)	Antr (%)	Number of Measures
Automatic	0,30	0,88	16 (in 24)
Semi-Auto.	1,39	2,35	109 (in 120)
Manual	1,74	1,99	41 (in 48)

It is important to mention that, with CraMs, measures MAL and MDH were obtained using projection planes and the measures OBB and OBH were obtained through the orbit detection method. These values showed a decrease in error between observers when compared to the values obtained with traditional methods.

6. CONCLUSIONS AND FUTURE WORK

To the best of our knowledge, CraMs is the first tool proposed for supporting anthropologists in craniometric analysis. Its approach, based on 3D models of the skulls, provides an innovative way to accomplish a set of tasks that, otherwise, would be very difficult to carry out, and could potentially result in degradation of ancient specimens. Using CraMs, it is possible to obtain 24 commonly used craniometric measures, and the results we obtained, based on eight skulls, clearly suggest an error reduction when using the application. While working with anthropologists, we managed to foster a dialog leading us to methods that were not only technically feasible, but also made sense to the anthropologists. One good example of the positive outcomes deriving from this dialog is the orbit detection method, which produced interesting results.

Although already providing a considerable set of useful features, CraMs is far from being complete. The next step will be to further improve the presented computational methods, making them more accurate and automated, and to test them in a larger number of skulls, including different population origins and different chronologies. Exploring new measurement methods and the detection of other morphological structures is also a future goal. Finally, the most ambitious goal is the alignment and reconstruction of fragmented skulls. Besides being an innovation, it would be a great asset in anthropological practice where skull fragmentation is frequent, which hinders the craniometric analysis.

7. ACKNOWLEDGEMENTS

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