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# Procedure for the systematic orientation of digitised cranial models. Design and validation

M. Bailo [a,*], S. Baena [b], J.J. Marín [a], J.M. Arredondo [b], J.M. Auría [a], B. Sánchez [a], E. Tardío [a], L. Falcón [b]

[a] Grupo IDERGO Escuela de Ingeniería y Arquitectura Edificio Torres Quevedo C/María de Luna 3 50018 Zaragoza, Spain
[b] Instituto de Medicina Legal de Aragón Calle del Nuevo Parque 50015 Zaragoza, Spain

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ABSTRACT

Comparison of bony pieces requires that they are oriented systematically to ensure that homologous regions are compared. Few orientation methods are highly accurate; this is particularly true for methods applied to three-dimensional models obtained by surface scanning, a technique whose special features make it a powerful tool in forensic contexts.

The aim of this study was to develop and evaluate a systematic, assisted orientation method for aligning three-dimensional cranial models relative to the Frankfurt Plane, which would be produce accurate orientations independent of operator and anthropological expertise.

The study sample comprised four crania of known age and sex. All the crania were scanned and reconstructed using an Eva Artec™ portable 3D surface scanner and subsequently, the position of certain characteristic *landmarks* were determined by three different operators using the Rhinoceros 3D surface modelling software.

Intra-observer analysis showed a tendency for orientation to be more accurate when using the assisted method than when using conventional manual orientation. Inter-observer analysis showed that experienced evaluators achieve results at least as accurate if not more accurate using the assisted method than those obtained using manual orientation; while inexperienced evaluators achieved more accurate orientation using the assisted method.

The method tested is a an innovative system capable of providing very precise, systematic and automatised spatial orientations of virtual cranial models relative to standardised anatomical planes independent of the operator and operator experience.

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## 1. Introduction

The morphological study of skeletal remains, including metric indices and characteristic features, has traditionally been of interest in forensic medicine and disciplines such as archaeology and physical anthropology. Such studies permitted us to obtain information about variability of human beings and establish patterns associated with sexual dimorphism [1–4], age [5–8] or other individualizing characteristics, such as size [9–11] or ancestry [12].

Callipers, thickness compasses, craniophors and osteometric tables [13] are among the instruments conventionally used in the study of biometrics. These systems, although may produce good results they are subject to dimensional tolerances and the accuracy of the resulting data is dependent on the skill and experience of the operator, as well as the spatial orientation of the specimen during the analysis. Current trends in forensic practice and research, head towards the implementation of more quantitative and objective techniques which exploit the latest technological advances. In recent years many different branches of science have begun to make use of 3D surface scanning systems [14,15]. The development of this new technology has resulted in the availability of simple handling equipment, fast, safe, relatively cheap and able to provide highly reproducible data, both within and between operators, which has already shown its value in the legal context [14,16,17] and may promote and enhance international professional collaborations by facilitating the remote access to digitised anthropological collections or pieces of special interest all over the world.

In anthropology having the capacity to produce highly realistic representations, the usage of 3D surface scanning systems opens

* Corresponding author. Tel.: +34 669 11 21 21.
*E-mail address:* martabbarrena@gmail.om (M. Bailo).

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the door to large number of applications, ranging from unambiguous localisation of landmarks and a general reduction in measurement error to development of new techniques or updating of existing ones [18–21].

Comparative analysis of models obtained by 3D scanning necessarily involves establishing their relative spatial orientation in order to ensure that homologous regions are compared. A search of extant literature on the development and application of systematic and/or automated methodologies for orienting three-dimensional cranial models relative to standardised anatomical planes revealed little references [22–24].

Based on the agreement found in the 1884 World Congress of Anthropology, the standard anatomical position of the human skull is established as that one in which the Frankfurt Plane, plane defined by left Orbital and right and left Porion *landmarks*, appears horizontally oriented to the ground [25]. The wide international acceptance of the Frankfurt Plane as system of cranial reference makes it suitable for use with three-dimensional virtual models; however the fact that the plane is defined on the basis of a triad of *landmarks* whose localisation is highly dependent on the orientation of the cranium itself which constitutes its most important source of error and presents an important obstacle.

The first objective of this research was to use 3D modelling software to develop a systematic procedure for orienting three-dimensional cranial models relative to standardised anatomical planes, in particular relative to the Frankfurt Plane, making usage for that purpose of 3D modelling software. Our second objective was to investigate the robustness of the new procedure and determine whether this new orientation procedure its implementation on the same anatomical piece, performed by different people and with different levels of experience provided statistically equivalent results as well as more accurate orientations compared with those obtained by conventional manual orientation.

## 2. Method and material

The study was carried out on a sample of 4 crania selected from the 130 pieces of known sex and age which currently make up the Institute of Legal Medicine of Aragon's Anthropological Collection. To maximise coverage of the spectrum of human variation, 4 crania, 2 of each sex, aged 83, 25, 37 and 69 years were selected. Skulls were chosen on the basis of good conservation and lack of fragmentation or loss of elements (with the exception of post-mortem tooth loss). The only treatment to which the skeletal remains had been subjected was cleaning and skeletonization by immersion in solutions of oxidising agents at low concentrations to remove the organic material adhering to them.

An Artec Eva$^{TM}$ 3D portable scanner [26] was used to obtain three-dimensional virtual models of the 4 skulls under investigation. This scanner, structured light based and able to capture scans at a rate of 16 frames per second, it allows automatic alignment and real-time capture of meshes, enabling high definition digitalisation and texturing of the surface of all the facets of a piece.

Two complementary scans of each piece were performed to capture cranial morphology in full. The first scan was made with the skull resting on its base and was used to reconstruct the Frontalis, Occipitalis and both Lateralis Normae; the second scanner was performed with the piece resting over the occipital bone, this allowed reconstruction of the Verticalis Norma and the complex morphology of the cranial base. In cases where it was considered appropriate additional scans were recorded to provide further data on areas with details of particular interest.

Post-processing operations, including alignment, registration, removal of outliers and fusion of scans, were carried out using Artec Studio v.9.2 software to produce the final mesh (Fig. 1).

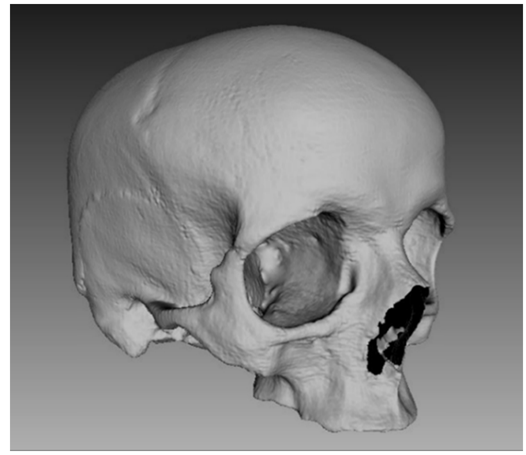

**Fig. 1.** Perspective view of one of the cranial models under study.

The 3 operators who participated in the study were selected on the basis of their experience in forensic anthropology. Two operators (Op 1 and Op 2) were specialists with proven experience and expertise in the establishment of craniometric *landmarks*; the third (Op 3) was an early-stage researcher, aware of the procedures and *landmarks* used in craniometry but with little previous practical experience.

### 2.1. Procedure

Since accurate localisation of any craniometric landmark is determined by previous cranium's spatial orientation, the here proposed orientation procedure comprise a two-stage process of *landmark* selection and reorientation involving first, the approximate orientation of the model relative to the anatomic standard position, and second, a further iteration to establish the location of the landmarks in a more objective, accurate and mathematical criterion-based way, such that they more closely conformed with the desired theoretical position.

Additional software with specific functions for analysis and processing of polygonal meshes was used to perform the orientation procedure on the surfaces obtained during the scanning and post-processing operations described above. We imported the surface of every digital model under investigation and used the software to identify characteristic points or *landmarks*, following the protocol set out below.

Step 1. Manual determination of the three Frankfurt Plane characteristic *landmarks* (left Orbital and right and left Porion) by direct selection on the three-dimensional mesh (Fig. 2).

Step 2. Union by means of a line through both Porion *landmarks*. The perpendicular passage through the Orbital was traced and the intersection point was used as the Origin of a coordinate system as follows, X axis: Porion-Porion connection line (positive direction from left to right); Y axis: Origin-Orbital segment (Fig. 3a).

**Fig. 2.** Estimation of first Orbital landmark using direct manual selection.

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