AJFSC JOURNAL

3D Digitization and Digital Anthropometric Measurement of Skeletal Remains in Forensic Anthropology

Youssouf Khelidj, Chawki Bisker, Lakhdar Bourabia*, Mohamed Lamine Benseddik.

Abstract— **Human identification remains a major objective of forensic investigations, particularly in cases involving fragmented, degraded, or incomplete skeletal remains, as well as victims of mass disasters and clandestine burials. This study aimed to evaluate the feasibility of a digital anthropometric system for performing osteometric measurements on three-dimensional (3D) models of skeletal remains in a forensic anthropology context.**

Skeletal specimens, including skulls and long bones, were digitized using a structured-light 3D scanner to generate high-resolution digital models. Following data preprocessing, including point-cloud cleaning, mesh reconstruction, and geometric optimization, a software prototype developed in Python was used for 3D visualization, anatomical landmark selection, and osteometric distance measurements. Measurement data were exported in standardized formats to ensure traceability, reproducibility, and long-term digital archiving.

The developed system enabled the efficient import, visualization, and manipulation of 3D skeletal models, as well as the rapid acquisition of anthropometric measurements suitable for forensic applications. The complete digital workflow, from data acquisition to measurement generation, was successfully validated without compromising the integrity of the original specimens.

The findings highlight the potential of 3D digital models as reliable tools for forensic anthropological analysis. In response to the request for validation, a preliminary comparison with conventional caliper measurements was performed. The digital measurements showed a mean absolute difference of 0.12 mm, a mean relative difference of 0.144%, and no statistically significant difference from conventional measurements (paired t-test, p = 0.741). This approach contributes to evidence preservation, measurement reproducibility, and digital documentation of skeletal remains. Further work will extend the statistical validation to larger samples and integrate automated anatomical landmark detection methods to enhance operational applicability.

Keywords— **Forensic Anthropology, Human Identification, Skeletal Remains, Digital Evidence, 3D Digitization.**

I. INTRODUCTION

Human identification remains one of the primary objectives of forensic investigations. In numerous circumstances, including homicide cases, mass disasters, armed conflicts, judicial exhumations, and the recovery of isolated human remains, forensic practitioners are frequently confronted with severely decomposed or otherwise compromised bodies for which conventional visual identification methods are no longer applicable. Under such conditions, the scientific examination of skeletal remains becomes a critical source of information for establishing the biological identity of unknown individuals [1], [2].

Forensic anthropology plays a pivotal role in this process by facilitating the reconstruction of the biological profile from skeletal evidence. Through the analysis of osteological characteristics, forensic anthropologists can estimate sex, age at death, stature, and, in certain cases, population affinity. These parameters contribute significantly to narrowing the pool of potential matches and supporting medico-legal investigations [3]–[5]. Anthropometric methods constitute a fundamental component of this approach, relying on the identification of anatomical landmarks and the acquisition of standardized osteometric measurements [6]–[8]. Standard osteometric and geometric-morphometric approaches are also used for population-affinity assessment [9], while anthropometric and vertebral measurements contribute to stature estimation [10], [11]. Recent developments include automated landmark detection in three-dimensional anthropometric applications [12] and three-dimensional skeletal growth modeling [13]. Classical stature reconstruction from long bones remains grounded in foundational osteometric studies [14]–[16], within the broader historical development of anthropometric identification methods [17].

The challenges associated with human identification become even more pronounced when dealing with fragmented, burned, commingled, or severely degraded skeletal remains, as well as in the context of mass fatality incidents, judicial exhumations, clandestine burials, and mass graves. In such scenarios, preserving the integrity of skeletal evidence, ensuring rigorous documentation, and maintaining full traceability throughout the forensic examination process are essential requirements. Consequently, methods enabling the acquisition, preservation, and re-examination of anthropological data in digital form represent a significant advancement for evidence management and forensic identification practices [1], [4], [5], [18].

Despite their well-established scientific value, conventional anthropometric approaches based on manual measurements present several limitations. They often require repeated handling of fragile skeletal specimens and remain partially dependent on operator expertise and experience. Furthermore, measurement records are commonly preserved as paper-based or digital datasets that do not always allow complete reconstruction of the original examination conditions or subsequent verification of the analytical process [6], [8], [20], [21].

Recent advances in digital technologies have opened new perspectives for forensic anthropology. Three-dimensional (3D) digitization enables the generation of accurate virtual representations of skeletal remains that can be permanently archived, shared among forensic laboratories, and reanalyzed without direct manipulation of the original specimens. This

Manuscript received June 08, 2026; accepted August 17, 2026. Date of publication September 13, 2026. This work was conducted at the Research and Development Center of the National Gendarmerie and the National Institute of Criminalistics and Criminology, Algiers /Algeria.

Y. Khelidj, L. Bourabia, M.L. Benseddik are with the Research and Development Center of the National Gendarmerie (e-mail: khelidjyoucuf@gmail.com, bourabia@gmail.com, benseddik.mohamedlamine@gmail.com).

C. Bisker is with the Department of Forensic Anthropology-National Institute of Criminalistics and Criminology, Algiers /Algeria (email: chawkibisker@gmail.com).

paradigm aligns with the growing importance of digital evidence management, scientific traceability, and quality assurance within modern forensic science laboratories [18], [19]. Three-dimensional craniometry and landmarking studies have further demonstrated the applicability and reliability of virtual skeletal analysis [20], [21], including cranial morphology-based sex estimation in virtual environments [22].

Within this framework, the present study aims to evaluate the feasibility of developing a digital system for the visualization and anthropometric measurement of three-dimensional skeletal models. The objective is to implement a software prototype capable of supporting the acquisition, analysis, and long-term preservation of digital anthropometric data while contributing to evidence preservation, enhancing measurement reproducibility, and strengthening human identification capabilities in forensic anthropology.

II. MATERIALS AND METHODS

A. Three-Dimensional Data Acquisition

In forensic anthropology, human identification frequently relies on the examination of skeletal remains that may be fragmented, altered, or difficult to handle. Preserving the integrity of such specimens is therefore a critical requirement, particularly in criminal investigations, mass fatality incidents, and the management of collective burial contexts [1], [4], [5], [18].

To minimize direct handling while preserving the morphological information required for anthropometric analyses, several skeletal specimens, including crania and long bones, were digitized using a structured-light 3D scanner (Creaform Go!SCAN 50). This technology enables rapid, non-destructive acquisition of high-resolution digital models that accurately reproduce the external geometry of skeletal structures [18], [19].

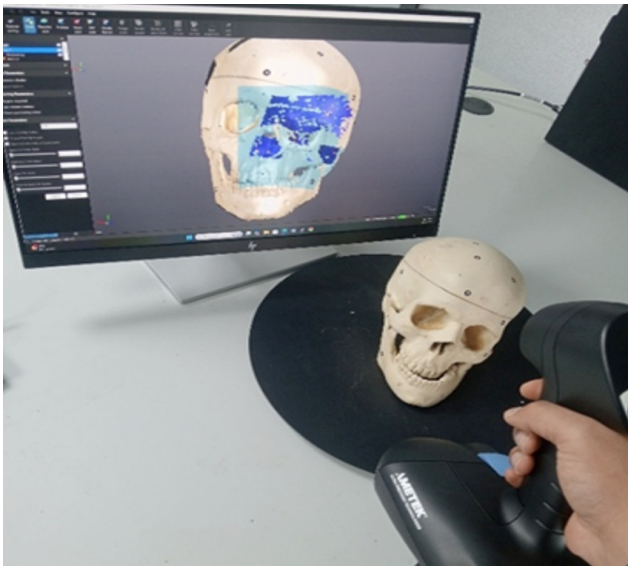


Fig1. 3D scanner used in this study and example of a reconstructed digital skeletal model.

Scanning procedures were conducted following the manufacturer's recommendations after system calibration to ensure measurement reliability and geometric consistency. The resulting models were exported in standard three-dimensional file formats (OBJ, STL, and PLY) to ensure interoperability with the processing and analytical tools employed in this study.

B. Digital Model Preprocessing

The acquired datasets underwent a preprocessing phase designed to improve geometric quality and ensure the reliability of subsequent anthropometric measurements. This stage included point cloud cleaning, removal of scanning artifacts, and reconstruction of a usable triangular mesh [19].

Filtering and optimization procedures were performed using MeshLab software. Outlier removal and geometric smoothing algorithms adapted to anthropological datasets were applied to reduce noise while preserving anatomically relevant morphological features. In the illustrative case presented herein, the final processed model contained 92,482 points and 164,124 triangular faces.

These preprocessing operations produced an accurate digital representation of the skeletal specimen while minimizing potential sources of error that could influence anthropometric measurements and forensic interpretation [19].



Fig 2. Example of a raw point cloud prior to preprocessing.

C. Development of the Anthropometric Measurement Prototype

A dedicated software prototype was developed in Python to support anthropometric analysis of three-dimensional skeletal models. Rather than replicating the functionalities of a general-purpose 3D modeling platform, the system was specifically designed to address the operational requirements of forensic anthropology.

The prototype enables the importation and interactive visualization of 3D models, manual selection of anatomical landmarks, and automated calculation of osteometric distances. The three-dimensional coordinates of selected landmarks are recorded and subsequently used to compute metric parameters commonly employed in anthropological examinations [8], [20], [21].

To ensure traceability, reproducibility, and long-term data preservation, generated results can be exported in standardized formats (CSV and JSON), facilitating their integration into anthropological and forensic databases as well as their use in subsequent analyses.

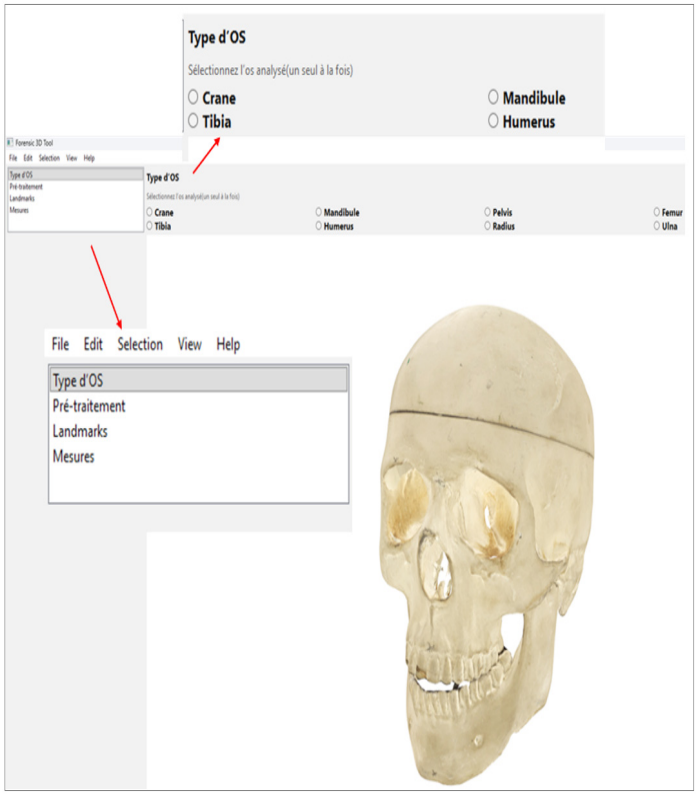


Fig 3. User interface of the developed anthropometric measurement prototype.

D. Processing Workflow

The proposed workflow consists of four principal stages: (i) digitization of the skeletal specimen, (ii) preprocessing and reconstruction of the digital model, (iii) anatomical landmark selection and anthropometric measurement, and (iv) exportation and archiving of the resulting data.

This workflow enables the creation of a permanent digital replica of the examined skeletal remains, allowing future reanalysis without additional handling of the original specimen. Such an approach is particularly valuable in forensic contexts where evidence preservation, management of degraded human remains, and comprehensive documentation of identification procedures are essential [18], [19].

Beyond facilitating anthropometric analysis, the workflow contributes to the development of digital forensic records that can be archived, reviewed, and shared among experts while maintaining the integrity and traceability of the examination process [18].

For preliminary validation, a subset of five osteometric distances was measured using both conventional anthropometric instruments, particularly a digital caliper, and the developed digital measurement tool applied to the corresponding 3D models. For each distance, the absolute difference and relative difference were calculated. In addition, mean absolute error, root mean square error, mean signed bias, Pearson correlation coefficient, and a paired t-test were used to assess agreement and to identify any potential systematic difference between the two measurement approaches. Statistical significance was considered at $p < 0.05$.

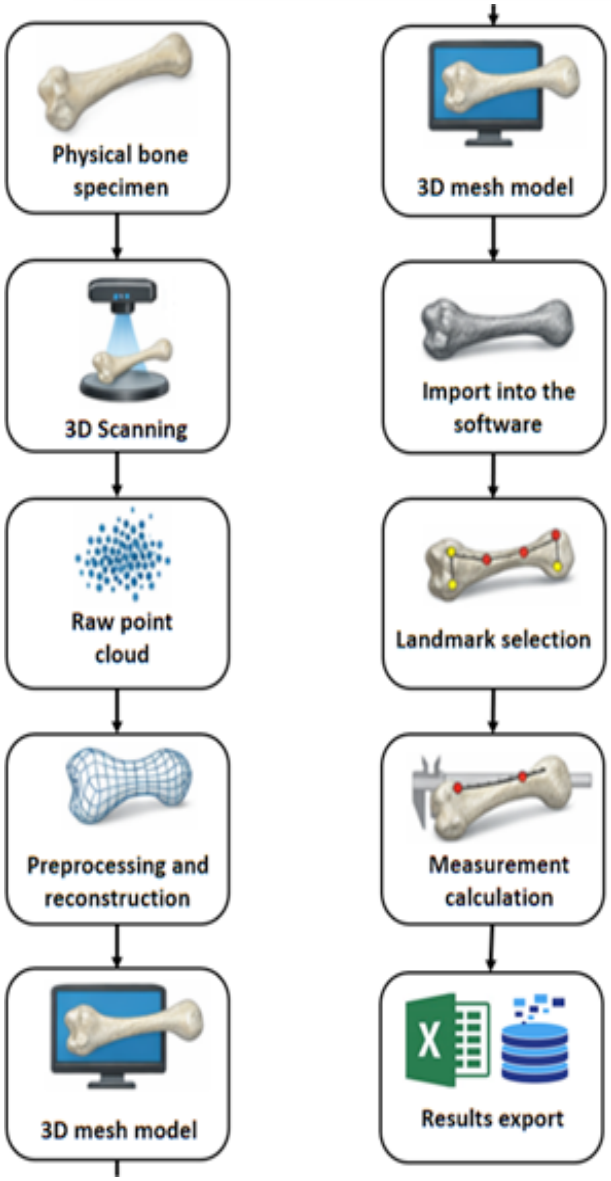


Fig 4. Overall workflow of the proposed digital anthropometric measurement system.

III. RESULTS AND DISCUSSION

A. Technical Performance of the Developed System

The experimental evaluation conducted in this study validated the functionality of the entire digital workflow, from three-dimensional data acquisition to the generation of exploitable anthropometric measurements. The developed prototype successfully supports the importation of 3D models in OBJ, STL, and PLY formats, interactive visualization of skeletal structures, anatomical landmark selection, and automated calculation of osteometric distances.

The tested skeletal models, including cranial and long-bone specimens, were imported and processed without observable alteration of their geometric integrity. Interactive rendering functions, including rotation, translation, and zooming, provided sufficient visualization quality to facilitate the accurate identification of anatomical landmarks commonly used in forensic anthropological protocols.

The technical evaluation was conducted on five digitized skeletal models, comprising three skulls and two femora.

The main technical performance indicators of the developed system are summarized in Table I, based on measurements performed on two types of skeletal specimens: a skull and a Femur.

Table I.

Technical performance of the developed system

Evaluated Parameter	Obtained Value	
Number of analyzed models	5	
Types of skeletal elements analyzed	Skull	Femur
Average number of points per model	75 125	53 847
Average number of mesh triangles	148 912	137 867
Average model loading time	< 1 second	
Average landmark selection time	05 seconds	
Average measurement execution time	10 seconds	
Supported formats	OBJ, STL, PLY	
Export formats	CSV, JSON	
Maximum number of stored landmarks	All landmarks	
Measurement success rate	100 %	

Overall, the obtained results demonstrate the operational feasibility of the proposed system and its ability to generate anthropometric measurements efficiently while preserving the integrity of the analyzed skeletal specimens.

B.Preliminary Validation of Anthropometric Measurements

To assess the consistency of the measurements produced by the developed platform, a preliminary comparison was performed between measurements obtained from digital 3D models and those acquired using conventional anthropometric instruments, particularly a digital caliper [8], [20].

The comparison focused on several osteometric distances routinely employed in forensic anthropological examinations. The preliminary results are presented in Table II [6], [8], [20].

Table II.

Comparison between conventional and digital anthropometric measurements

Anthropometric Measurement	Digital Caliper (mm)	Digital Tool (mm)	Absolute Difference (mm)	Relative Difference (%)
Measurement 1	87.74	87.86	0.12	0.137%
Measurement 2	82.55	82.31	0.24	0.291%
Measurement 3	129.66	129.72	0.06	0.046%
Measurement 4	79.82	79.95	0.13	0.163%
Measurement 5	60.64	60.69	0.05	0.083%
Mean ± SD			0.12 ± **0.08**	0.144 ± **0.094%**

The comparison showed close agreement between conventional and digital measurements, five independent osteometric measurements were acquired from the same skull specimen by a single trained operator using both the conventional digital caliper and the proposed digital measurement tool. The mean absolute difference between the two measurement methods was 0.12 ± 0.08 mm, the mean relative difference was 0.144 ± 0.094%, and the root mean square error was 0.138 mm. The maximum absolute difference was 0.24 mm. The mean signed bias was 0.024 mm, indicating no relevant systematic over- or under-estimation by the digital tool. The correlation between both measurement series was very high (Pearson r = 0.99998), and the paired t-test did not reveal a statistically significant difference between digital and conventional values (p = 0.741).Although the validation sample remains limited, these preliminary observations provide an initial quantitative basis for evaluating the accuracy, repeatability, and reproducibility of the proposed system. A more comprehensive statistical assessment involving larger sample sizes, additional skeletal elements, and inter- and intra-observer repeatability tests will be required before operational implementation in forensic casework.

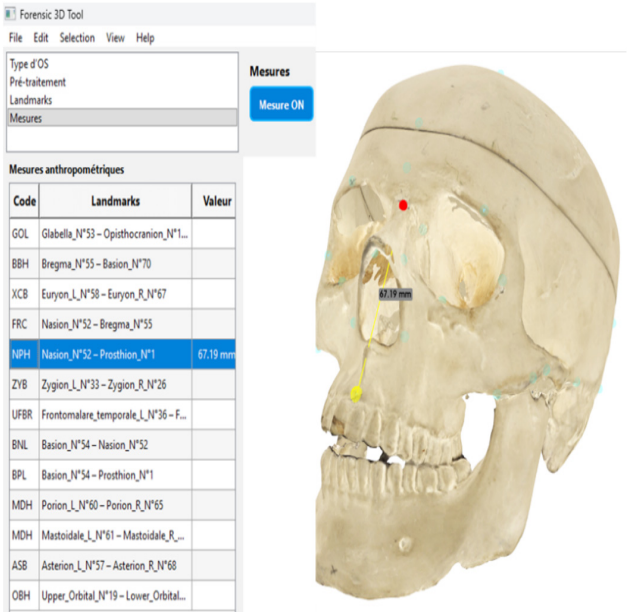


Fig 5. Example of a digital anthropometric measurement performed on a three-dimensional cranial model.

C. Discussion

The results obtained demonstrate that the integration of three-dimensional digitization and digital anthropometric measurement constitutes a promising approach for contemporary forensic anthropology. Beyond its technical feasibility, the proposed workflow addresses several practical challenges frequently encountered in forensic identification and skeletal analysis [18]–[21].

One of the principal advantages of the approach lies in the reduction of direct handling of skeletal remains. This aspect is particularly relevant when dealing with fragile, fragmented, burned, incomplete, or environmentally degraded specimens. By generating a faithful digital replica of the original evidence, the proposed methodology contributes to specimen preservation while minimizing the risk of accidental damage during examination [18], [19].

From a forensic perspective, the use of digital skeletal models also enhances documentation, traceability, and quality assurance. Anatomical landmarks, three-dimensional coordinates, and associated measurements can be permanently archived and subsequently reviewed by independent experts. Such capabilities are highly valuable in judicial contexts where methodological transparency, reproducibility, and expert verification are critical components of evidentiary reliability [18], [20], [21].

The establishment of digital osteological repositories further offers important opportunities for forensic laboratories and medico-legal institutions. Three-dimensional models can be securely archived, exchanged among experts, and reanalyzed without requiring repeated access to the original remains. This capability supports long-term evidence preservation and facilitates collaborative forensic investigations [18], [19].

The proposed methodology may be particularly beneficial in mass fatality incidents, armed conflicts, judicial exhumations, clandestine burials, and mass grave investigations. In such scenarios, rapid digitization of skeletal remains enables the preservation of morphological information at the time of recovery, facilitates subsequent anthropometric analyses, and contributes to the management of large volumes of forensic evidence throughout the identification process [1], [5], [18].

Despite these advantages, several limitations remain. Measurement accuracy is directly influenced by scanning quality, scanner resolution, and preprocessing performance.

Furthermore, anatomical landmark identification currently relies on manual operator intervention, introducing a degree of inter-observer variability comparable to that observed in conventional anthropometric procedures. Consequently, the reported accuracy should be interpreted as a preliminary validation under controlled conditions involving a single trained operator [20], [21].

The preliminary statistical comparison included in this revised version supports the consistency of the digital measurements when compared with conventional caliper measurements; however, the number of measurements remains limited and should be expanded in future validation studies.

Future developments should therefore focus on the implementation of landmark-assisted or fully automated landmark detection algorithms, combined with comprehensive statistical validation using larger datasets. Such improvements would enhance measurement standardization, reduce operator-dependent variability, and strengthen the scientific robustness of the system for forensic applications [12], [20], [21].

Nevertheless, the present findings demonstrate that the proposed digital workflow provides a solid foundation for the development of a comprehensive digital forensic anthropology platform capable of meeting the increasing demands of modern forensic laboratories in terms of evidence preservation, analytical traceability, and human identification.

IV. CONCLUSION AND FUTURE PERSPECTIVES

This study demonstrated the feasibility of integrating three-dimensional digitization and digital technologies into anthropometric analyses of skeletal remains. The developed prototype successfully enabled the visualization of 3D skeletal models, the identification of anatomical landmarks, and the execution of osteometric measurements within a dedicated digital environment.

The findings highlight the potential of digital anthropometry as a valuable complement to conventional measurement methods, particularly in forensic anthropology. The proposed approach contributes to the preservation of skeletal evidence, improves the traceability and reproducibility of measurements, and facilitates the long-term archiving and re-examination of forensic data. These advantages are especially relevant in contexts involving degraded human remains, mass fatality incidents, judicial exhumations, and other complex human identification scenarios [18], [19].

The preliminary validation performed in this study showed close agreement between digital and conventional anthropometric measurements, with a mean absolute difference of 0.12 mm and a mean relative difference of 0.144%. Nevertheless, before routine implementation in forensic practice, the system requires larger-scale statistical validation through additional comparisons with conventional anthropometric instruments, as well as repeatability and reproducibility assessments involving multiple observers and a broader range of skeletal specimens.

Therefore, the present study should be considered as a proof-of-concept demonstrating the feasibility and promising accuracy of the proposed digital workflow.

Future developments will focus on the automation of anatomical landmark detection, the integration of anthropological index calculation modules, and interoperability with specialized forensic databases such as FORDISC. In the longer term, the incorporation of artificial intelligence and machine learning approaches may further enhance human identification capabilities and support forensic decision-making in complex medico-legal investigations [7], [12], [22].

REFERENCES

[1] Christensen A.M., Passalacqua N.V., Bartelink E.J. Forensic Anthropology: Current Methods and Practice. 2nd ed. Academic Press, Elsevier; 2019.

[2] Byers S.N., Juarez C.A. Introduction to Forensic Anthropology. 5th ed. Pearson Education; 2017.

[3] Stojanowski C.M., Seidel A.C. Forensic Anthropology: An Introductory Laboratory Manual. Springer International Publishing; 2018.

[4] Quatrehomme G. Traité d'Anthropologie Médico-Légale. Paris: Elsevier Masson; 2015.

[5] Delabarde T., Baccino E., Martrille L., et al. Manuel Pratique d'Anthropologie Médico-Légale. Elsevier Masson; 2015.

[6] Farkas L.G. Anthropometry of the Head and Face. 2nd ed. New York: Raven Press; 1994.

[7] Ousley S.D., Jantz R.L. FORDISC 3.1: Personal Computer Forensic Discriminant Functions. Knoxville (TN): University of Tennessee; 2005.

[8] Langley N.R., Jantz L.M., Ousley S.D., Jantz R.L., Milner G.R. Data Collection Procedures for Forensic Skeletal Material 2.0. Knoxville (TN): University of Tennessee; 2016.

[9] Spradley M.K., Jantz R.L. Ancestry estimation in forensic anthropology: geometric morphometric versus standard osteometric techniques. Journal of Forensic Sciences. 56(4), pages 1032–1039. 2011.

[10] Krishan K., Kanchan T., Passi N. Estimation of stature from anthropometric measurements in forensic examinations. Forensic Science International. 221(1–3) , pages 1–10. 2012.

[11] Sharma S., Jeelani W., Pandey A.N., et al. Application of anthropometric measurements for stature estimation from the vertebral column: a systematic review. International Journal of Legal Medicine. 134(6), pages 2221–2239. 2020.

[12] Porto L.F., Oliveira H.C., da Silva J.V.L. Automatic landmark detection in three-dimensional medical images and anthropometric applications: a review. Computers in Biology and Medicine. 107, pages 1–12. 2019.

[13] Klop L., van de Kamp T., et al. An open-source three-dimensional growth model of the human mandible. Scientific Reports. 11, page 3068. 2021.

[14] Dupertuis C.W., Hadden J.A. On the reconstruction of stature from long bones. American Journal of Physical Anthropology. 9(1) , pages 15–54. 1951.

[15] Trotter M., Gleser G.C. Estimation of stature from long bones of American Whites and Negroes. American Journal of Physical Anthropology. 10(4), pages 463–514. 1952.

[16] Trotter M., Gleser G.C. A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. American Journal of Physical Anthropology. 16(1), pages 79–123. 1958.

[17] Bertillon A. Identification Anthropométrique: Instructions Signalétiques. Paris: Gauthier-Villars; 1893.

[18] Errickson D. Virtual forensic anthropology: novel applications of anthropological science in the digital era. Forensic Sciences Research. 2(2), pages 65–71. 2017.

[19] Carew R.M., Morgan R.M., Rando C. A preliminary investigation into the accuracy of 3D modeling and 3D printing in forensic anthropology evidence reconstruction. Journal of Forensic Sciences. 64(2), pages 342–352. 2019.

[20] Guyomarc'h P., Santos F., Dutailly B., et al. Three-dimensional computer-assisted craniometrics: a comparison of landmarking methods. Forensic Science International. 217(1–3), pages 196.e1–196.e7. 2012.

[21] Villa C., Buckberry J., Cattaneo C., Lynnerup N. Technical note: reliability of landmark placement on 3D CT-derived skull models. American Journal of Physical Anthropology. 150(3), pages 460–465. 2013.

[22] Franklin D., Cardini A., Flavel A. Accuracy of sex estimation using cranial morphology in virtual anthropology. International Journal of Legal Medicine. 127(4), pages 825–833.2013.