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Accuracy and Benefits of 3D Bone Surface Modelling: A Comparison of Two Methods of Surface Data Acquisition Reconstructed by Laser Scanning and Computed Tomography Outputs

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A B S T R A C T

The aim of this study is to compare two different methods of frontal bone surface model acquisition. Three dimensional models acquired by laser scanning were compared with models of the same bones acquired by virtual replicas reconstructed from a sequence of computed tomography (CT) images. The influence of volumetric CT data processing (namely thresholding), which immediately preceded the generation of the three-dimensional surface model, was also considered and explored in detail in one sample. Despite identifying certain areas where both models showed deviations across all samples, their conformity can be generally classified as satisfactory, and the differences can be regarded as minimal. The average deviation of registered surface models was 0.27 mm for 90% of the data, and its value was therefore very close to the resolution of the laser scanner used.

***Key words**: frontal bone, three-dimensional imaging, laser scanning, computed tomography, surface registration*

Introduction

The methods employed in virtual modelling – a dynamically developing area – have been used to a large extent in both anthropology and medicine, where the potential for advanced imaging techniques and digital technologies has not yet been fully exploited. These image-based technologies help solve various types of problems: they allow for the reconstruction of missing parts of fragmentary fossils, they create source data by which analyses may be followed from the areas of traditional and geometric morphometrics, and another point which must be mentioned is the sharing aspect involved in comparing virtual osteological databases, enhancing study opportunities and making available high-quality replicas of rare exponates[1–4].

Nowadays in the field of medicine commonly available imaging systems allow for better examination of internal organs, monitoring changes, preoperative planning and prediction and evaluation of final treatment results[5–7]. In addition, it is possible to create virtual models of complex anatomical structures and then transfer them back into physical space. This last procedure makes it possible to model and manufacture individual, custom-made components of joints or parts of the skull[8,9]. There are also numerous applications in the area of forensic medicine where it is possible to create copies even from very thin, delicate and degraded remains without the risk of destroying the originals, enabling further research, identification and potentially also allowing for a reconstruction of the victim's visage or accurate imaging of the historical figure's appearance[10]. Issues regarding the correct and effective imaging of craniofacial structures are currently of great interest in the areas of neurosurgery, oral and maxillofacial surgery, plastic surgery, orthodontics, forensic medicine and customized medical implant design.

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New dimensions are opening up in the field of anthropology, where it is becoming possible to model and analyse skeletal components of very recent (living) populations. The reliability and accuracy of computer-based technologies of reverse engineering (RE) and rapid prototyping (RP) have been tested in numerous studies[11–16] in various ways (mostly by measuring of linear dimensions) and on different anatomic structures. The digitalisation of such difficult and complex shapes as the human skull is performed with the help of optical and laser technologies, which are quite complicated and require the utilisation of an effective SW[17]. Moreover their output represents only the surface of the observed object without a chance to create an image of the internal structures. These inside structures can be perfectly depicted by computer tomography, though with certain limitations in the case of laminae thinner than 1 mm[1]. Modern CT scanners analyse objects in a sequence of layers, typically in thickness of 0.3–1 mm. Alongside financial considerations another limitation of CT examination is associated with radiation exposure of a live organism.

In our study we propose to evaluate the accuracy and define the benefits of the selected methods, as well as detecting particular places that are normally difficult to image by means of one or the other approach. For the purpose of this study we will focus on the entire surface of the frontal part of the human skull.

Material and Methods

The frontal bone was selected to evaluate the accuracy of bone surface acquisition. Although it may appear quite straightforward and relatively easy to create an accurate image from, there are in fact convex areas *(squama frontalis)*, concavities, edges *(margo supraorbitalis)* and discontinuities in the form of small foramens or incisions. Moreover, in this area there are both prominent and shadowed (pterion area) structures, and structures that are either massive or very narrow.

The surface models of 5 frontal bones from the skeletal collection of early medieval dating were first created by methods of reconstruction employing virtual 3D modelling from the DICOM (Digital Imaging and Communications in Medicine) image sequence of CT outputs. The initial raw data was acquired through the helical scanning of the appropriate areas. Data was received from 40-slice Somatom Sensation 40 (Siemens, Erlangen, Germany) tomograph. Slice thickness was selected as 0.6 mm, with an X-ray tube adjustment of 120 kV and 300 mAs. These adjustments correspond to the usual settings for cranial examinations of living patients. The kernel was adjusted on 60 units, i.e. with the upper-most kernel highlighting the edges. The Field of View was set to 250×250 mm, defined by a matrix of 512×512 pixels in 12-bit gray-scale levels. This tomographic data was first treated with image processing which was followed by generation of bone surface defined by a high number of polygons (STL format).

Another method for the creation of three-dimensional models of real objects is to capture their shape by means of laser scanning. A three-dimensional Roland LPX-250 laser scanner (Roland DG, Hamamatsu, Japan) with a lateral resolution of 200μm was used for digitizing the surface of the frontal bone. The scanning was performed using Dr. Picza 3 software (Roland DG). The skulls were scanned on a rotating plate from a direction perpendicular to the frontal plane. The raw scanned data was processed using Pixform reverse engineering software (Roland DG). This procedure included cleaning, merging of multiple scans, hole filling, smoothing, and global re-meshing.

Due to the different nature of data outputs from the individual systems, it was necessary to find a way of matching volumetric data from the computed tomograph and the surface data of the same skull captured using the 3D laser scanner. Current software equipment in both participating departments makes it possible to carry out image registration with the necessary pre-processing of input data. Before the realisation of the registration itself, it was initially essential to adjust tomographic data sets in SW Avizo 6, because the volumetric CT derived data (especially in the facial region) significantly exceeded the area scanned by the 3D laser.

These two models were then imported into SW VG Studio Max. The volumetric CT derived data required calibration by determination of the isosurface levels and thresholds, which specified the minimum voxel/pixel value to be represented in the newly created volume data surface. The following registration is realised on the surface (laser scanner) data like a reference model. The registration method was performed by surface fitting using Gaussian algorithm. In practice, this means that changes of position and orientation minimize the distance deviations between the surfaces of two registered objects without modifying their original sizes.

The registered models were analysed in this way, and the result of these comparisons was visualised as a colour-coded overlay of volumetric data, illustrating the size of deviations in the individual parts of the frontal bone.

On skull No. 1, the influence of the image processing phase of volumetric data (which precedes the generation of the surface model) was investigated in more detail. The main effort was aimed at determining the isosurface level.

Results

Effects of threshold value on the total deviation of both models

The determination of the ideal isosurface threshold value resulting from the corresponding histogram (Figure 1) was evaluated thoroughly on skull No. 1. For the rest of the skulls this threshold value was verified by an option of several values. The detailed analysis consisted in determining the ideal threshold values in range from –800 up to –200 with the ensuing consequences. By de-

Fig. 1. Histogram from volumetric data of skull (axis x – intensity values, axis y – frequency).

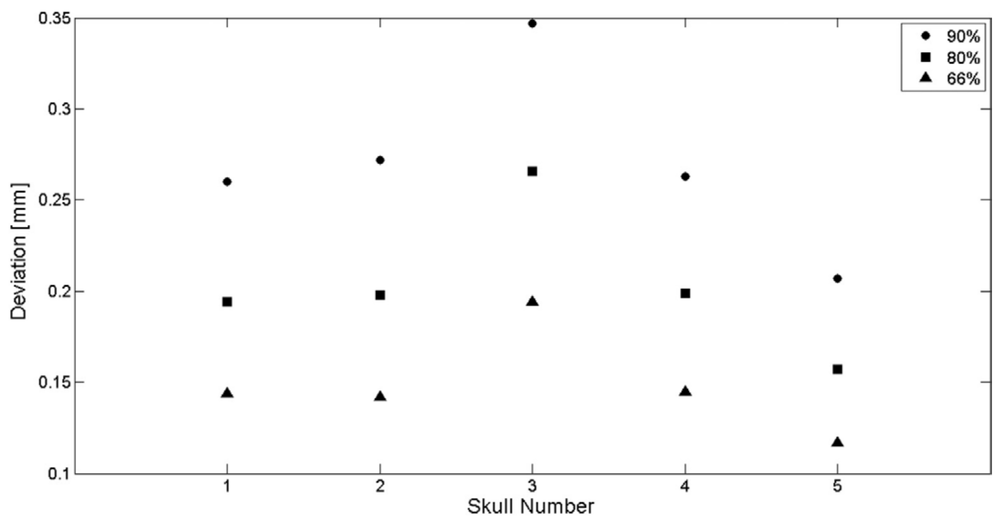

Fig. 2. Deviations of corresponding models for individual skulls.

creasing threshold values below –600, an isosurface is generated including noise surrounding the skull (isolated points in free space). In contrast, values above the threshold of –200 leave voxels on the skull with an intensity value below –200 not visualized, and the object created will thus be incomplete, with many holes and cavities. The ideal threshold value for searching the minimum deviation in both models was found as a value of –600.

A threshold value of –600 was then used to generate surface models from sequences of CT images. Several repeated analyses referring to this optimal value were implemented in order to define the method errors. It was proved that within five repetitions the standard deviation would be smaller than 0.005 mm. Therefore the method error does not influence the final result.

Comparison of two surface models

A comparison analysis was carried out on 5 skulls, defining the maximum absolute deviation in mm for certain data percentages and vice versa. In our study, the mutual assessment of both surface models was established subsequently with 90%, 80% and 66% data. The deviations for individual skulls are summarised in Table 1 and illustrated in Figure 2.

TABLE 1
COMPARISON OF MEAN DEVIATION FOR THE FIVE ANALYZED SKULL MODELS

% dat	$\overline{X}$ [mm]	SD [mm]
90	0.27	0.05
80	0.20	0.04
66	0.15	0.03

Including the 80% data into our comparison, the average deviation reached 0.20 mm; increasing the data evaluated by another 10% (at 90% of data) the final deviation increased to a value of 0.27 mm. The magnitude of deviation values is very close to the defined resolution of the laser scanner used. The highest differences were recorded on skull No. 3 (Figure 2), where values close to a quarter of millimetre were obtained for 80% data analysed, and 90% of data differed by almost 0.35 mm. On the other hand the highest level of models conformity was registered on the skull No. 5, where the conformity level is quantified by deviation slightly exceeding 0.2 mm for 90% of data (Figure 2).

Subsequently, both surface models were visually analyzed (Figure 3) in order to establish their authenticity relative to the real objects. Polygons generated from the volumetric data describe details (depressions, cavities, and holes) much more accurately, and consequently they correspond better to the real surface of skull than the surface model acquired through the use of the laser scanner. The laser scanner is not sensitive enough to slight changes in the bone terrain. For this reason, the observation area of one of the skulls was reduced to a smaller area eliminating these »critical locations«. After the elimination of these critical locations the resultant deviations are minimally influenced by the threshold determination in range of –600 to –200.

The main considerations were localized on critical areas where more significant differences occurred regularly (Figure 4). These areas are behind and above the lateral border of the orbit (where the *linea temporalis* is formed), and the pterion area, where small pores manifested themselves at incorrectly determined threshold values on the CT scan. At correctly determined thresholding it is evident that in the area of the pterion the surface models differ by 0.5–0.9 mm. More significant differences (in the sense of larger surface extensions of these differences) were observed on all skulls in the right hemispheres, either at the pterion area, a region above the *margo supraorbitalis*, or at places where the *pars orbitalis* bordered the *pars nasalis*. This asymmetry is probably associated with the way the laser scanner operates and should be taken into account during surface model scanning requiring high degrees of accuracy. The blue colour of the frontal bone scales is due to the fact that the CT derived model is about 0.3 to 0.5 mm below the surface captured by the laser scanner.

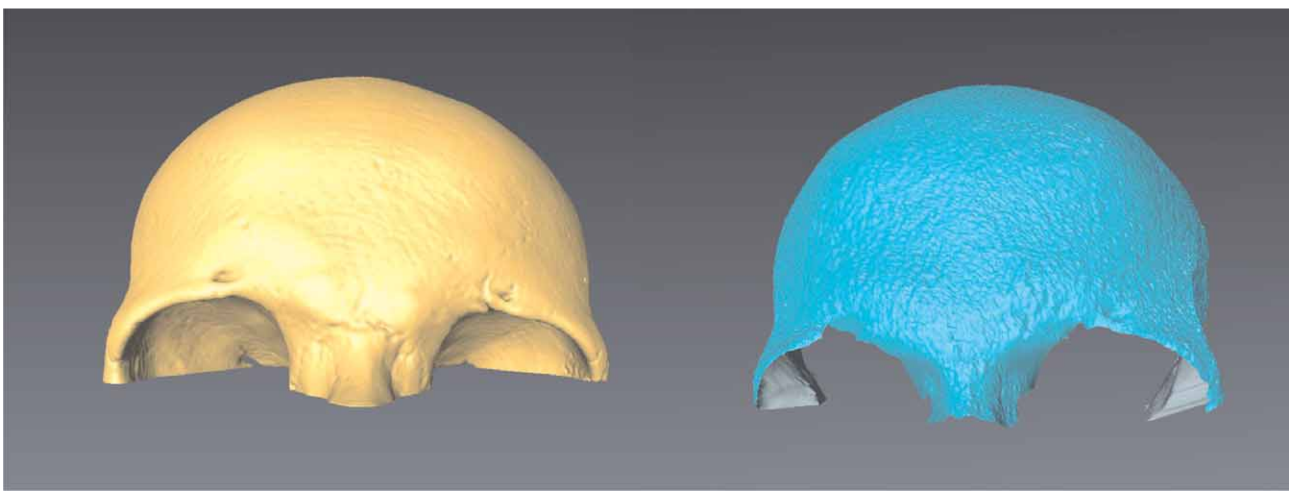

Fig. 3. Frontal bone scanned by both methods, left CT derived model, right model from laser scanner.

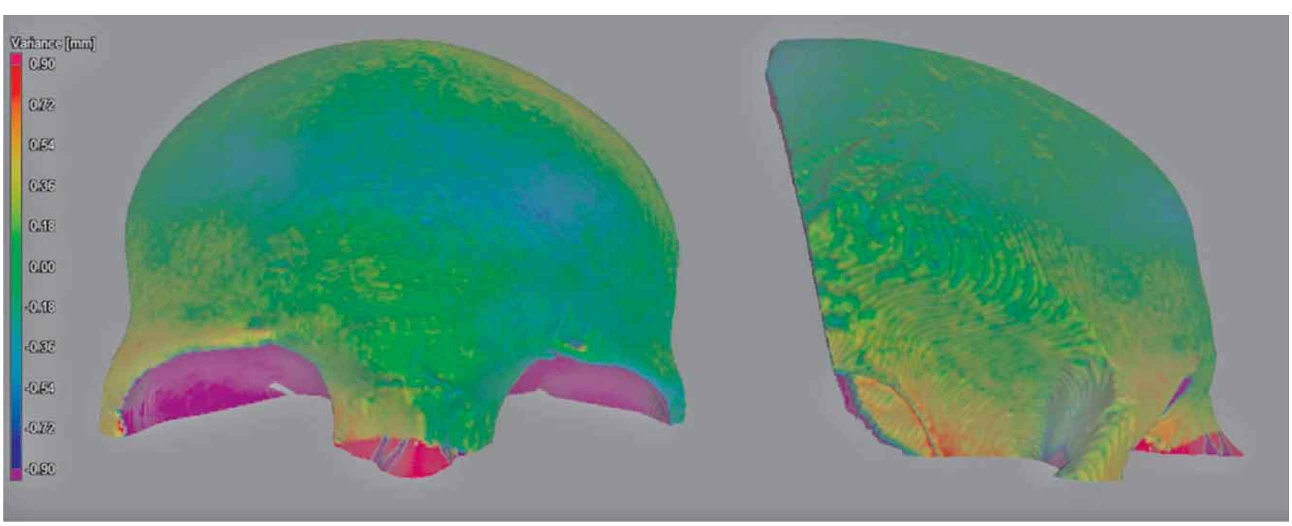

Fig. 4. Comparison of two surface models.

Discussion

We are currently at the pioneering stage, when anthropological research – thanks to 3D modelling – will not be restricted only to skeleton collections originating from archaeological excavations or recent and subrecent cadavers. For this reason it is important to evaluate the potential indications, limitations, reliability and applications of various methods of virtual bone model generation which could be studied and eventually included into future comparisons.

In analogous studies the original bone is often compared with a copy made using stereolithography. Choi et al. (2002) investigated errors generated during the production of a RP model of a complete human skull. The copy they produced is extremely accurate, and the absolute mean deviation between the original dry skull and the RP model over the 16 linear measurements was 0.62±0.35 mm. The difference between the skull and the 3D model (stl) was 0.49±0.34 mm. Factors affecting the final size of this deviation were specified: protocol settings of CT imaging (especially section thickness), patient movements, metal artefacts, empirical determination of the threshold value and difficulties in the exact replication of landmark location. Landmarks situated on sharp peaks were very sensitive to volume-averaging effect.

The method we have chosen was a global evaluation of the differences using a colour-coded visualisation of both models. Along with Däuber et al. (2003), DeVries et al. (2008) and Ramme et al. (2009) we revealed the size and localisation of differences on the entire observed area using this method.

Comparing our results with the findings of other studies is difficult as we must take into account the various methods of obtaining and processing volumetric data, and the wide range of the examined skeleton components (skull, phalanges, animal vertebra). An analogue image-capturing protocol (based on slice thicknesses of up to 1 mm) was used by Choi et al. (2002), DeVries et al. (2008) and Ramme et al. (2009). The bone tissue of the phalanges of the index finger (surrounded by soft tissues) was segmented manually by DeVries et al. The overall mean difference between the manually segmented CT model and the laser surface scan was 0.20 mm. The influence of two types of smoothing filters had minimal effect on the size of this deviation and did not significantly alter the surface representations. Identical data (additionally the IIIrd to Vth beam) was processed by Ramme et al. (2009), who recorded an overall mean difference 0.45–0.46–0.51 mm (continually for proximal, medium and distal phalanx) with the help of a semi-automatic segmentation algorithm. The larger average distance for the distal phalanx (in comparison to manual tracing) was probably caused by the incorrect assigning of bony tissue at the articulating surfaces.

From CT slices with thicknesses of 0.6 mm we generated a surface model very similar to the surface scanned by high definition laser scanner. The total deviation did not exceed 0.27 mm for 90% of the data. The highest difference between both methods of surface data recorded was localised at the lateral edge area of the orbit. We suppose this more significant deviation is caused by laser scanning, because at certain moments of the scanning process this area is partly shadowed by other parts of the skull. Another disadvantage of laser scanning is the time-consuming data scanning process and the difficulty of matching partial scans with complex models. Deviations can occur either due to imperfect fixation of the observed object or during the matching of partial scans into a final model. A disadvantage of using model segmentation from volumetric CT derived data is the heavy financial burden of CT imaging. Although the final models are very accurate, incorrectly selected threshold values can cause CT derived models to have very small holes at areas of very thin lamellae (such as in the pterion area), which are not accurate representations of the original object.

Conclusion

From the sequences of two-dimensional images of frontal bones acquired by computer tomography it is possible to generate a very accurate 3D model if certain conditions of the scanning procedure (fine slices) and the empiric determination of the threshold value are met. Ideally, these conditions would be met for each scanned bone separately. We evaluated two methods of surface model acquisition – the above-mentioned computed tomography variant and a high-definition laser scanning method. The average difference of the mutually registered models was 0.27 mm for 90% of data.

Although we observed the part of skull whose structure is less complicated when compared with others, it was still possible to detect some critical locations where greater differences occurred regularly. One of these locations is the region behind the lateral border of the eye socket, where the temporal line is formed and is partly shadowed during laser scanning. The second area is that of the pterion, where small pores became visible at incorrectly determined threshold values on the CT derived model. The comparison process and the search for optimal, fast and – above all – reliable methods of medical imaging should be extended to other components of the human skeleton in the future.

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PRECIZNOST I KORISNOST 3D MODELIRANJA POVRŠINE KOSTIJU: USPOREDBA DVIJE METODE PRIKUPLJANJA PODATAKA REKONSTRUIRANO LASERSKIM SKENIRANJEM I KOMPJUTERSKOM TOMOGRAFIJOM

SAŽETAK

Cilj ovog istraživanja bio je usporediti dvije različite metode dobivanja informacija o površini frontalne kosti. Trodimenzionalni modeli bazirani na laserskom skeniranju su uspoređivani s modelima istih kostiju analiziranih virtualnim replikama rekonstruiranim na temelju sekvence kompjuterske tomografije. Također je na jednom uzorku u detalje procijenjen značaj rezultata dobivenih kompjuterskom tomografijom u usporedbi s rezultatima starije metode trodimenzionalnih modela. Iako su utvrđena određena područja gdje oba modela pokazuju odstupanje u svim uzorcima, njihova usklađenost se može okarakterizirati kao zadovoljavajuća, a razlike minimalnima. Prosječna razina odstupanja bila je 0,27 mm za 90% podataka, što je vrlo blizu rezoluciji korištenoj pri laserskom skeniranju.