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Research Article

Quantitative Evaluation of 3D Printed Anatomical Objects: A Comparison of Optical Surface Scanning and Micro-Computed Tomography

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Abstract

Additive manufacturing technologies are increasingly used for medical purposes. However, questions are regularly raised about the accuracy of the anatomical models thus obtained. The present study compares two investigative methods that are used for assessing the degree of trueness of 3D printed replicas and presents recommendations for future analyses. The two techniques compared are optical surface scanning by structured light (OSS) and micro-computed tomography (μCT). The comparison was made by investigating an original cranial vault and its replica obtained by selective laser sintering (Eosint P 385, EOS GmbH, Krailling, Germany). OSS tests were conducted using a kolibri Cordless scanner (Fraunhofer IOF, Jena, Germany); μCT was performed with a vltomelx 240/180 machine (phoenixlx-ray, GE, Wunstorf, Germany). The degree of trueness of the replica was assessed with an iterative closest point algorithm (Geomagic Qualify software, Version 12, Geomagic GmbH, 3D Systems, Rock Hill, USA).The replica's deviations from the original, measured by OSS and μCT, respectively, were as follows: Homogeneous enlargement factor: 1.3% *vs* 1.2%; Mean shape deviation: +0.27mm (±0.15mm) *vs* +0.24mm (±0.23mm); Shape deviation <1.0mm: 99.95% *vs* 99.35%; Maximum positive shape deviation: +1.62mm *vs* +1.43mm; Maximum negative deviation: -1.65mm *vs* -3.51mm. Considering the coherent results obtained, we conclude that both OSS and μCT are appropriate for quantitative evaluation of 3D printed preoperative models. For objects with complex geometry, which are to be examined not only with respect to their visible surface, μCT is recommended. For highly x-ray absorbent materials and authentic bone material, OSS is preferable.

Introduction

Additive manufacturing technologies are increasingly used in medicine. The applications include preoperative planning and training in surgery. The 3D printed physical models currently obtained in this manner are frequently presumed to be exact representations of the patient-specific anatomy. However, the real accuracy and the definition of accuracy in this context are often challenged. According to Martelli et al. [1], 20.9% of articles on 3D printing in surgery, published between 2005 and 2015, stressed that the accuracy of the models was not always satisfactory [2-4]. Thus, scientific investigations are needed to evaluate how true the replicas are with respect to the original object. Furthermore, given the trend towards more customised medical and surgical care there is an increasing need for more precise models – notably in the field of reconstructive surgery of the bony skull and of the cranial vault [5-12]. Finally, the paucity of well preserved human cadavers for surgical training is encouraging the rising use of alternative techniques such as printed replicas in hands-on courses.

Against this background, the present study sets out to compare two investigative methods for assessing the degree of trueness of 3D printed replicas and provide recommendations for future analyses.

Materials and Methods

Materials

Two techniques were compared; optical surface scanning with structured light (OSS) and micro-computed tomography (μCT). The comparison involved investigating an original cranial vault (calvaria) and its replica which had been obtained as follows (Figure 1): A post mortem clinical computed tomography of the skull was performed on the donated body of a 53-year-old lady. In conformity with the national and cantonal legal framework, the donor had given informed, written

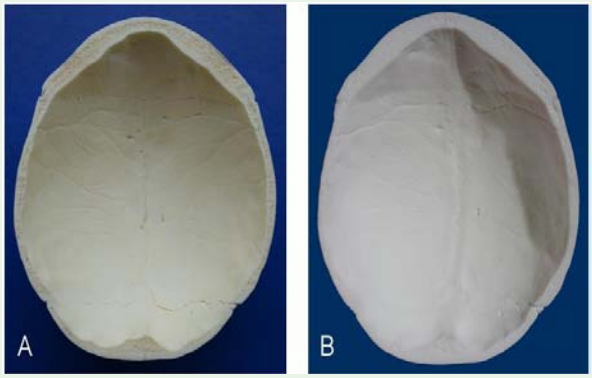

Figure 1: Objects evaluated. Inferior views of the original cranial vault (A) and the replica produced by selective laser sintering (B).

consent during her lifetime and bequeathed her body to our Anatomy Department, which provided the fresh frozen cadaver. Automatic segmentation, manual editing of the DICOM images (Digital Imaging and Communications in Medicine) and subsequent conversion into the STL format (Standard Tesselation Language) were performed using Mimics Software (Version 19, Materialise, Leuven, Belgium). The replica was then manufactured by selective laser sintering using an Eosint P 385 machine (EOS GmbH, Krailling, Germany).

Digitising the original and the replica

The original calvaria and its replica were digitised to 3D models. For this purpose, the two scanning methods were applied for each object: (i) optical surface scanning by structured light (OSS), using a kolibri Cordless scanner (Fraunhofer IOF, Jena, Germany) and (ii) micro-computed tomography (μCT), using a v|tome|x 240/180 machine (phoenix|x-ray, GE, Wunstorf, Germany). The OSS scan had a resolution of 170μm and a 3D point accuracy of <50μm. 22 scan positions were merged to acquire the complete surfaces. The μCT scan was performed with a voxel size of 88μm. At this resolution, the accuracy was also <50μm.

Comparing the replica with the original

The trueness of the replica compared to the original was assessed with respect to dimensional fidelity and, separately, to shape analogy. The dimensional fidelity was determined as a homogeneous enlargement factor between both models. To characterize the shape analogy, this factor was applied to the replica's digital 3D model, which was then aligned by the iterative closest point algorithm [13] to the 3D model of the original. After the alignment, the surface distances between both models were calculated. Geomagic Qualify software was used (Version 12, Geomagic GmbH, 3D Systems, Rock Hill, USA). The shape deviations were displayed as colour-coded maps.

Results

The analysis by structured light Optical Surface Scanning (OSS) showed that the replica was homogeneously enlarged compared with the original. The enlargement factor equalled +1.3%. After compensating for this factor, the replica's mean shape deviation was +0.27mm, with a standard deviation of ±0.15mm. This can be interpreted as a thickening of the calvaria by +0.54mm. Apart from the homogeneous dimensional deviation, 99.95% of the replica surface had a shape deviation of less than 1.0mm compared with the original. The maximum positive shape deviation amounted to +1.62mm, the maximum negative to -1.65mm. The first difference was located on the right side of the groove of the superior sagittal sulcus (sulcus sinus sagittalis superioris), while the second one was found along the left lambdoid suture (sutura lambdoidea) (Figure 2).

The investigations using micro-computed tomography (μCT) revealed a homogeneous enlargement of the replica by +1.2%. The mean shape deviation was +0.24mm (±0.23mm). 99.35% of the surface deviated less than 1.0mm. The maximum deviations equalled +1.43mm and -3.51mm. Some, but not all of the maxima were located at the same anatomical site as in the OSS study (Figure 3).

Discussion

In the present study, two methods used for assessing the degree of trueness of preoperative 3D printed replicas were evaluated: optical surface scanning by structured light (OSS) and micro-computed tomography (μCT). Two objects were investigated with both methods: an original calvaria (O) and its replica (R) produced through additive manufacturing (Figure 1). Our hypothesis was that

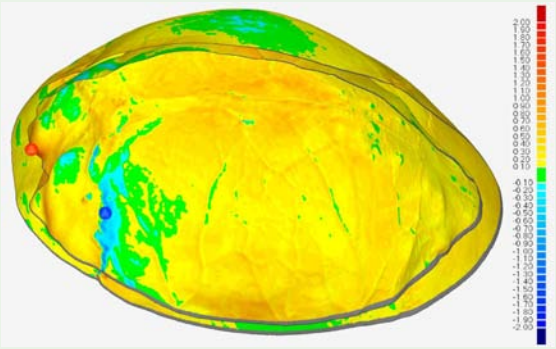

Figure 2: Results obtained by OSS. The replica's shape deviations against the original are shown as a colour-coded map (in mm). 99,95% of the surface deviated less than 1mm, apart from the homogeneous size deviation of 1.3%. The maximum shape deviations were +1.62mm (red dot) and -1.65mm (blue dot).

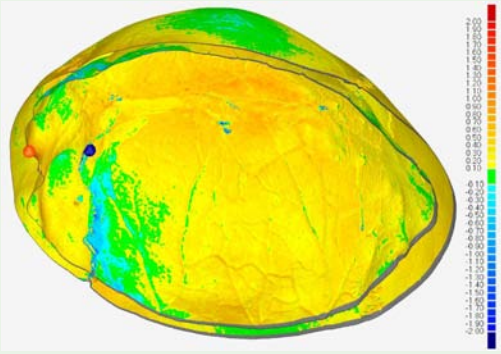

Figure 3: Results obtained by µCT. The replica's shape deviations against the original are shown as a colour-coded map (in mm). Apart from the homogeneous size deviation of +1.2%, 99,35% of the surface deviated less than 1mm. The maximum shape deviations were +1.43mm (red dot) and -3.51mm (blue dot).

both techniques would reveal consistent deviations between O and R. The results confirmed, or as Popper [14] would have it, do not falsify the hypothesis. Indeed, the homogeneous mean dimensional error R was measured +1.3% and +1.2%, respectively. The surface proportion of R deviating less than 1.0mm from O was determined to be 99.95% and 99.35%. The mean shape deviation equalled +0.27mm (±0.15mm) versus +0.24mm (±0.23mm). The maximum positive shape deviation reached +1.62mm versus +1.43mm and was found at the same location with both methods.

The only discrepancy between the results obtained with the two techniques concerned the maximum negative shape deviation (-1.65mm versus -3.51mm). The reason for this difference becomes apparent by comparing Figures 2 and 3. Unlike the maximum positive shape deviation, the maximum negative shape deviation lay in the same structure (the left lambdoid suture), but not at the same location. This difference may have occurred because OSS is unable to capture deep narrow cracks as is possible with μCT.

As a matter of fact, both methods have advantages and disadvantages. OSS only acquires the object's surface. This is an advantage when the investigation's sole purpose is to evaluate the outer, visible surface. However, acquisition by OSS is incomplete for objects with complex surfaces. Examples of such surfaces include the bottom of deep, narrow grooves, the lumen of canals or undercuts. Further difficulties for OSS occur with transparent, translucent or reflecting materials [15]. On the other hand, structures that are not accessible by optical inspection and entities within the object to be investigated can be captured by μCT. The limitation here relates to scanning of materials with high x-ray absorption. This limitation does not exist for OSS. Furthermore, μCT scanner costs are higher than OSS scanners, and they are more difficult to operate.

The fact that the investigation of one and same object (either the original or the replica) led to coherent measurements using both methods also suggests that the reported results are reliable (Table 1). Moreover, the differences between the two techniques, as measured on the same object, were significantly smaller compared to those measured between O and R. For example, the main shape deviation between OSS and μCT equalled -0.03mm (±0.05mm) and -0.02mm (±0.05mm) (Table 1), whereas it reached 0.27mm (±0.15mm) and +0.24mm (±0.23mm), that is to say ten times higher, between O and R. It thus seems justified to conclude that, for the quantitative evaluation of replicas, both methods are appropriate. Further, we conclude that deviations do indeed exist due to the production chain and they are not caused by inaccuracies of the investigative methods.

Table 1: Comparison of the methods on identical objects. The table shows the differences between the measurements obtained with the two methods (OSS versus μCT) on the one and same object (either the original – left column, or the replica – right column).

Parameter	Original (O)	Replica (R)
Mean size deviation (%)	+000.00	+000.00
Mean shape deviation (mm)	-000.03 (±0.05)	-000.02 (±0.05)
Shape deviation <1.0mm (%)	+000.00	+000.00
Shape deviation <0.1mm (%)	+007.20	+003.65
Maximum positive Shape déviation (mm)	+000.69	+001.07
Maximum negative shape deviation (mm)	-000.31	-000.85

Table 2: Assignment of deviations to the two main process steps. The table shows the deviations of the replica against the original, measured by OSS, as assigned to each of the two steps in the production chain (generation of the STL model; additive manufacturing).

Parameter	Clinical CT - STL model	STL model - 3D printed replica
Mean size deviation (%)	+001.10	+000.20
Mean shape deviation (mm)	+000.29 (±0.24)	-000.04 (±0.14)
Shape deviation <1.0mm (%)	+000.56	+000.00
Maximum positive shape deviation (mm)	+001.48	+001.05
Maximum negative shape deviation (mm)	-003.72	-001.01

Furthermore, the two main steps in the production chain – (i) from clinical CT to STL model and (ii) from STL model to 3D printed replica – were evaluated separately, in order to determine to what extent they contribute to the final deviations between O and R (Table 2). These results suggest that, in the production chain used, both the deviations of size and of shape were mainly caused by the first step (generation of the STL model), and less by the second one (additive manufacturing). However, taking into account the numerous factors that influence the accuracy of the final 3D printed models during their manufacturing (from the CT scan parameters, threshold values for segmentation of DICOM images up to the printing technology and the material used) each workflow will have to be evaluated specifically [3,4,16-20]. For a more detailed analysis of process errors, further investigations using the DICOM images as the benchmark, are to be undertaken.

Finally, with respect to future studies aimed at evaluating the accuracy and precision of preoperative models, the following remark can be made: The ideal gold standard for such investigations is the authentic anatomic original. In contrast to other disciplines working with cadavers (pathology, forensic medicine), Institutes of Gross Anatomy are the only ones allowed to use organs, parts or even whole bodies for such research purposes within the framework of Federal laws [21-23]. That is why these institutes have a central role to play in this kind of study. This fact is of strategic importance because as competition from the fields of cell and molecular biology increases, gross anatomists have a vital interest in research projects that can be conducted in cooperation with clinical disciplines, especially surgery and radiology [24,25].

Conclusions

Considering the coherent results obtained, we conclude that both OSS and μCT are appropriate for quantitative evaluation of 3D printed preoperative models. The choice of technique depends mainly on the study's purpose, the complexity of the object's surface and the material in which the replica has been produced. μCT is recommended for objects with complex geometry, where one is interested in more than the visible surface. For original bone material, as in the present study, OSS is preferable because when using μCT, large volumes of inner structural material (e.g. spongiosa) need to be removed from the digital model. For highly x-ray absorbent materials (like gold or platinum) OSS is advantageous.

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References

1. Martelli N, Serrano C, van den Brink H, Pineau J, Prognon P, Borget I, et al. Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review. Surgery. 2016; 159: 1485-1500.
2. Fasel JHD, Beinemann J, Schaller K, Gailloud P. A critical inventory of preoperative skull replicas. Ann R Coll Surg Engl. 2013; 95: 401-404.
3. Salmi M, Paloheimo KS, Tuomi J, Wolff J, Mäkitie A. Accuracy of medical models made by additive manufacturing (rapid manufacturing). J Craniomaxillofac Surg. 2013; 41: 603-609.
4. Huotilainen E, Jaanimets R, Valasek J, Marcian P, Salmi M, Tuomi J, et al. Inaccuracies in additive manufactured medical skull models caused by the DICOM to STL conversion process. J Craniomaxillofac Surg. 2014; 42: e259-e265.
5. Kim GB, Lee S, Kim H, Yang DH, Kim YH, Kyung YS, et al. Three-dimensional printing: basic principles and applications in medicine and radiology. Korean J Radiol. 2016; 17: 182-197.
6. Ploch CC, Mansi CS, Jayamohan J, Kuhl E. Using 3D printing to create personalized brain models for neurosurgical training and preoperative planning. World Neurosurg. 2016; 90: 668-674.
7. Radenkovic D, Solouk A, Seifalian A. Personalized development of human organs using 3D printing technology. Medical Hypotheses. 2016; 87: 30-33.
8. Wang YT, Yang XJ, Yan B, Zeng TH, Qiu YY, Chen SJ. Clinical application of three-dimensional printing in the personalized treatment of complex spinal disorders. Chin J Traumatol. 2016; 19: 31-34.
9. Eltorai AEM, Nguyen E, Daniels AH. Three-dimensional printing in orthopedic surgery. Orthopedics. 2015; 38: 684-687.
10. Owusu JA, Boahene K. Update of patient-specific maxillofacial implant. Curr Opin Otolaryngol Head Neck Surg. 2015; 23: 261-264.
11. Weinstock P, Prabhu SP, Flynn K, Orbach DB, Smith E. Optimizing cerebrovascular surgical and endovascular procedures in children via personalized 3D printing. J Neurosurg Pediatr. 2015; 16: 584-589.
12. Wu AM, Shao ZX, Wang JS, Yang XD, Weng WQ, Wang XY, et al. The accuracy of a method for printing three-dimensional spinal models. PloS ONE. 2015; 10: e0124291.
13. Besl PJ, McKay HD. A method for registration of 3D shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence. 1992; 14: 239-256.
14. Popper K. Logik der Forschung: Zur Erkenntnistheorie der modernen Naturwissenschaften. Schriften zur wissenschaftlichen Weltauffassung. 1935; 9: 1-248.
15. Go J, Hart AJ. A framework for teaching the fundamentals of additive manufacturing and enabling rapid innovation. Additive Manufacturing. 2016; 10: 76-87.
16. Choi JY, Choi JH, Kim NK, Kim Y, Lee JK, Kim MK, et al. Analysis of errors in medical rapid prototyping models. Int J Oral Maxillofac Surg. 2002; 31: 23-32.
17. Ibrahim D, Broilo TL, Heitz C, de Oliveira MG, de Oliveira HW, Nobre SM, et al. Dimensional error of selective laser sintering, three-dimensional printing and PolyJet models in the reproduction of mandibular anatomy. J Craniomaxillofac Surg. 2009; 37: 167-173.
18. Santana RR, Lozada J, Kleinman A, AlArdah A, Herford A, Chen JW. Accuracy of cone beam computerized tomography and a three-dimensional stereolithographic model in identifying the anterior loop of the mental nerve: a study on cadavers. J Oral Implantol. 2012; 38: 668-676.
19. Farzadi A, Solati-Hashjin M, Asadi-Eydivand M, Abu Osman NA. Effect of layer thickness and printing orientation on mechanical properties and dimensional accuracy of 3D printed porous samples for bone tissue engineering. PloS ONE. 2014; 9: e108252.
20. Lee KY, Cho JW, Chang NY, Chae JM, Kang KH, Kim SC, et al. Accuracy of three-dimensional printing for manufacturing replica teeth. Korean J Orthod. 2015; 45: 217-225.
21. IFAA (International Federation of Associations of Anatomists 2012) Recommendations of good practice for the donation and study of human bodies and tissues for anatomical examination. Plexus. 2012: 4-5.
22. Riederer BM, Bolt S, Brenner E, Bueno-Lopez JL, Circulescu ARM, Davies DC, et al. The legal and ethical framework governing body donation in Europe - 1st update on current practice. Eur J Anat. 2012; 16: 1-21.
23. University of Florida. Body donation programs in the United States. 2016. http://anatbd.acb.med.ufl.edu/donor-packet/general-information/
24. Peck D, Skandalakis JE. The anatomy of teaching and the teaching of anatomy. Am Surg. 2004; 70: 366-368.
25. Fasel JHD, Morel P, Gailloud P. A survival strategy for anatomy. Lancet. 2005; 365: 754.