INFLUENCE OF DIFFERENT MANUFACTURING TECHNIQUES AND MATERIALS ON THE ACCURACY OF ANATOMICAL SFF MODELS DERIVED FROM CT DATA

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ABSTRACT

Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) are gold standards for cross-sectional images of the human body. Furthermore, several images reformatting softwares have been developed in order to assist pre-operating diagnosis and treatment planning. These softwares offer the possibility to interface scanning equipments with Solid Free-form Fabrication (SFF) systems, to build a custom made replica of the anatomical site. Selective Laser Sintering (SLS) and Stereolitography (SLA) manufacturing techniques are two kinds of SFF processes that produce physical models through a selective solidification of a variety of fine powders and liquids. SLS and SLA technologies are getting a great amount of attention, particularly in oral and maxillofacial surgery. When applying 3-D medical models to clinical cases, model accuracy is a major concern. We investigate the influence of different SFF manufacturing techniques and materials on the shape accuracy of anatomical models, derived from CT acquisition of a dry mandible, using full-field measurement system such as fringe projection techniques. The application of such a method, allows for objective decisions regarding the precise location of bony anatomical landmarks.

KEY WORDS
Selective Laser Sintering, Stereolitography, Solid Free-form Fabrication, 3-D Digitizing Techniques

1. Introduction

Oral and maxillofacial surgeries are time consuming activities. Surgical planning helps minimizing surgical time and pre-operative decisions, reducing any risk connected with surgical treatment. Conventional radiographs, Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) are the imaging methods used to support the surgical planning process. 3-D visualization techniques can also be used in order to facilitate surgical planning [1]. Moreover, quite a few images reformatting softwares have been developed for that purpose (i.e. Analyze - Mayo Clinic, Mimics - Materialise NV, 3D Doctor - Able Software Corporation, SliceOmatic – TomoVision, DentalVox - EraScientific). These tools supply the surgeon with a set of images useful to a 3-D site analysis and measurement tools. Implant positioning planning instruments and the possibility to interface the CT/MRI scan with Solid Free-form Fabrication (SFF) equipments are often provided by the mentioned softwares. SFF technology, originally developed for industry, is getting a great amount of attention in the medical sector during the last few years [2]. Anatomical models find applications particularly in oral, maxillofacial and neurological surgery. In medicine they are used mainly for assisting diagnosis, planning treatment and manufacturing implants. SFF models effectiveness has been demonstrated in various surgical procedures [3]. Patients find the medical models helpful for informed consent. Medical modelling is an intuitive, user-friendly technology that facilitates diagnosis and surgical planning allowing surgeons to rehearse procedures readily and moreover improves communication between colleagues and patients. Furthermore SFF models can be utilized in the reconstruction of post-traumatic defects, tumoral resections and other complex craniofacial defects. SFF technology can be of benefit in the pre-operating estimation of the quantitative surgical outcome, reduces operating time and produces more predictable results. Currently the SFF techniques used for medical applications are: three-dimensional printing (3D-P), stereolithography (SLA), selective laser sintering (SLS), fused deposition modelling (FDM) and laminated object
manufacturing (LOM) [4]. Each of these different techniques builds up a model layer by layer using various materials (wide variety of powder materials in 3D-P, fine powders in SLS, UV sensitive resins in SLA, thin sheets of material, such as paper, in LOM and thermoplastics filaments in FDM) under various process conditions.

Model accuracy, a major concern for 3D medical models, had been previously studied. Lill et al. [5] generated CT data from a real skull, and produced a physical model by milling hardened polyurethane foam. The model deviation from the original skull was 1.47 mm (2.19%) on average. Klein et al. [6] reported that SFF techniques are more accurate than milling (a subtractive technique derived from numerically controlled machine processing). Barker et al. [7] studied the dimensional accuracy of an SFF model replicated from a CT scan of a dry bone skull. They found a mean difference of 1.90 mm and reported an accuracy ranging from 97.7% to 99.12%. Kragskow et al. [8] reported a similar study on patients with four different bone defects. They compared 3D visual models and SLA models. The mean difference in all cases was 1.98 mm (3.59%). Bianchi et al. [9] found that an SLA mandible replica, derived from CT scan data, exhibited dimensional errors ranging from 0.42% to 4.03%. Bouyssie et al. [10] reported about surface reconstruction accuracy. Their results for dimensional analysis showed an average difference of 0.12 mm with an accuracy of 97.9%. Choi et al. [11] reported about 16 linear measurements on a dry skull, a replicated 3-D visual model and a SLA model. The results showed that the absolute mean deviation between the original dry skull and the SFF model was 0.62 ± 0.35 mm.

The mentioned papers use repeated measurements, between anatomical landmarks, for comparison of the original anatomical site and the replica. The main reason is because they are quite well understood and very often used in anthropometrics and clinical medicine.

Differently from such classical approaches, our methodology uses a measurement technique based on the application of a full-field 3D shape acquisition process, described in a previous work of the authors [12], to evaluate and validate models derived from CT acquisition of a dry mandible. The long-term goal of the research is the adjustment of the optimal manufacturing process configuration, materials, manufacturing and post-processing parameters etc., relatively to each specific medical application. The aim of the present work is a preliminary models’ accuracy evaluation comparing two of the most used SFF techniques in the medical field, SLA and SLS. In the last case different materials were considered.

2. Materials and methods

We made 3-D visual, SLS and SLA models from a dry mandible. The manufactured models underwent fringe optical measurement techniques in order to acquire the 3D surface shape. Dense point cloud data, containing all the geometrical and dimensional information, are needed to compare the physical models. In this way it is possible to evaluate the influence of the selected manufacturing process and material on the accuracy of the replica. This section describes the process of models production and the related measurements.

2.1 SFF models manufacturing

Figure 1 shows the overall process of producing a medical SFF model. First, a dry human mandible, was prepared. It was placed on a CT scanner table, so that the Frankfort plane and the occlusal plane of the mandible were both perpendicular to the plane. This assured that the scanning position and orientation were identical to those of clinical practice CT scan.

![Figure 1. The general process of medical SFF model production.](image)

The mandible was acquired with 73 cross-sectional CT images. The CT data acquisition was performed using a Toshiba Xvision with a 1.0 mm section interval, a 1.0 mm section thickness, a 512×512 resolution matrix and at 0° degrees gantry tilt. Scanning was carried out with a tube current of 208 mA at 120KV. The resultant 2-D image data were stored in DICOM3 (Digital Imaging and Communications in Medicine) format, the international standard for interconnecting medical imaging devices on standard networks. The CT-slice images were used as the basic data for reconstructing the 3-D model. The bony areas were first segmented out from each slice image using 800 (12 bit depth=4096 grey values) as threshold value. The next step was the extraction of the surface of the object of interest within the data set. The 3-D visual model of the mandible was obtained stacking the segmented slices. We created surface model in STL (Standard Triangulation Language) format, the de facto standard interface from CAD to SFF. The transformation from sliced images to STL format was carried out employing the marching cubes algorithm [13], a well-known 3-D reconstruction algorithm. When creating the sliced file, a cubic interpolation algorithm can be used to enhance the resolution of the SFF models. Finally the
STL file was interfaced with the SFF machines. Two different manufacturing equipments were used: SLS Sinterstation 2500 and SLA 7000 System, 3D Systems, Valencia, CA, USA. The SLS mandible models were manufactured in DF (Duraform™) [14] and AC (AlpaCem) [15]. The SLA model was manufactured in RES (Somos® 11120 WaterShed™) [16], as described in Figure 2.

![Figure 2. Dry mandible (A), SLA-RES model (B), SLS-DF model (C), SLS-AC model (D).](image)

2.2 Measurements

Direct measurements were done on the manufactured models, using a 3-D digitizing system called Modela MDX (by Roland). Such a device allows the scan of an object through a point-to-point piezoelectric sensor. Using this system, we acquired a great part of the object without a repositioning. The accuracy is +/- 0.01 mm, even if the acquisition time is extremely long. The manufactured models were acquired by the above device, using a measurement methodology based on reference points system, as described in a previous work of the authors [12], combined with a best-fit alignment algorithm. In this way it is possible to objectively compare the replica models. The aim of the measurement is to highlight the influence of the manufacturing techniques and different materials on the accuracy of the replica. Dense point cloud data were generated and processed to obtain usable information. The software’s tools allow to: overlay, evaluate and report the measured deviation between different models. Polygonal CAD models are reconstructed using a low triangulation tolerance value, so that the loss of information is minimum.

3. Results

Figure 3 shows the results for the mandibles acquisitions. Filtering and smoothing, using the same parameters values, were applied to the point cloud data to obtain effective information.

![Figure 3. Point clouds superposition. Upper: SLS manufactured mandible in AC and SLS manufactured mandible in DF. On the left is depicted the error distribution and its average value. Middle: SLS manufactured mandible in DF and SLA manufactured mandible in RES. Lower: SLS manufactured mandible in AC and SLA manufactured mandible in RES.](image)

The SLS technique, upper part of figure 3, shows an average error value around 0.02 mm and the error distribution is very sharp. In the case of SLA, the average error value is around 0.1 mm but the coloured error maps show an excellent correspondence between the three models.

Measurement noise and shadow effects cause data dispersion (around 10% of points are outside an acceptable interval), as reported in the above graphs. However, from a functional point of view, such a phenomenon is not a meaningful effect for medical applications.
4. Discussion

When applying 3-D medical models to clinical cases, model accuracy is a major concern. This issue has been dealt with in other studies as described in a previous section of our work. In the literature the SFF model shape deviation from the dry anatomical shape is evaluated through the positioning of anatomical landmarks and the linear measurements of their distances. Full-field measurement systems, on the contrary, obtain the complete geometric information of an anatomical part, so that anatomical landmarks are not necessary. In this way, it is possible to compare, not only corresponding linear dimensions, but also free-form shapes. In a previous work of the author [12] was established the accuracy of an SLS manufactured mandible, in AC, with respect to the original dry one acquired by CT scan. The zone of maximum displacement is located around the gonion and the deviation is in the order of tenth of mm. The replica deviates from the original in the range [-0.17, +0.1] mms. As with any complex system, there are many potential sources of error and noise in such a process. These errors derive from:

- CT acquisition process,
- 3-D visual model generation,
- selected manufacturing process and materials.

The CT scanning stage is important, since the quality of the original CT images directly influences the accuracy of the 3D model. This stage can introduce errors in different ways, such as section thickness, pitch, gantry tilt, tube current and voltage, patient movements, metal artifacts or oral implants and the slice image construction algorithm itself. The section thickness is a primary factor [17]. One possible explanation for the satisfactory quality of our results is the use of thinner sections. In previous works [7,8] 1.5 mm and thicker (2-4 mm) sections were used, whereas our CT was taken with a 1.0 mm section thickness.

The 3-D model reconstruction stage is also subjected to errors. To select a proper threshold value is the major source of errors in this stage [18]. We selected different threshold values, between 700 and 1200 grey values, to reconstruct the mandible. The choice of a proper threshold is a very difficult decision. Low threshold will yield too big models, while high threshold will cause fine structures not to be reproduced. This makes it impossible to find a “correct” threshold. A solution for the threshold problem is to work with local thresholds for different regions of the models. We found the best results, in terms of accuracy, choosing a threshold value of 800 grey values. Additional sources of errors in 3-D model reconstruction include tessellation, proper connection between triangles edges, decimation ratio for surface smoothing and interpolation algorithms. The SFF manufacturers, that provide 3-D reconstruction softwares, are concerned with the ability to deal with topological incompleteness and surface smoothness. Some of these software packages, for example, use a bilinear interpolation algorithm in-plane, along the axial slices, and a cubic interpolation algorithm in the scanning direction, to improve the surface accuracy of the 3-D generated models derived from the segmented masks. More accurate technical data are beyond the scope of this paper.

Errors can arise also during the manufacturing of the model due to laser diameter and path, layer thickness, transformation of SFF materials etc. In order to evaluate the contribution of these factors to the accuracy of the models, we decided to manufacture the same STL file, derived from the dry mandible, with different manufacturing techniques (SLS and SLA) and materials (AC, DF and RES).

In the SLA process a laser exposes the photopolymers in the bath, causing curing from liquid to solid. Once the first layer is cured, the elevator type stage lowers by 0.06 to 0.15 mms depending on the desired accuracy, and further layers are cured and connected by self-fusing to the previous ones. At the end of the process, the elevator rises and the component is lifted out and cured in its entirety. Curing is needed before the prototype is ready for use. Hand-sanding may be required to mitigate the stair-stepping effect described later. The SLS manufactured object always presents overhanging areas about half-way down its height dimension. During the actual process these will need to be supported by slender sacrificial columns. Without these, the horizontal part of the component will sag. Thus, additional hand-finishing will be needed to snap-out these slender sacrificial columns and hand-sand any small stubs away from the surface. Additionally post processing can take the form of “baking” the model in a UV oven to fully cure thick sections. SLA parts are quite brittle and have a tacky surface, moreover, uncured material can be toxic so that ventilation is a must. On the other side, models’ transparency is very useful in some medical applications, such as for example orthognathic surgery treatment planning for impacted or ectopic teeth (pseudoanodontia). SLS mostly resembles SLA, except that the laser is used to sinter and fuse powder, rather than solidify liquid polymer. A piston moves upward incrementally to supply a measured quantity of powder for each layer. A laser beam is then traced over the surface of this tightly compacted powder to selectively melt and bond it to form a layer of the object. The fabrication chamber is maintained at a temperature just below the melting point of the powder so that heat from the laser need only elevate the temperature slightly to cause sintering. This greatly speeds up the process. The process is repeated until the entire object is fabricated with a layer thickness by 0.05 to 2 mms. Uncured material is easily removed, after the manufacturing, by brushing or blowing it off. No supports are required with this method since, overhangs and undercuts are supported by the solid powder bed. This saves some finishing time compared to SLA. Differently from SLA, no final curing is required, but since the objects are sintered they are porous. Much progress has
been made over the years in improving surface finish and porosity. The method has also been extended to provide direct fabrication of metal and ceramic objects and tools. Anyway, considerably stronger than SLA, sometimes structurally functional parts are possible.

SLS technique offers the advantage of the variety of thermoplastic usable powders. Moreover, considerable potential for the development of new materials for SLS remains, both to make them more suitable for casting processes and for the direct implantation of biocompatible materials [19]. In many cases SLS manufactured models are preferred to SLA ones, because the opaque material looks and feels more like bone, as can be seen in Fig. 2. It seems, from our measurements, that the selection of the manufacturing process and material does not affect considerably the shape accuracy of the final part. In fact the measured average error values and distributions are comparable between different technologies and materials. It seems reasonable that is the field of application of the model to select the proper manufacturing process and material.

SLS manufactured models are durable parts without tooling, heat and chemical resistant, machinable, weldable, readily-joined-mechanically or with other adhesives, showing an excellent surface quality, high feature definition, detail, high durability and stability. DF models are USP Level VI certified sterilized in an autoclave. AC models are fully functional prototypes with higher mechanical and thermal resistance [15]. On the other side SLA manufactured models offer the advantage of transparency but some problems are connected with this technique, as previously described in this section.

5. Conclusions

Although the influence of model accuracy on surgical planning is a key factor to the applicability of SFF technology, we could not quantify exactly how much each error source contributes to the model accuracy. The obtained results are merely qualitative and show that the selected process and materials do not affect considerably the shape accuracy of the final part. Some issues need further investigation. They include the possibility of an automatic threshold selection in the segmentation process and the SFF model manufacturing with various CT protocols. Furthermore, an in-depth study of technologies and materials is necessary to identify the better manufacturing solution relatively to the specific medical application.

References:
