Legal Medicine 33 (2018) 48–52

Contents lists available at ScienceDirect

Legal Medicine

journal homepage: www.elsevier.com/locate/legalmed

Short Communication

Applying 3D prints to reconstructing postmortem craniofacial features damaged by devastating head injuries

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ARTICLE INFO

Keywords:
3D printing
Reconstructive techniques
Postmortem examination
Autopsy
Facial identification

ABSTRACT

Postmortem facial identification is one of the most common techniques for establishing a deceased person's identity. In victims suffering from devastating cranial injuries, the feasibility of facial identification tasks can be compromised by damage to or disfigurement of the identifying cranial features. Although there are several reconstructive approaches, which help experts to restore the essence of person's physical appearance, thus enhancing the chances of recognition, only a few of them involve restoring the fractured cranial bones as the foundation for the reconstructed soft tissues. Here, we propose a technique based on replacement of heavily damaged hard tissues with generic prosthetics manufactured by 3D printing. Our approach does not require medical imaging technologies or other costly lab equipment. It is simple, affordable and relatively labor-efficient. The deceased's reconstructed craniofacial features can be subsequently assessed, photographed, drawn or otherwise reproduced in order to help determine his or her identity. In addition, the imagery can be displayed, published or broadcasted in media without concerns of being overly graphic.

1. Introduction

Facial features convey important information about a person's identity which is evident *a prima vista* and easy to assess with minimum technical demands [1,2]. Hence, facial identification, particularly if performed by law-enforcement authorities or family and next-of-kin ranks among the first identification techniques to be used on a dead body in forensic setting [3,4]. However, it is generally acknowledged that postmortem facial identification is extremely dependent on the decedent's state of preservation. For instance, in late stages of body decomposition, the facial features are altered extensively due to decompositional changes of the skin [5–7]. Similarly, victims suffering from extensive cranial injuries (e.g., comminuted fractures, bone compression, tissue loss) due to traffic or industrial accidents, explosions, falls from height, self-inflicted incidents involving fast-moving vehicles, etc. regularly exhibit major facial alterations.

To assess postmortem facial features of trauma victims visually or to depict his or her *in vivo* appearance (photography, sketches, facial approximation) [8], several facial reconstructive techniques have been proposed. Some of them, grounded in the cosmetic treatment of the skin and muscle patches, are applicable only if the head trauma is classified as slight or moderate, and damage to cranial bones is insignificant [9]. Others have shown that for substantial skeletal trauma, a complete soft tissue removal and external re-arrangement (on a fitting dummy, for instance) is the most appropriate approach [10]. In such cases, which are very frequent, there is often no effort (or only minimum effort) directed towards the hard tissue damage. This is mostly because repairing or re-assembling heavily fragmented skulls, with or without adhering soft tissues, is a non-trivial, and sometimes unjustifiable, task [11,12], especially if the features to be restored lack a proper foundation.

Lately, innovations in materials engineering have shown that a variety of anatomically accurate bio-models can be synthesized and implemented for living subjects in the form of prostheses or implants. One of the important aspects that made this possible is 3D printing. 3D printing, or 3D prototyping, allows experts to build a physical object from a computer-aided concept or a digital reproduction of a real-life object. It emerged as early as the 1980s [13–15], and further developed throughout 1990s and 2000s [16,17].

The first applications in biomedicine and morphological disciplines introduced 3D printers as an efficient commodity for manufacturing faithful copies of anatomical elements [18–26], valuable museum

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https://doi.org/10.1016/j.legalmed.2018.05.005
Received 26 February 2018; Received in revised form 16 May 2018; Accepted 21 May 2018
Available online 22 May 2018

displays [27] and rare paleoanthropological fossils [28,29]. Gradually, the technology has been adopted in clinical fields – while producing surgical prosthetics in ophthalmology [30], maxilla-facial surgery [31,32], traumatology [33], and cardiology [34]. In the field of pathology, 3D prints have been used to demonstrate rare morphological anomalies [35]. Applications in forensic settings were first proposed by Abramov in 1998 [36]. Since then, a number of publications have underlined the benefits in many aspects of forensic proceedings, ranging from initial evidence processing [12], to evidence examination [37], and ultimately to courtroom testimony [38–41].

Nowadays, 3D printing offers relatively affordable and user-friendly services. However, building physical copies requires printable 3D datasets pre-processed into digital point clouds with closed triangulated surfaces, otherwise known as polygonal models. In the context of forensic postmortem examination, polygonal models are accessible by a variety of acquisition modalities: computed tomography (CT) and its variants – multidetector CT (MDCT) or cone-beam CT (CBCT) [42]; angio-CT [43]; and magnetic resonance imaging (MRI) [44,45]. These systems produce volume data or volumetric 3D models. Alternatively, 3D optical scanning [12] and photogrammetry [46,47] have been largely emphasized as capable of producing high-resolution 3D digital reproductions, including color specifications. As opposed to volumetric data, the optical scanning is limited to surface morphology, which is reflected in terms of surface data or surface models.

The present paper aims to introduce novel applications of 3D printing for postmortem facial restoration, using as examples two forensic cases of unidentified individuals suffering from devastating head injuries.

2. Materials and methods

The studied material consisted of two forensic cases admitted for postmortem examination. Both individuals suffered from multiple trauma – Case 1 represented a 50-year-old male having suffered severe head trauma, whereas Case 2 was a 26-year-old female, who committed suicide by jumping onto railroad tracks. Her body was admitted for a postmortem examination with a devastating damage to her head featuring decapitation.

For both cases, in order to restore the facial features, damaged hard tissue elements were removed and replaced with artificial prosthetics manufactured by 3D printing. All 3D prints were built from generic digital volumetric models retrieved from the Digital Data Archive at our department. The models were selected on the basis of the individual's demographic profile (i.e., sex, age) and morphological concordance as assessed from contextual information and relevant autopsy protocols. Because the models in the archive represent a mixture of forensic and archeological skeletal cases with varying degrees of fragmentation, the overall state of preservation of the original skull was also taken into account.

In Case 1, a digital volumetric model of a male skull (cranium and mandible, CBCT: voxel size of 0.25, matrix of 640×640 px) was selected and edited to accommodate the head morphology and to match the cranial elements to be replaced. In Case 2, the printable 3D digital models were acquired by editing a female volumetric 3D model (MDCT: voxel size of 0.781, matrix of 512×512 px). The digital models were edited in the GOM Inspect program. This step was conducted outside the autopsy room by a trained forensic expert, although not a pathologist. Photographs and a preliminary sketch drawn by an autopsy assistant served as primary guidelines to adjust the digital model as closely as possible to the damaged skeletal parts. Once edited, the digital segments were error-checked and hole-filled.

In order to manufacture physical replicas, a MakerBot Replicator 2 printer was employed. MakerBot printers build a physical object using a fused deposition modeling technique and polylactic acid-based (PLA) materials with a glass transition temperature (Tg) of 60–65 °C, a melting temperature of 173–178 °C, and an ultimate tensile strength exceeding 50 MPa [48]. 3D prints are formed by layers of building material ejected additively from a moving computer-guided nozzle. In all cases, the cranial prints had to be supported by additional pillars of the building material (referred to as supports) identical to that from which an actual model is built. Prior to implementation the temporary constructions were broken off by hand or cut off with a scalpel.

The home interface for the 3D printer allows setting a layer thickness, inclusion of supports, infill (interior supports), temperature, and the speed at which the head moves across the workspace. The printing options were set as follows, layer thickness was set to 0.2 mm and 0.3 mm for Case 1 and Case 2 respectively; heat to 215 °C; speed to 50 mm/s; infill to 5%. The printed size was limited by workspace dimensions, which for the 3D printer in question are 28.5 cm by 15.3 cm by 15.5 cm. The accuracy of the prints varies from 11 μm vertically and 2.5 μm horizontally.

Re-shaping of the physical replicas was conducted inside the autopsy room by an oscillating autopsy saw. Initial, rough re-attachment of the prints to the preserved bones was accomplished by passing a metallic wire through small holes drilled with a power drill.

3. Results

The proposed technique for restoring damaged cranial elements in forensic trauma cases is grounded on a four-step pipeline, which includes: 1) editing of a pre-selected generic 3D model in order to match roughly the skeletal elements to be replaced; 2) fabrication of 3D prints with an appropriate setting to ensure accurate yet rapid processing; 3) adjustment of the physical copies and attachments to the preserved bones; and 4) re-arrangement and esthetic treatment of the soft tissues.

In both cases, the selected digital models had to be adjusted considerably to fit the preserved skeletal elements. In Case 1, the maxilla model was digitally separated from the cranium with a horizontal cut running at the level of the infraorbital foramina and then a diagonal cut across the maxillary sinuses (the resulting model of 28,500 polygons) (Fig. 1a). The digital mandible was used almost intact, edited only for small inconsistencies in geometry (the resulting model of 39,100 polygons). The editing was conducted in less than 20 min. The two printed items were manufactured in four hours and forty minutes (Fig. 1b). The consecutive adjustments, assembly and soft tissue treatment were carried out within one hour and thirty minutes (Fig. 1c).

In Case 2, the left part of the facial skeleton and the braincase were replaced by two separate 3D prints (Fig. 2a–c). In order to reduce the workload in editing and subsequent production, the teeth and alveoli were cropped off of the original model. While the facial component consisted of 25,200 polygons, the braincase part included 13,800 polygons. All additional morphology-related modifications were conducted on the printed fragments. The remote PC-assisted editing took approximately 20 min, while each print was produced separately in three hours (with a total processing time of six hours). The inside autopsy room phase featuring adjustments, repositioning and cosmetic treatment took approximately eight hours.

4. Discussion

Owing to massive technological developments in recent years, 3D printing today is a widely used technology, and there are a variety of simple, accessible and cost-effective printing devices available on the market. Although dependent on 2D or 3D imagery, 3D prints have several advantages over images (photographs, 3D images). They are minimally graphic, but effective in demonstrating the three-dimensional relationships between structures, features or pieces of evidence; they protect the integrity of forensic evidence; they are scaled, and can be produced at actual size, or at an increased or reduced scale in order to emphasize evidence specifics [12,49]. Most importantly, they permit demonstration and reproduction of forensic evidence in a tactile format [50]. In the era of digital data, this represents a novel medium of