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TECHNICAL NOTE

GENERAL

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An Overview of 3D Printing in Forensic Science: The Tangible Third-Dimension*

ABSTRACT: There has been a rapid development and utilization of three-dimensional (3D) printing technologies in engineering, health care, and dentistry. Like many technologies in overlapping disciplines, these techniques have proved to be useful and hence incorporated into the forensic sciences. Therefore, this paper describes how the potential of using 3D printing is being recognized within the various sub-disciplines of forensic science and suggests areas for future applications. For instance, the application can create a permanent record of an object or scene that can be used as demonstrative evidence, preserving the integrity of the actual object or scene. Likewise, 3D printing can help with the visualization of evidential spatial relationships within a scene and increase the understanding of complex terminology within a courtroom. However, while the application of 3D printing to forensic science is beneficial, currently there is limited research demonstrated in the literature and a lack of reporting skewing the visibility of the applications. Therefore, this article highlights the need to create good practice for 3D printing across the forensic science process, the need to develop accurate and admissible 3D printed models while exploring the techniques, accuracy and bias within the courtroom, and calls for the alignment of future research and agendas perhaps in the form of a specialist working group.

KEYWORDS: forensic science, evidence reconstruction, 3D printing, additive manufacturing, 3D imaging, courtroom, interpretation

There has been a rapid development of 3D printing materials, techniques, and printers in the last decade, as well as an expansion in the application of 3D printing across industries such as manufacturing, health care, and dentistry. There are dedicated journals to "*3D Printing in Medicine*" and "*Additive Manufacturing*," as well as primers for forensic radiologists (1,2), and practitioners can draw knowledge from these specific journals and publications. However, there are very few examples of 3D printing being applied in forensic scenarios in the published literature (3). This paper aims to demonstrate examples where 3D printing could be applied in forensic reconstructions and discuss some of the advantages and challenges involved.

3D printing uses successive layering of a material to build up an object in three-dimensions (x, y and z axes). 3D printing can also be known as additive manufacturing, due to the process of adding materials, or rapid prototyping (which encompasses both additive and subtractive manufacturing) (4). There are several phases to progress from a digital model to a printed replica including: image acquisition, image processing, 3D model creation, and translation of model data to 3D printer language (2). Digital models can be generated from volumetric data (e.g., from radiographic techniques such as computed tomography scanning), from point cloud data (e.g., from laser scanners), as well as from computer-aided designs (CAD) (3). Digital models saved as STL files can then be converted into machine language (G-code) via slicing, to enable reading by 3D printers.

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3D Printing in Forensic Science

The potential applications for 3D printed reconstructions in forensic science are numerous. Replicas could be utilized across the forensic science process: in crime scenes, in intelligence gathering, analysis and interpretation of materials, in police investigations, and in courtroom presentation of evidence. Furthermore, 3D replicas could be beneficial in forensic science teaching and public outreach programs. In order for 3D printing to be utilized in forensic science, particularly in courts of law, the discipline needs a recognizable evidence-base that underpins its reliability and applicability (5). At present, there is a distinct lack of empirical research around 3D printing in the forensic sciences, an issue that needs addressing. As a first step, this paper outlines some applications of 3D printing in forensic science, with the aim to inform the community of the potential benefits surrounding 3D replicas and to stimulate further research and discussion.

3D Printing Methods

The different methods of 3D printing were standardized into seven groups by The American Society for Testing and Materials in the US (ISO/ASTM 52900) (2). These technologies are described in Table 1 and illustrated in Fig. 1. Method selection will depend on the desired use and visual appearance of the replica, the material properties required, and the limitations of the printer (e.g., cost, time, print volume) (6). For example, to create a quick, low-cost replica a user may use a desktop FDM printer, whereas if a replica was required to have a higher printer resolution or use multi-colored materials, users may choose an SLA printer. Additionally, several printers and materials have been cleared for use in diagnostic medicine in the United States by the US Food and Drug Administration (FDA) (7-9).

TABLE 1—*Descriptions of the seven types of 3D printing technologies (2,6,13)*

Method	Description
Material extrusion (or fused deposition modeling, FDM)	In FDM, the material is released from a spool via an extrusion head that heats-up to dispense the material via a nozzle; this is deposited in layers onto a build platform. A variety of materials can be used (such as metal, plastic and polymers) that can vary in properties and are available in a variety of colors.
Vat polymerization (e.g., stereolithography, SLA)	Vat polymerization uses a liquid photopolymer material (plastic or polymer) that is selectively cured using a light source (e.g., a laser) within the build chamber. The print is built up layer by layer, with the build platform moving downwards after each layer is cured. The final part is cleaned and postprocessed by exposure to UV light to strengthen the build, followed by removal of support materials.
Binder jetting (BJ)	A bed of powder material (e.g., gypsum, metal or acrylic) is selectively bound using a jet of liquid bonding agent. The layers are successively added and fused, and unfused powder is removed postprinting. Postprocessing (such as thermal sintering) is needed to finish the build. Binder jetting is capable of full-color prototyping and does not use support structures.
Material jetting (MJ) (Polyjet)	Material jetting uses a liquid photopolymer material (e.g., plastic, metal or wax), which is jetted onto a build tray and cured (e.g., using light/heat) similar to a traditional inkjet printer. Multiple colors and materials may be used in one build. Additionally, separate support materials are used (e.g., from gel or wax) that can be easily removed.
Powder bed fusion (e.g., selective laser sintering, SLS)	A chamber containing a powder bed of material (metal, plastic, ceramic, or glass) is selectively fused by a source of high energy (e.g., a laser or electron beam). The build is supported by the un-sintered powder material, enabling features such as overhanging edges to be built without the use of support structures.
Sheet lamination	Layers of material (e.g., paper, plastic or metal composite) are bonded together as they are laid using an adhesive. The desired shape is cut into each layer (e.g., using a laser or knife).
Direct energy deposition (DPD)	The material (e.g., polymer, ceramic or metal) is fused simultaneously as it is deposited onto the build platform using a high energy source (e.g., using a laser or electron beam) layer by layer. DPD uses a deposition nozzle on a multi axis arm for specific deposition.

Fused deposition modeling (FDM) is generally a popular technique due to the affordability of FDM printers and the simplicity of the method; the majority of desktop printers use FDM technology. Conversely, material jetting is a highly precise method, but also the most expensive (6). Direct energy deposition (DPD) and sheet lamination are not commonly used in medicine or the forensic sciences, but Hodgdon (2018) notes that the latter technique has displayed potential for printing accurate osteological models (2). Carew (2019) tested the accuracy of 3D prints from six commercially available printers and found each to produce metrically accurate replicas, with replicas produced using selective laser sintering (SLS) found to be the most aesthetically true (4).

3D prints have been shown to be accurate, robust, and reproducible models (4,10-12) across disciplines, including in anatomy and medical sciences. Printed replicas have reported accuracy in the order of less than 1 mm (or 3%) difference from the true object (13). The accuracy of a 3D print is dependent on factors such as the image acquisition resolution, modeling parameters and printer resolution, which can be as fine as 0.01 mm (3-4,14,15). Optimization of printer settings, such as using a smaller printing thickness, can aid print quality (13).

Potential Applications

Crime Scene Reconstruction

The documentation of crime scenes using a terrestrial laser scanner is not a new concept; however, the literature is limited on the printing of these models. Rapid prototyping can help create a scaled-down model of a scene, which could illustrate complex information as a physical demonstration within a courtroom (16). The discussion of creating physical models has largely been applied to an indoor scene, but the creation of 3D prints does not need to be restricted to this (Fig. 2). For instance, Liscio (2013) 3D printed a vehicle accident that helped visualize its final position in relation to other objects (17). It was hypothesized that this technique could be taken even further by printing multiple models of vehicles in conjunction with the environment to demonstrate the engagement between them.

Ballistic Reconstructions

With the advancement of digital imaging, the reconstruction of bullet trajectories has also progressed. Traditionally, the path of a bullet from (or through) an object in a crime scene was demonstrated using the probe and string method, or more recently using laser pointers (18). Bullet trajectory reconstructions can now be generated using a variety of digital imaging techniques (such as laser scanning) as part of a virtual crime scene reconstruction (3). Trajectories within a human body (both living, or decedent) can also be modeled to show injuries or understand a sequence of events.

While digital imaging has been applied in bullet trajectory reconstructions, there is no evidence of research extending into 3D printing. It is perfectly feasible that a bullet trajectory could be 3D printed into a physical replica that can be handled as an alternative source for visualization. Such a printed replica could be a scaled-down model of a crime scene, providing a physical replica that allows the user to fully visualize the entire scene from potentially any angle (19). Further, it may be possible to 3D print a reconstruction of a bullet trajectory from within a living or deceased person. Villa (2017) illustrates an animation in

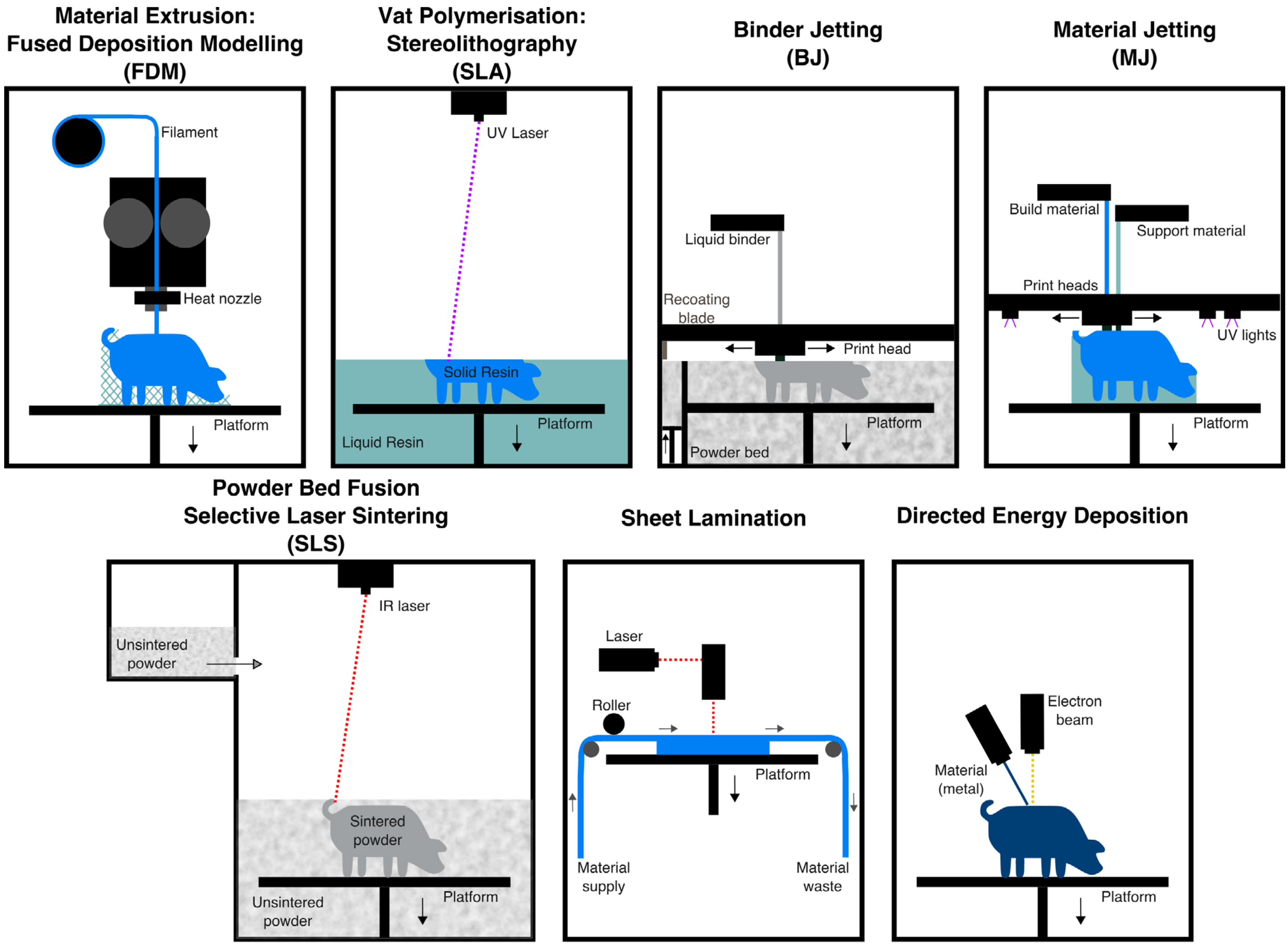

FIG. 1—*Illustrations of the seven types of 3D printing technologies (61,62). [Color figure can be viewed at wileyonlinelibrary.com]*

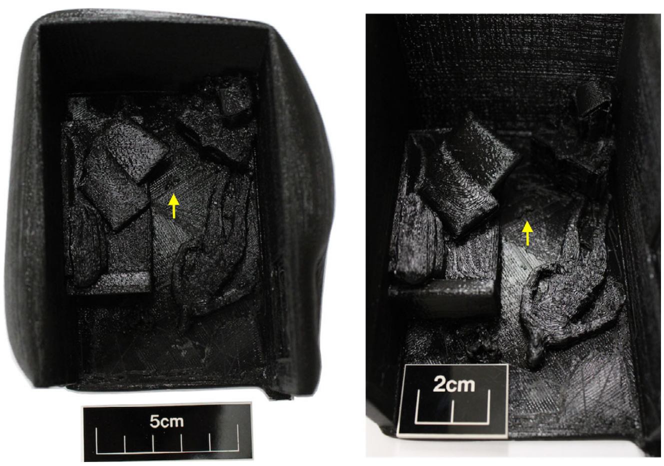

FIG. 2—*Photographs of a 3D printed mock crime scene. The 3D printed room is to scale, and the image depicts a room with a settee and a night-stand with a lamp. A mannequin is lying on the floor, and a gun is in the center of the room (arrow). Scale 1:30. [Color figure can be viewed at wileyonlinelibrary.com]*

which bullet paths represented by colored lines pass through a virtual skeleton (20). This scenario is a prime example of where a virtual 3D reconstruction could be replicated using 3D printing. 3D printing in trajectory reconstructions is a rich area with much scope to explore. Furthermore, this is not limited to bullet paths, and a similar workflow is applicable in bloodstain pattern analysis.

Pattern and Impression Evidence

For trace evidence, the use of 3D printing has focused on matching tool marks to injuries, normally in cases where there has been a homicide. Although Baier (2018) noted the potential for cognitive bias by adding to the existing evidence, using a 3D printed model the authors attempted to maximize the jury's understanding and retention of information by demonstrating cranial injuries created by tools thought to be used in an attack (21). This use of 3D printing tool marks on bone has also been achieved by Baier (2017) in the printing of tool marks in a case of dismemberment (22) and by Woźniak (2012) in a case of blunt force trauma to the head (23).

The concept of 3D printing a fingerprint at an increased scale for demonstrating comparisons in courtrooms has been discussed (17,24); some examples can also be found online that have trialed this concept and produced replica prints (25). However, while 3D printing a replica of a fingerprint (from a finger) is achievable, it is thought that printing a latent fingermark (from a surface) would be conceivably more difficult due to the difficulty in adequately capturing the mark, or given that the mark is only perceivably present in two dimensions (3).

The rapid capture of impression evidence is important, and optical recovery of footwear has been discussed at length (26). This has also incorporated the high-resolution documentation of tire impressions (27,28). In conjunction with the nondestructive documentation, it has been demonstrated that a 3D print can illustrate characteristics that cannot be seen on a traditional case (29). For interpretation, this is important as small features (such as feathering) will be better visualized and the comparison to the actual footwear more appropriate. In turn, the 3D printed model could be scaled to demonstrate these features within a courtroom (30).

Other aspects of 3D printed trace evidence are often overlooked. This technology could be applied to the *in situ* documentation of toolmarks in objects from a forced entry into a house or a safe. This could preserve striae before casting mediums have been applied. Likewise, 3D printing a complete scene could incorporate blood patterns on the walls to demonstrate its distribution; however, this notion has yet to be explored (see section on crime scene reconstruction). Finally, Liscio (2015) noted the potential to 3D print marks from the surface of a cartridge case, suggesting that a scaled-up model could be printed for inspection (31). This method could also be useful to show bullet deformation.

Forensic Archaeology

Forensic archaeological sites such as clandestine graves and mass graves contain themselves many different types of features that could be forensically relevant, such as human remains, personal effects, vegetation, as well as patterns or impressions (such as from spades, or tire tracks) (30). 3D recording processes can potentially capture entire sites including documentation of these features. Indeed, the use of digitization techniques for recording graves and remains *in situ* has been investigated, with promising results reported for accuracy, color, and spatial features (32,33). However, no empirical research exploring the use of 3D printing in forensic archaeology has been identified. Examples found online demonstrate the potential applications of 3D printing in archaeology, such as 3D printed replicas of a grave containing human remains *in situ* (34), underwater shipwrecks (35), and archaeological excavation sites (36).

The use of 3D printing in forensic archaeology is extremely novel, but has the potential to complement forensic archaeological practices, being a useful tool for visually demonstrating features that have since been destroyed or removed through excavation (Fig. 3).

FIG. 3—*A photograph of a 3D printed replica mass grave. The track marks from the mechanical excavator can be observed on the outside of the grave. The grave itself takes the appearance of a mass grave excavated by a 180 front-loader with a ramped entrance and a flat base. In the center, a secondary cut can be observed. Scale 1:100. [Color figure can be viewed at wileyonlinelibrary.com]*

Forensic Medicine

Imaging modalities have demonstrated their usefulness for documenting the internal and external changes to soft tissue and bone. This was demonstrated by Ebert (2011), who successfully printed various models that were documented using CT angiography, MRI, and surface scanning (37). These models included a ruptured kidney, an infarcted heart, and trauma to the cranium. In addition, the authors illustrated the need for 3D printing with regard to evidence that may change (such as in the case of a healing bruise); a bite mark in tissue was recorded using surface scanning and 3D replicated with full-color information (37).

Not only does 3D printing anatomy help demonstrate the relationships between lesions and bony features as an aid for teaching, it can also significantly improve the knowledge and skills of new surgeons, anatomists, anthropologists, and other professionals (38). For instance, these potential benefits were addressed by Dhumale (2018), who created a feasibility study for producing 3D printed hand models for cadaveric dissection in anatomy education (39). It is currently debated that these 3D printed models are minimally graphic in comparison to photographic images of the actual changes to the human body and therefore are suitable for permanent documentation (40). In turn, the printed replicas are ideal for courtroom demonstration, especially with regard to lay persons who are not familiar with anatomy (41). However, with the continuous improvement of technology, it could be argued that because of the accuracy of 3D printed models they can be as equally graphic as traditional documentation methodologies.

As outlined, there are numerous benefits for the use of 3D printing in forensic medicine; however, there are ethical implications that should also be considered. This is discussed at length by Jones (2019) who formulates ethical arguments on the permissions for use, acquisition of anatomical structures, treatment of the body, and commercialization (42).

Forensic Anthropology

Forensic anthropology is one of the few areas of forensic science (outside of medicine) where the application of 3D printing is beginning to be fully explored (4,22,40,43). Nevertheless, there is still very little published research directly related to this subject area. A case report by Baier (2018) introduced the use of 3D printed dismembered skeletal elements for courtroom presentation (21), and Carew (2019) assessed the accuracy of 3D printed skeletal models in forensic anthropology (4). Other publications using skeletal elements often stem from forensic pathology or radiology.

The anthropology discipline relies heavily on visual analysis and visual comparison and is well suited to the creation of physical replicas. When 3D printing is combined with volumetric imaging, internal bony structures that would not normally be visible can be printed out for analysis (Fig. 4) (3). For example, printing out internal structures, such as cranial sinuses or the endocranial vault, could be beneficial for teaching or training purposes, or for the exploration of such features for use in the assessment of biological profiling of human remains or pathology. 3D printed models could also be used to generate a new standard of illustrative models, replacing traditional cast models with replicas based on modern population data. Likewise, it might also be useful to perform analysis on 3D prints if the skeletal elements are not immediately accessible, such as when tissue is still present.

Forensic Taphonomy

The 3D documentation of taphonomic processes has been addressed by a number of authors (44,45). However, the potential of 3D printing for assessing documented minor details that allude to the decomposition process and visual insights into the deposition of a body remains largely unexplored. With regard to skeletonized remains, the bone taphonomy may limit the digitized process (46). However, with optimized capture, Mitchell (2015) demonstrated that using a 3D platform, the imagery can extend to the preservation of the body *in situ,* and analysis where 2D methods may be limited (47).

There is the potential for 3D printing and archival in this format. 3D printing of human remains that were documented *in situ* can also help understand the postprinting changes that have since happened to a recovered skeleton. For example, these changes could be due to the increased handling of the body. The research by Mickleburgh (2018) demonstrated the complexity involved in the decomposition of a human body (including body movement, disarticulation, and bone displacement) using 3D imaging, and this could be further replicated and analyzed using 3D printed replicas that can be handled and inspected (48). In addition, there is the possibility of creating a "multi-layered" printed model that could have removable layers or pieces to help demonstrate the taphonomic processes, or multiple "sequential models" that demonstrate how the taphonomic processes change over time. Such replicas would be beneficial in teaching, public outreach or courtroom demonstrations.

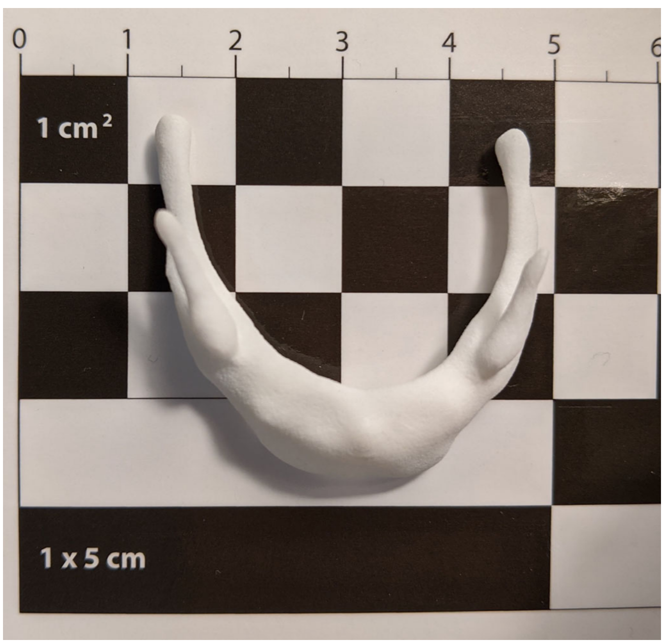

FIG. 4—*A photograph of 3D printed hyoid bone reconstructed from a postmortem CT scan. Scale 1:1. [Color figure can be viewed at wileyonline library.com]*

Forensic Odontology

The application of 3D printing is well established in dentistry and dental restorations, while more recently, 3D printing is beginning to be applied in forensic odontology (13). As with forensic anthropology or pathology, 3D printing is well suited to forensic odontology as replicas of human bones and teeth can be 3D printed with straightforward methods. 3D printing could be applied within in forensic odontology to bite mark analysis, facial reconstructions, age estimations, or for identification of individuals (13).

Rajshekar (2014) suggested that 3D printed replicas could aid in disaster victim identification and proposed that research to establish if it could be possible to digitize and 3D print fragmented portions of maxilla and mandible found at disaster scenes would be valuable (49). Portions that fit together could be digitally reconstructed and printed out as one piece, or the fragmented pieces printed out to demonstrate that they fit together. 3D printing was also suggested as a way to facilitate simpler and faster collection and interpretation of data (49).

A recent report by Biggs (2019) demonstrated how the application of 3D printing assisted in a disaster victim identification (DVI) case following a mass fatality incident (50). The authors were able to 3D print the maxilla and maxillary teeth from CT scan data of severely charred human remains, which was compared with an ante-mortem photograph of the decedent. This application of 3D printing aided in achieving a positive identification without performing unnecessary invasive procedures and used (CT) data that was already acquired via the DVI plan (50). Replicas of dentition from both ante-mortem and postmortem dental scans could also be printed out for a physical comparison to aid in identification investigations.

While forensic odontologists are accustomed to working with 2D images such as radiographs, any dentition was originally a 3D object, as such a physical 3D replica could provide a more realistic visual aid to support interpretation of dental features. Chaudhary (2018) suggests that while practitioners may be wary of 3D printing due to the advanced technology, high cost or a lack of awareness of the technique, 3D printed replicas offer the possibility of producing more robust forensic reconstructions for use in medico-legal cases, and as such ought to be further explored (13).

Facial Reconstructions

3D printing has been a useful development in forensic facial reconstructions with 3D printed skulls being utilized instead of traditional clay or plaster-based methods (24). For example, forensic facial reconstructions have been developed using 3D printed skulls produced from digital models of unidentified deceased individuals (51,52). While forensic facial reconstructions are unlikely to be considered admissible in court (particularly in the United States) (51), they are useful for forensic investigations and in intelligence gathering and have led to positive identifications taking place.

A study by Decker (2013) compared facial reconstruction methods using a 3D printed skull reconstructed from CT scan data from a living individual (53). This allowed the authors to use a realistic model that could subsequently be quantitatively compared to the original scans of the individual (53). Further studies could use clinical CT databases to further develop and validate novel facial reconstruction methods using 3D printed skulls, which could ultimately lead to facial reconstruction methods that are admissible in courts of law.

Forensic Engineering

The advantages of using digitization in forensic engineering cases were previously discussed (3). Forensic engineering and accident reconstruction can involve sample types such as buildings, large structures, and vehicles. While these are large scale and accordingly would need to be scaled down for printing, they are stable man-made structures that were likely originally developed using rapid prototyping and thus are highly suitable to 3D printing methods. Such 3D printed replicas may be used in the reconstruction or investigation of forensic engineering cases, and industrial accidents (16). For example, a crane was 3D printed for analysis following a structural failure (17).

Advantages

A primary advantage of implementing 3D printing into forensic reconstructions is the creation of a physical 3D replica that can be handled. 3D printed replicas allow for a higher level of interaction by the observer, since users can hold, rotate, feel, and inspect the object, something that is not possible with traditional 2D photographs or virtual 3D models.

3D replicas allow for the visual representation of evidence that otherwise would not be able to be presented in a court of law. For example, human remains themselves are not permitted to be presented in UK courtrooms (41), whereas a replica would not have the same ethical considerations or safety limitations. Additionally, the reenactment of events using a 3D printed replica of a room or a scene could potentially provide a more accurate representation than the traditional doll-house method (as in [54]).

3D printing can be carried out using data acquired from scanning techniques that are noninvasive and noncontact, providing an ethical workflow that does not further disturb any human remains or trace materials. The production of a 3D printed replica also helps to maintain the integrity of the original material, by reducing the handling of a material and thus helping to protect any fragile elements (55). Further, through having a physical replica it is possible to re-evaluate printed samples many years later; for example, after the original sample has degraded or after the burial/cremation of human remains, one could re-evaluate the existing print or even reprint the digital model.

3D printing allows for complex geometries to be printed out (either with or without the use of support structures), including obstructed or internal features, something that would not be possible to recreate using traditional casting methods. Additionally, objects can be scaled down to fit within a 3D printer or to make an object easier to hold, or conversely scaled up to make small features more visible to the naked eye or to enable tactile interaction (31). Rapid printing turnaround times are also feasible, depending on the method and the size of the sample (4).

Further, replicas may be printed using a range of materials, colors, textures, and flexibility (e.g., flexible clear resins available with SLA). It is possible to print using multiple colors on one build with certain printing methods, something that could potentially aid the visualization and interpretation of the replica, for example by using different colors for different features (2,37).

While some printers remain at a high purchase cost, the price of printers is rapidly decreasing with many low-cost options available (56). Additionally, users can also order prints from online ordering platforms, which allows the use of a variety of techniques without having to purchase the equipment (56), although there are drawbacks to this, such as questions around confidentiality and sharing of data.

Limitations

Published examples of 3D printed replicas in court are specific to demonstrative evidence and are limited to only a few cases (4). Baier (2018) suggests that this could be due to bias with regard to specific evidence demonstrations (21). Perhaps this is due to the underexplored validation of the techniques for courtroom application. Although 3D printed models can disseminate information to individuals, such as the public or jurors, the likelihood of it replacing the actual object or scene is debated, and the use of printing should be considered as complementary data. For example, it is currently suggested that bone replicas do not imitate exactly bone density (57) and that printed replicas ought to be presented alongside the original data such as a CT scan (4).

Likewise, for metallic or fragile surfaces, it is highly unlikely that the printing quality can replicate these characteristics. This limitation is not necessarily due to the printer itself, but a limitation in the initial documentation process as for example, surface scanning techniques can encounter difficulties when documenting such objects (3,40). There may be some loss of detail as a result of the 3D printing process that is dependent on the technique used, and the visual representation of the object may be further hindered in the stages of postprocessing. For example, build lines may be visible on the surface giving a false representation of the actual object. This is a particular trait of material extrusion (Fig. 5). Techniques, such as material extrusion and SLA, create support structures and build rafts in the printing process to ensure the object is securely built (Fig. 5), and the removal of these structures can also leave defects on the surface of the object (56). Furthermore, the physical properties of 3D printers vary widely between materials and printers, for example a print may be anisotropic or lack robustness, and powder-based methods such as SLS can result in a granular or brittle surface (56).

On the other hand, simplification of the evidence (potentially through smoothing parameters) may also raise questions. Aalders (2017) questions how much detail can actually be removed from object reconstructions, and at what point is that data no longer truly and accurately reflecting the findings (58). Questions should also be asked of those who are creating the models. Any technique undertaken by a “scientific expert” should ensure the individual has appropriate training to carry out their duties. Therefore, the authors ask, should these individuals be experts in the evidence type that is being replicated, the printing technique used, forensic science or anatomy, or all of these? As demonstrated by Errickson (2015), the intended outcome of 3D imaging and printing is highly dependent on the skill set of the professional (59). Therefore, an appropriate background is one of the most important factors in creating 3D printed models. If this is not considered, the value of the evidence is risked in court under the examination of the expert as a witness, which in turn may make the evidence inadmissible.

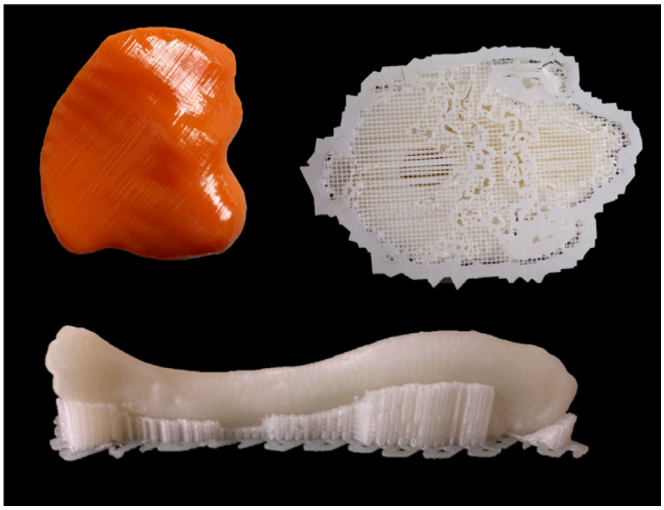

FIG. 5—*Photographs of three 3D printed replicas illustrating striations on the surface (upper-left), build raft (upper-right), and support scaffolding (lower). [Color figure can be viewed at wileyonlinelibrary.com]*

Similarly, there is little exploration into the risk of bias using 3D printed models. Baier (2018) suggests that the probative value of using 3D printed evidence should outweigh the potential prejudice, and rightly that the admission guidelines are followed (21). The issue is, only a few studies have addressed the use of 3D printed evidence in the courtroom (see [43]), Erickson (2019) recently highlighted the need for further studies to be undertaken before the implementation of 3D printed models because they may evoke emotional response and influence the decision-making process (60).

Future Facing Research

One reason that there is under-reporting of 3D printed models being used in courts of law is that it is not possible to determine the effect of the prints as visual aids because you cannot assess their impact on juries. This leads to a skewed representation of the use and application of 3D printed replicas, which is likely to be much greater than what is reported in the scientific literature. In addition, it is difficult to assess a "true representation" of one population in such a study. To address this imbalance and to work toward developing a best practice in 3D printing across the forensic sciences, key research questions and agenda points are set out below.

Key research questions:

- How are 3D models being created, who is creating these models, and where are these being created?—what is the intended goal?
- How and where are 3D printed models currently being used within the forensic science framework?
- Who is best prepared to produce 3D printed models?
- Who should defend a 3D printed model in a courtroom?
- Do we need specific training for producing 3D printed models in forensic science?
- Who owns a 3D printed replica in forensic science scenarios, what are the associated ethical considerations, and what happens to this data beyond the close of a case?

Thankfully, as demonstrated in this article there are a few publications striving to validate the development of 3D printed models in the forensic sciences (2,4). However, this validation process is sporadic and further communication between the forensic disciplines is recommended. This would allow a traceable, accurate, legal, and standardized approach. Therefore, the authors have suggested a potential research agenda for the future of 3D printing in the forensic sciences:

Agenda:

- Formation of a working group; to develop best practices for 3D printing in forensic science and to act as a validation committee for the development of protocols.
- Development of a primer for the use of 3D printed replicas in courts of law.
- Greater inclusivity between forensic science disciplines, multidisciplinary discussions and liaisons with other disciplines/bodies (e.g., radiology, additive manufacturing engineers, and material scientists consolidating their research).
- Widen awareness that validation of 3D printed models in forensic science is needed

Conclusion

In the forensic sciences, much of the 3D modeling that has been undertaken is in a virtual format. Initially, this was due to the inaccessibility of 3D printing technology. However, since the expiration of patents that controlled the availability of 3D printers, there has continued to be a slow uptake in its application. There are a number of different 3D printing techniques available, the selection of which must depend upon the sample type and the desired use of the print.

Overall, it is evident that the creation of 3D replicas in forensic science can be beneficial. As demonstrated in this technical note, there are a number of sub-disciplines that can utilize physical models. Advantages for the incorporation of 3D printing include physical interaction, visualization of transient objects and scenes, demonstration within courts of law, and in turn an increased understanding of the object or areas. On the other hand, there are issues such as the potential of evidence becoming inadmissible and the discussion on accuracy and representation. With the increasing potential of 3D printing and its application across the forensic sciences, there will be a community effort to create good practice guidelines that in turn will increase its future use.

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