Three-Dimensional Printing and Medical Education: A Narrative Review of the Literature

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ABSTRACT

Objectives: Three-dimensional (3D) printing has emerged in the past decade as a promising tool for the world of medicine. The focus of this article is to review how 3D printed models have been used in medical education.

Methods: PubMed was the article database used, and the search criteria included the terms *3D printing* and *education*. The exclusion criteria filtered out articles that were older than ten years, were not in English, and did not target a human population. There were 90 discovered articles, and 38 appropriate articles were determined after reviewing titles and abstracts.

Results: Three main themes emerged from this review: general medical education, surgical education, and patient education. The more specific findings can be further divided into: using 3D printed models for teaching anatomy and simulation training; and preoperative planning, intraoperative guidance, and postoperative evaluation.

Conclusions: The general consensus was that 3D haptic modelling was a useful tool for educating trainees, staff physicians, and patients. The models helped in increasing participants' understanding of anatomy and pathologies, and improving trainee skill set and confidence. There is much support to continue research in this area and to further develop ways in which 3D printing can help improve medical education.

RÉSUMÉ

Objectifs : L'impression tridimensionnelle (3D) s'annonce comme un outil prometteur pour le monde de la médecine. Le présent article révisera comment les méthodes d'impression 3D ont été utilisées dans l'éducation médicale.

Méthodes : La base de données utilisée pour les articles fut PubMed et les critères de recherche ont inclus les termes *impression 3D* et *éducation*. Les critères d'exclusion ont omis des articles qui dataient de plus de dix ans, qui n'étaient pas en anglais, et qui n'avaient pas comme cible la population humaine. Il y a 90 articles qui furent trouvés en tout et 38 de ces articles ont été jugés adéquats pour la révision.

Résultats : Trois grands thèmes ont été ressortis lors de cette révision : éducation médicale générale, éducation chirurgicale, et éducation des patients. De façon plus précise, les thèmes spécifiques suivants furent dégagés : l'utilisation d'impression de modèles 3D pour l'enseignement de l'anatomie et la formation par simulation, la préparation préopératoire, le guide intraopératoire, et l'évaluation postopératoire.

Conclusion : Les modèles haptiques 3D étaient reconnus comme un outil efficace pour éduquer les stagiaires, les médecins, et les patients. Ces modèles ont aidé à augmenter la compréhension de l'anatomie et de la pathologie des participants et ont augmenté la confiance et les habiletés des stagiaires. Ces preuves démontrent l'importance de continuer la recherche dans ce domaine afin de développer davantage de façons d'optimiser l'éducation médicale à l'aide de l'impression tridimensionnelle.

INTRODUCTION

The advancements of three-dimensional (3D) printing or rapid prototyping has been realized in several industries, such as manufacturing, engineering, and aerospace [1]. There has been an evolution in the 3D printing field in recent times due to the opening up of patents, and more affordable 3D printing [1]. In medicine, the applications of 3D printing have been noted in a variety of areas, such as bio printing, customized prostheses, and as an educational tool [1].

3D printing is the means of creating a physical model by continually printing in two dimensions while moving up the vertical axis. This process is commonly referred to as additive manufacturing [1]. 3D model designs can either be newly synthesized by a user or created through utilizing common imaging modalities such as magnetic resonance imaging or computerized tomography data [1]. The design of each model involves an image that has a variety of two-dimensional slices. The 3D printer is able to build a model based on all of the data points derived from the two-dimensional slices [2]. Many printers are able to automatically build proper

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support scaffolding for the models in order to ensure the model can be printed according to the design. There are a variety of different types of 3D printers, with some being industrial-built for research, and others built for the hobbyist, such as desktop printers. Along with these different printers, there are different methods of additive manufacturing as well. The more common methods are fused deposition modelling, selective laser sintering, and stereolithography [1]. In fused deposition modelling, heated synthetic elements are extruded through a nozzle according to the design, while moving up a vertical axis one layer at a time. This process can be likened to a hot glue gun that is progressively pushing glue out one layer at a time on top of the already hardened glue. With selective laser sintering, a laser or electron beam melts a shape out of a powder bed. More powder is added after the previous layer has hardened and the process repeats itself to build a model. Stereolithography involves a laser beam building up the model by focusing on certain parts of the liquid polymer in a vat. Consequent layers can be created through lowering the base of the vat as each resin layer is cured.

The focus of this review is to explore how 3D printing can be used as an educational tool; it is therefore important to define education. Education in this regard involves using 3D printed haptic models to teach a certain topic or to aid in the understanding of a certain principle or case. This type of review is quite novel in exploring how 3D printing may be used in general medical education, surgical education, and patient education. Other articles, which are described below, have focused on one of these specific topics, but have not explored all of these areas in one concise review. This type of literature review is important as the knowledge in this area is rapidly expanding. In July 2015, a similar review process lead to the discovery of 56 articles, with 29 directly appropriate for use in this review. At the current time—six months later—there are 90 articles, with 38 of them appropriate for use in this review.

Three main themes were determined in this review: general medical education, surgical education, and patient education. More specifically, these sections entail using 3D models for teaching students, simulating procedures, as a learning aid in specific surgical cases, and to educate patients.

METHODS

The PubMed database was searched in January 2016, with MeSH search terms including the keywords *3D printing* and *education*. The screening was carried out by the author. There was filtering for articles written in English, being published within the past ten years, and using humans. Filtering within the past ten years was intended to highlight the most current use of 3D printing in medical education. The initial search generated 90 articles, and was reduced to 38 appropriate articles after screening the titles and abstracts. Additional articles were added after reviewing the reference section of these initial studies. Article titles and abstracts were screened to ensure that the studies included models being used for educational purposes in either patients, students, resident trainees, or physician samples. Articles related to 3D modelling, surgical planning, and simulation were also included. Excluded were articles not related to medicine, or those that used 3D printing to explore transplantation, lab medicine, prostheses, or the creation of novel instruments. The present review includes 10 review articles, 9 pilot studies, 9 randomized controlled trials, 6 case studies, 3 prospective cohort studies, and 2 editorials.

RESULTS

General Medical Education

The premise of this section explores how 3D printed haptic models of human anatomy can be used effectively as a teaching tool and learning aid. These articles evaluated teaching and learning from a variety of perspectives. This section, however, will specifically discuss two major areas that have been highlighted: learning anatomy, including associated pathology and structure function; and using the models as a part of simulation training. The trainees under discussion in this section include medical students and residents. The education that trainees receive can be from general anatomical models or patient-specific models, allowing for both broad and targeted learning experiences.

Anatomy

The articles that specifically explored 3D printed models as a means of teaching medical anatomy all showed positive and promising results [2–4]. Human anatomy has traditionally been taught through cadaver dissection and, more recently, even through plastinated specimens. When analyzing these articles, there was clear discussion surrounding how 3D models were superior for anatomy teaching over the use of a cadaver or a plastinated specimen. This discussion included that 3D models are easy to store, reproducible, relatively cheap, scalable, capable of showing rare cases, dissectible, and do not entail the same ethical/legal issues as the previous methods of teaching anatomy [3]. Anatomy teaching has been further improved with recent advancements in 3D printing, such as being able to print in multicolour and using polymaterials in the models. In a pilot study by Lim et al. (2015), it was noted that for teaching anatomy, 3D models could also have value as an adjunct to a cadaveric-based curriculum [5].

In a randomized controlled trial by Li et al. (2015) there was examination of 120 medical students' understanding of complex spinal anatomy [2]. This examination occurred through a teaching module across groups utilizing a CT image, 3D image, or 3D printed model [2]. The results showed the 3D printing model group to have a significantly superior, confident, and more rapid response (75% compared to 62.5% in the 3D imaging group). It was also noted that "pleasure, assistance, effect, and confidence were more predominant in students in the 3Dp [printing] group than in those in the 3D and CT groups" [2]. Another study by Huang and Zhang (2014) went on to further explain that 3D printed models were superior to book or digital learning. There were additional studies that solely examined the use of 3D printed models for learning anatomy [2–4,7,8], while other articles discussed anatomy learning as an aside to their main study objective [9–14].

Through the use of 3D modelling there was an increase in the understanding of organ functions, various pathologies, and how disease processes may occur [15]. Using models to help facilitate learning or aid trainees to gain a more comprehensive understanding of a topic is supported by several of the articles reviewed [4,6,9,11–13,15–20].

Simulation training

A major benefit to using 3D haptic models is in simulation training for trainees. The simulation training literature corresponding to 3D modelling was discovered in a variety of medical fields, such as Otolaryngology [21,22], Orthopedics [23], Cardiology [11,12], Plastic and Reconstructive Surgery [15,16,24], Ophthalmology [6,25], Neurosurgery [9,17,18,26–32], Urology [14,20,33], Cardiovascular Surgery [34,35], General Surgery [19], and Anaesthesia [10]. The simulation training on these models allowed trainees to explore specific anatomy and improve their understanding of spatial pathology [23]. These simulated dissections and mock procedures were performed on patient-specific or general models. There were positive outcomes in all of the simulation studies, where they found models being received with high likeness to human anatomy. Participants found the models helpful in increasing their knowledge base and surgical skill set [13]. It was additionally noted that this type of simulation training provided a safe and comfortable environment for trainees to learn from their mistakes [6,22,29,32]. In another study by Abla and Lawton (2015), there was mention that these simulations might present more like a video game in which trainees and surgeons could work on specific skills in a stimulating environment. When practising with the 3D models, individuals felt free to play around in training and push their limits, as the models could be easily replaced [19]. Certain increased skills reported were dexterity [25], communication skills, exposure to real life experiences including complications and a changing environment [25,32], surgical instruments such as manual twist drills and catheters [18], laparoscopic techniques and minimally invasive surgical procedures [33], and various other operative techniques [4,19]. In one study by Mashiko et al. (2013), students were taught how to clip an aneurysm through use of a 3D haptic model, and were shown the procedure in an actual operation video. Once the students had learned about the "clipping direction, selection of clip, and the shape of the aneurysm in the actual operation" [29] they were better able to understand the procedure prior to the actual surgery. Of the total number of surgeons in this study, 75% rated their level of understanding of the aneurysm structure as excellent, while 25% rated it as good [29]. The assessment from the trainees reported excellent (83%) and good (16%) in regards to how the 3D printed elastic model increased their knowledge of the patients' aneurysm. In addition to trainees, staff physicians reported benefits from using 3D haptic models. Through using 3D models, staff physicians ensured that they received adequate maintenance of their skill set, increased competency training, and practised rarely seen surgical techniques [32].

In addition to positive feedback, there were also limitations noted for the 3D simulation models. One limitation lay in the lack of differing materials to replicate certain soft tissues. It was mentioned that "due to the imaging processing techniques, the model does not have the ability to demonstrate the presence or extent of an intra-arterial thrombus and the aneurysm wall thickness" [27]. An additional limitation was in the lack of the model's ability to mimic the consistency of various aneurysms or branch arteries. This included the lack of complications that one would find if an intraoperative aneurysm was to tear [9]. A similar idea was mentioned in that the models did not show intra-aneursymsal hemodynamic information or true aneurysm thickness [32]. However, in one neurosurgery simulation the scientists created a 3D model with an inbuilt pathology of differing consistency and density. In this way Waran et al. (2014) were able to create a more realistic model including densities reflecting differing tissues types, such as skin, bone, dura, and tumour [31].

In a few of the articles it was mentioned that using 3D models may be a good form of trainee evaluation. This could allow for standardized testing of trainees' surgical skills, where they could receive rapid feedback in a safe and realistic setting [22,32].

Surgical Education

This section explores the use of educational 3D models for surgical cases. Specifically, this surgical education is categorized into preoperative planning, intraoperative guidance, and postoperative evaluation.

Preoperative planning

Simulation can be a vital part of a training curriculum, however surgical training differs in that it is targeted as practice for an upcoming surgery [32]. This way residents and staff can appreciate patient-specific anatomy, practise the procedure prior to the actual operation (making note of potential difficulties), and map out the best surgical routes while determining the most appropriate tools needed [6,15,26–28,36]. In speaking towards surgical planning, Gerstle et al. (2014) suggested that by being able to handle the models, staff were able not only to appreciate complex underlying conditions and possible complications, but also to cut down on operating room time and increase efficiencies as well. Similar findings were echoed in other literature, noting that increased accuracy was attained during operations [13]. In exploring two recent cases, both Kiraly et al. (2015) and Pietrabissa et al. (2016) found the use of 3D models to be beneficial to their preoperative plan. Kiraly et al. (2015) used a printed model to explore a congenital heart disease in a 5-month-old infant with a complex obstruction. Pietrabissa et al. (2016) used a variety of models to increase residents' understanding of laparoscopic splenectomy prior to their operating. In exploring the residents' opinions on the benefits of the 3D models, 60% reported them as "very much useful", and 40% as "very useful."

Intraoperative guidance

In some articles there was mention of 3D models being used as a reference during a procedure in the operating room [1,13,27,37]. The models were colour-coded to highlight certain areas; this indicated an area of pathology that a surgeon may want to excise or avoid [1]. This use of 3D modelling may also be helpful for the surgeons to orient themselves while operating, especially when there is complicated anatomy [37].

Postoperative evaluation

The final area of surgical education in this review is regarding the use of 3D models as a means of postoperative evaluation. The 3D models helped staff in reflecting on how procedures went, and in further learning from their operations [4]. In this study by Torres et al. (2011), the physicians were able to use the patient model to assess the accuracy of an orthognathic surgery they performed.

Patient Education

The last area of medical education explored was patient education. Patients had an increased understanding of procedures and outcomes through use of pre- and post-surgical models. This included an appreciation of possible complications and unintended results [15,38]. When the physician used the patients' 3D model for explaining procedures, patients were better informed and had an increased understanding of the procedure to which they were consenting [32]. In one study [38], patients and their families thoroughly enjoyed the anatomical models, and ten of these participants rated the models to be of "very high value" and the remaining two participants rated the models to be of "high value." In a separate case study by Liew et al. (2015), the patient responded a maximum positive value (5/5) in that the model provided her with much beneficial information preoperatively regarding her upcoming procedure. It was reported that the models used "during explanation gave her (the patient) a much better idea of what was to happen during surgery, which reassured her, and consequently she reported feeling more involved with decisions regarding her care" [17]. This section of the review did not contain a large amount of literature, which opens up an exciting avenue for future research.

Interpretation

In discussing the literature explored there was a variation in sample size and power. For example, the study by Li et al. (2015) included the use of 120 subjects that were divided into three different groupings, with one being a control group. The findings of this study can be interpreted with significance as there was an adequate number of participants to provide statistical power, as was the case in other studies [3,5,11]. Conversely, in the study by Mashiko et al. (2013) that explored using 3D models for teaching there were only six junior surgeons' responses collected. This means we cannot accept these particular responses with the same level of credibility as the Li et al. (2015) findings. This low number of participants used was a common theme in a select number of the various randomized control trials, pilot studies, and prospective cohort studies reviewed [10,12,17,18,21,23]. One reason that numbers may be lower than expected is due to the novelty of these studies. Many of these studies are exploring simulation or teaching using 3D models in a way that has not been documented before. The focus of these studies is concentrated on their proof of concept rather than in the number of participants utilized. As design and printing become refined, more studies will adhere to a high level of credibility and evidence in order to support their proposed findings.

It should be noted that this review has been limited in the use of only a single database for its search. Another limitation of this article is that most of the studies were related to surgery, and thus not many articles focused on other clinical areas of medicine.

CONCLUSION

This review article is consistent with other similar reviews, in that 3D models have a major benefit towards medical, and more specifically surgical, education [1,6,13,15,16,20,24,39]. This supports the current work being carried out in 3D haptic modelling, and in future work regarding 3D printing as a medical education tool.

The future of medical education and 3D modelling seems to point toward printing models with varying materials, and thereby featuring an even more realistic model. These models could have a variety of colours, densities, textures, materials, and may even consist of working vasculature. Through the process of this review it is clear that 3D printing can be of help for medical schools, physicians, and surgeons in a variety of manners. Medical training programs could avail 3D modelling to help teach anatomy, and allow students to have a more hands-on approach. By creating a 3D printer friendly environment, students may suggest, and even print, models that will further advance their own independent learning and research pursuits. Physicians are able to implement the use of models to help them explain to patients how a certain pathology may be occurring, and empower patients to ask specific questions about their own health. Surgical staff can use a patient-specific model to simulate a procedure with a resident. They might also use these models to help determine how best to plan an upcoming surgery, and even take the model into the operating room as a guidance tool. There are no limitations as to how 3D printing can be applied to the field of medicine and, as mentioned earlier, there has been a significant increase in the number of articles published on this topic over the past year. In considering these previous notions, it is evident that the current research is timely and a promising area to continue exploring.

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