Use of three-dimensional printing for simulation in ultrasound education: a scoping review

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ABSTRACT

Background There is a significant learning curve when teaching ultrasonography to medical trainees; task trainers can help learners to bridge this gap and develop their skills. Three-dimensional printing technology has the potential to be a great tool in the development of such simulators.

Objective This scoping review aimed to identify what 3D-printed models have been used in ultrasound education to date, how they were created and the pros and limitations involved.

Design Researchers searched three online databases to identify 3D-printed ultrasound models used in medical education.

Results Twelve suitable publications were identified for inclusion in this review. The models from included articles simulated largely low frequency and/or high stakes events, with many models simulating needle guidance procedures. Most models were created by using patient imaging data and a computer-aided design software to print structures directly or print casting molds. The benefits of 3D-printed educational trainers are their low cost, reproducibility, patient specificity and accuracy. The current limitations of this technology are upfront investments and a lack of optimisation of materials.

Conclusions The use of 3D-printed ultrasound task trainers is in its infancy, and more research is needed to determine whether or not this technology will benefit medical learners in the future.

INTRODUCTION

Ultrasound is an essential skill in many medical specialties and subspecialties.[1] Outside of radiology, specialties such as emergency medicine, anaesthesia and general medicine are now performing ultrasound-guided procedures.[2] The spatial understanding required for effective ultrasound use is challenging for learners because they must interpret various textures and shapes while conceptualising a 3D anatomical mental model from 2D ultrasound images.[3 4] Novice learners have also found it challenging to recognise sonographic anatomy and optimise ultrasonographic images.[5] Such complicated tasks can become more automated with practice, which reduces sensory overload when a learner performs the procedure on a patient. Therefore, practice opportunities that recreate realistic ultrasound scanning scenarios and allow trainees to develop the necessary psychomotor skills seem advantageous for training curricula.[6]

Simulation is becoming increasingly popular in medical education because it allows trainees to become proficient and confident in technical skills before performing procedures on patients.[7 8] Furthermore, simulation-based education provides a stress-free and safe environment for trainees to make mistakes and ask questions without the fear of harming patients.[7] As a result, simulation-based education has been found to improve patient safety and reduce errors.[9] Task-trainers, also known as phantoms, are models used to simulate various technical skills. They can help trainees develop a greater understanding of a medical procedure and help them develop the manual dexterity and coordination required to perform the procedure.[10] The recent advances in three-dimensional (3D) printing technology have enabled the creation of inexpensive, durable and anatomically accurate task-trainer models.[11] These models are superior to traditional 'homemade' and commercial task trainers because the designs can be shared which means that they are perfectly reproducible within and between training centres that own 3D printers. Furthermore, since the models are often made using imaging data from real patients, they can be patient-specific. Altogether, this makes 3D printing the ideal method to create ultrasound phantoms for medical education.

The use of 3D-printed task-trainers to teach ultrasound (and ultrasound-guided procedures) in medical education is a developing topic with relatively little research; therefore, we conducted a scoping review. The objectives of this review are to identify areas where 3D-printed task trainers are being used for medical education, compile validated strategies used to create phantoms appropriate for sonographic imaging and highlight the strong points and limitations for the future of ultrasound simulation. The results of this scoping review will help guide future research, model creation and ultrasound education.

METHODS

A scoping review was chosen for this study because it is an ideal framework to determine the breadth of available literature on a given topic.[12] To develop our search strategy, study selection and data charting, we used the Arksey and O'Malley (2005) methodology.[13] We also considered the Preferred Reporting Items for Systemic Reviews and Meta-Analyses-Extension for Scoping Reviews (PRISMA-ScR) scoping review methodology recommendations.[14] No a priori protocol was registered for this review.

Eligibility criteria

For studies to be considered for this review, they must have used 3D printing to create task-trainers for sonography. The task-trainer must have also been created for/used in the context of medical education. The review included all peer-reviewed articles, dissertations and technical reports. Conference abstracts were excluded from this review as they often do not provide enough information about the 3D-printed task-trainer. All studies must have been written in English to be included in this review. There were no limitations on study design or year of publication.

Search strategy

Our search was conducted in October 2019. With input from a librarian specialist at the Memorial University Health Sciences Library, our research team developed search terms related to our questions identified above. We searched PubMed, Embase and Scopus databases for all relevant sources. The reference lists of all included articles were then screened for additional studies. The following search string was used for the PubMed database, with analogous strings used in the other databases:

1. Simulat* OR model* OR train* OR phantom*.
2. Ultrasound* OR ultrasonography OR echo*.
3. Medical education.
4. Three-dimensional OR 3D OR 3-D.

Study selection

The search results were imported into Refworks (Proquest, Alexandria, VA), and duplicates were deleted. Two researchers independently screened the titles/abstracts of all retrieved articles; anything that met the inclusion criteria outlined above was retained and a full version of the paper was retrieved. Next, full texts were read by both screening authors and those that met the inclusion criteria were included. Any disagreements were resolved through discussion between screening authors (or a third author if needed). Figure 1 offers a visual depiction of this process.

Data extraction

All relevant information from the included articles was extracted using a data extraction tool developed by two authors. The following study characteristics were extracted, if available: (1) author and date of publication, (2) location of research, (3) sonography simulated, (4) educational target population, (5) 3D printing/model creation details, (6) main results and (7) cost estimates. As there were only a limited number of articles included in this review, each of the articles had the data extracted by two authors and the results were compared. Any disagreements between the two reviewers were resolved through discussion (or a third author if needed).

Critical appraisal of the evidence

A scoping review aims to determine all available evidence on a given topic, and the methodological quality of the included studies is generally not included (unless relevant to scoping review objectives).[12] Our study aimed to identify all 3D-printed task-trainers being used to simulate ultrasound-guided procedures in medical education; therefore, we did not assess the quality of the studies included in this review.

Data synthesis

The relevant results pertaining to the research objective are presented in the data extraction tool (online supplemental table 1).

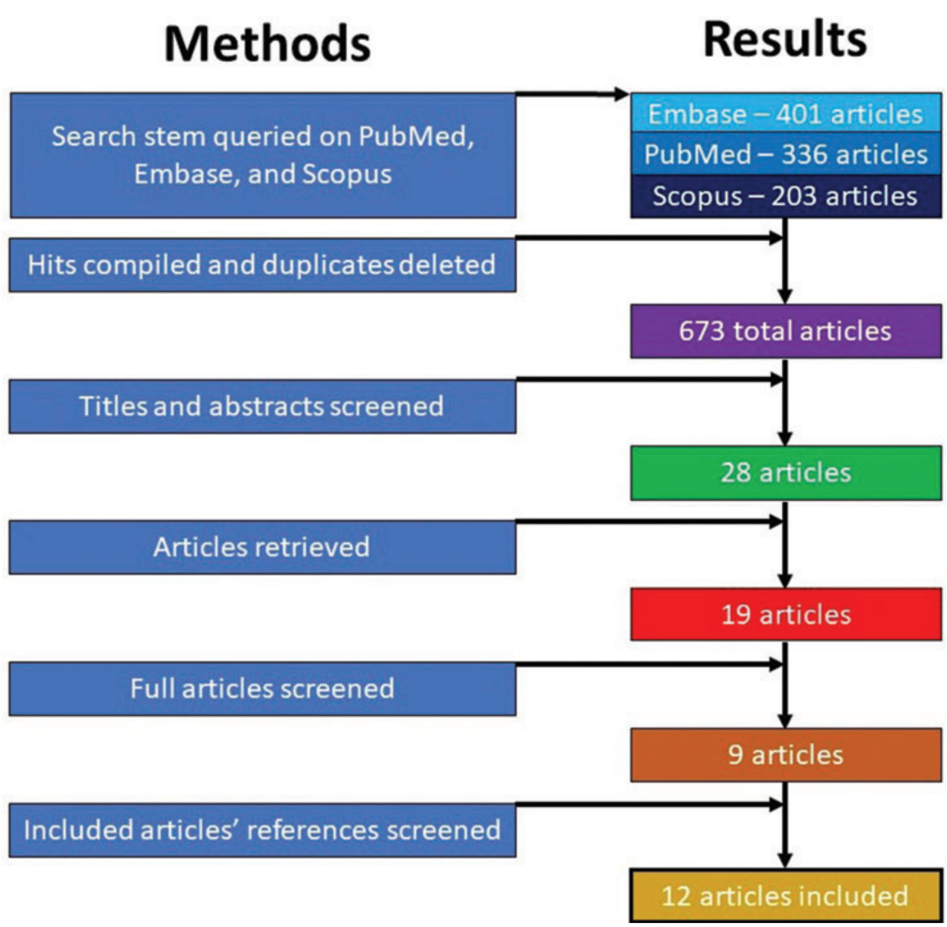

Figure 1 Flow chart depicting the methodology that led to the 12 articles considered for this literature review.

A narrative summary of the study characteristics is provided below.

RESULTS

Search results

The database search yielded 940 total results (401 from Embase, 336 from PubMed and 203 from Scopus). After duplicates were removed, 673 articles remained for title/abstract screening. Twenty-eight articles were identified that fit the inclusion criteria. Of these, 19 were successfully retrieved for further screening (reasons for loss: article not available in English (N=1), articles were only retrievable as posters (N=2), articles were only retrievable as conference abstracts (N=6)). After reading 19 full-text articles, nine met the inclusion criteria and an additional three were identified in their references; this resulted in 12 articles meeting the inclusion criteria for this scoping review. This process is presented pictorially in figure 1.

Study characteristics

The 12 included studies in this review were published between 2013 and 2019, and targeted medical trainees of all levels. The studies were published in eight countries, which included Canada,[8 15] India,[16] Ireland,[17] Japan,[18] Portugal,[19] the United Kingdom,[20] the USA[10 21–23] and Estonia.[24] There are task trainers for fine-needle aspiration of the thyroid, femoral artery access, renal biopsy and neuraxial procedures (N=5).[8 10 17 18 20–22 24] There are also task trainers for assessment of optic sheath diameter, EUS-guided biliary drainage, inter-atrial wall planning and intervention, and neonatal brain ultrasonography.[15 16 19 23] The majority of phantoms were created using a similar but varied approach discussed below and were well received by their testing population. All relevant study characteristics and key results pertaining to the study objectives can be found in online supplemental table 1.

DISCUSSION

How are 3D ultrasound simulators currently being used in medical education?

The majority of the 3D-printed ultrasound task-trainers in the literature are used to teach needle guidance procedures. Given that needle guidance procedures are invasive and require complex psychomotor skills, it is logical that these phantoms were developed to give medical trainees adequate practice before performing procedures on patients. For example, to complete neuraxial procedures, learners need to acquire the necessary hand–eye coordination to align the needle and ultrasound beam exactly.[25] Other trainers identified in the literature were used to simulate high stakes or low-frequency events. For example, one model simulated neonatal brain sonography, a procedure that is difficult to master due to a low number of patients to practice on and another simulated the measurement of optic sheath diameter, a procedure which can be uncomfortable for practice subjects.[15 23] Other models simulated guided biliary drainage and intra-atrial interventions which are invasive procedures.[16 19]

How are 3D-printed ultrasound simulators developed?

In all of the studies except one,[6] the 3D-printed ultrasound task trainers were created by processing CT or MRI images from real patients using computer-aided design software. The specific programs implemented to convert and process CT/MRI images differed between studies, but the overall procedure remained similar. Using real patient imaging data allowed researchers to construct anatomically correct models reflecting 'normal' and/or pathological features. From here, the 3D models differed depending on their intended use and the sonographic images that needed to be simulated. Echogenic anatomic features, such as osseous structures, were typically 3D printed directly, whereas hypoechogenic structures—also called tissue-mimicking material (TMM)—such as brain parenchyma, were created by casting various gels into 3D-printed moulds. 3D printed models must mimic different tissue densities to generate realistic images; therefore, researchers cast a spectrum of densities of agar, alginate, polyvinyl alcohol cryogel and silicone, with additives such as graphite powder. All model creation strategies are summarised in online supplemental table 1.

What is the future of 3D-printed ultrasound simulators?

This study revealed that the current use of 3D-printed task-trainers for ultrasound training is relatively limited. Given the portability and increased use of ultrasound by many clinicians, 3D-printed models may best serve as teaching tools for high stakes, low-frequency events. Specifically, ultrasound models for tasks that are invasive (eg, needle guidance), rare (eg, ectopic pregnancy) and time-sensitive (eg, acute appendicitis) may be of the highest yield, as practicing on standardised patients and volunteers may be impractical, inadequate and/or impossible. There may be an additional role for 3D-printed models in rural and remote locations, where patient volumes are low and resources are limited.[26] There are many commercially available ultrasound phantoms used to simulate tasks such as focused assessment with sonography for trauma, scrotal ultrasound, paracentesis and renal biopsy. However, these commercial models are often expensive (as much as 30 000 USD), require regular maintenance, are not able to reflect patient-specific anatomy, and may have anatomical inaccuracies.[21 24 27] Additionally, 3D-printed phantoms can be reflective of the anatomical variation seen in real life because they are printed from patient CT or MRI scans, which provides learners educational experiences beyond idealised anatomies. This is especially useful for perioperative planning when trainees and physicians alike may want to practice their approach for a patient with complicated anatomy.[10 21] This review demonstrates that it is possible to develop relatively low-cost and anatomically accurate ultrasound simulators via 3D printing, but the use of 3D printing for ultrasound simulators is in its infancy.

Current limitations of ultrasound simulators

There are some limiting factors for the widespread adoption of ultrasound simulators in medical education. Upfront production and maintenance costs are financial barriers that make it difficult for educators to access 3D printing teaching technology, including costs for 3D printers, computers, software, printing materials and troubleshooting.[28] Moreover, there are significant costs in terms of the time, creativity and expertise that are required for the first-time creation of 3D-printed task-trainers. As mentioned previously, a wide range of TMMs were employed in the literature, but a lack of overall suitability has hindered the development of 3D-printed ultrasound phantoms.[29] Discovering materials that allow for the independent manipulation of parameters such as the speed of sound, ultrasonographic scattering and attenuation, while also ensuring they are durable and inexpensive has been difficult for researchers.[18 29] The resulting time lag involved in testing and optimising the mechanical and acoustic properties of building materials to be used for 3D-printed structures has been another barrier to the widespread ability of educators to create ultrasound models with 3D printers.[30] The true educational efficacy of 3D-printed models also needs to be more rigorously assessed, as most of the studies evaluating ultrasound task-trainers had small population sizes and did not always include adequate validation by healthcare professionals.

Review limitations

This scoping review has some limitations. We did not register a priori protocol before beginning this review. Although we did not make changes to our outlined methodology, a registered protocol ensures that screening, selection and reporting of results is not influenced by search findings. Additionally, we only included studies published in English; therefore, we may have missed studies published in other languages. Even though the search strategy used in this review was intended to be as comprehensive as possible, we may have missed some articles. Our aim was to map out all available evidence of 3D-printed task-trainers used to simulate ultrasound-guided procedures in the context of medical education, so it is possible some articles were missed if they did not specifically mention their task-trainer was developed for the purpose of medical education.

CONCLUSION

This scoping review demonstrates that 3D printing can be used to create a variety of economically viable task-trainers to simulate sonographic image generation and ultrasound-guided procedures. Furthermore, this article highlights the various printing strategies and materials currently in use to create ultrasound training phantoms. Three-dimensional printed simulators are promising to be the optimal method for learners to develop ultrasound skills in low frequency, high stakes scenarios before performing these procedures on real patients, but the technology is yet to be perfected. The limited number of articles about 3D printed ultrasound simulators found in the literature suggest that implementation of this technology into medical student and resident curricula is under development and more research is needed to determine if this is a viable educational strategy for training future doctors.

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