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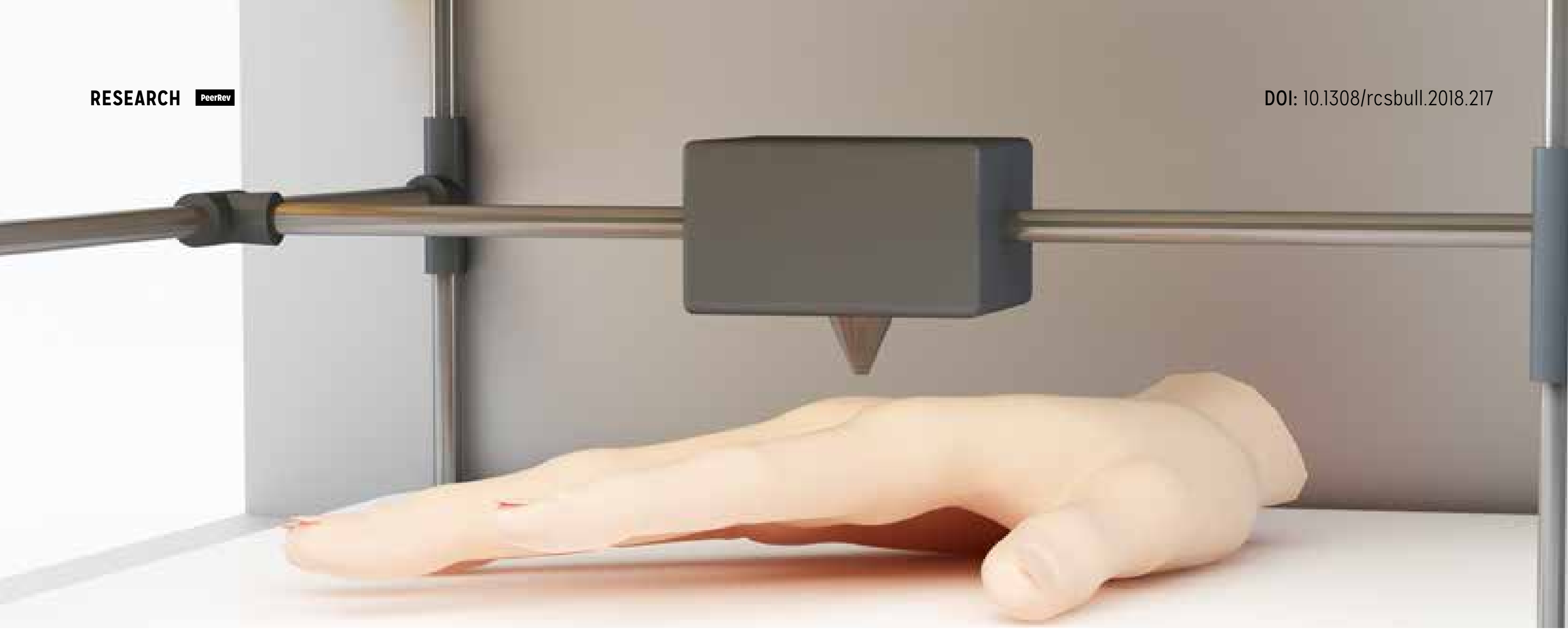

Producing 3D printed hand models for anatomy education using cadaveric dissection: a feasibility study

What are the potential benefits and problems?

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Many medical institutions are resorting to new methods of teaching anatomy to avoid the expense of using cadaveric material.[1] Dissection and prosection have been employed since the birth of anatomical science but, in light of changing social and ethical standpoints, the emergence of new health concerns and the unsustainable costs involved with teaching using cadavers, new resources are required to maintain a high level of anatomy knowledge for those planning to enter the surgical field.

Emerging technologies have been advancing, adding a clinically relevant approach to anatomical studies. Radio imaging, computer-assisted learning and cross-sectional anatomy have almost (and in some institutions, entirely) replaced dissection-based learning, despite evidence suggesting that these methods are not producing graduates with sufficient anatomical knowledge to enter medical practice.[2] Subsequently, there have been insufficient specialty applications to surgery, with the few applicants displaying below par capabilities, a concern voiced by The Royal College of Surgeons of England.[2] A discordance has emerged between effective and affordable anatomy teaching and learning resources, prompting calls for the development and validation of new alternatives.[3]

Three-dimensional (3D) printing is becoming widely available across many industries. Its applications are already widespread in the toy, architecture and electronics industries, but the education sector has yet to adopt and exploit its array of benefits. The object of this study was to introduce 3D printing to the anatomical model development process and to understand how the field of anatomy may benefit from affordable, portable and accurate learning devices.

METHODS

Dissection

Three freeze-preserved cadaveric hand specimens were obtained for dissection. The hands were dissected out from superficial to deep structures, with scans taken at intervals to display essential anatomy for undergraduate comprehension. The main structures presented within the superficial prints were tendons (*flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus*), the palmar aponeurosis, superficial palmar arch, median nerve, thenar and hypothenar eminences and extensor digitorum. The structures presented in the intermediate prints were the carpal tunnel, superficial palmar arch, common palmar digital arteries, proper digital arteries, recurrent branch of median nerve. Within the deeper prints were the carpal tunnel, palmar parts of tendons, lumbricals, adductor pollics (oblique and transverse head).

Figure 1 Trial scan showing clamp stand set-up providing 360-degree access to the hand for the scanner head (top left); superficial dissection (top right); extensor digitorum tendons (bottom left); superficial palmar arch and common palmar digital nerves (bottom right).

Scanning and printing

Once these structures were exposed in their respective layers, the hand was suspended by a clamp stand, allowing 360 degrees of access for the scanning head of the Hexagon Metrology ROMER Absolute Arm (Figures 1 and 2). The scanning took approximately 5–10 minutes per hand, taking care to overlap the scans so that all angles were covered – a process that is essential to the accuracy of the final print and overall model. The digits were pinned apart to allow for scanning of the interdigital spaces. The 3D scanner communicated with Remote Desktop Services software, to create a 3D point cloud of the object being scanned. This scanning technology allowed an accuracy of up to 4 microns. The 3D model was then converted to printer code by being 'sliced' using Makerbot Desktop for the Wanhao Duplicator-4 or Stratasys Catalyst for the Stratasys uPrint. The modified scanning data were then sent to the 3D printer for fabrication using polylactic acid filament in the Wanhao or Acrylonitrile butadiene styrene in the uPrint.

Once printed, the models were then filed using Marksman precision needle files, primed, painted and finished with a surface lacquer. The precision needle files were required to return the base of the model back to its correct anatomical shape following removal of support material (ie additional material added by the slicer to support the model while it is being printed). The models were then painted by an anatomy artist, with supervision from an anatomist.

Figure 2 Deep dissection showing carpal tunnel and flexor digitorum tendons passing through (top left); tendon of *flexor pollicis longus* and oblique and transverse heads of *adductor pollicis* (top right); elevated branches of median nerve and superficial palmar arch for detection by scanner (bottom left and right).

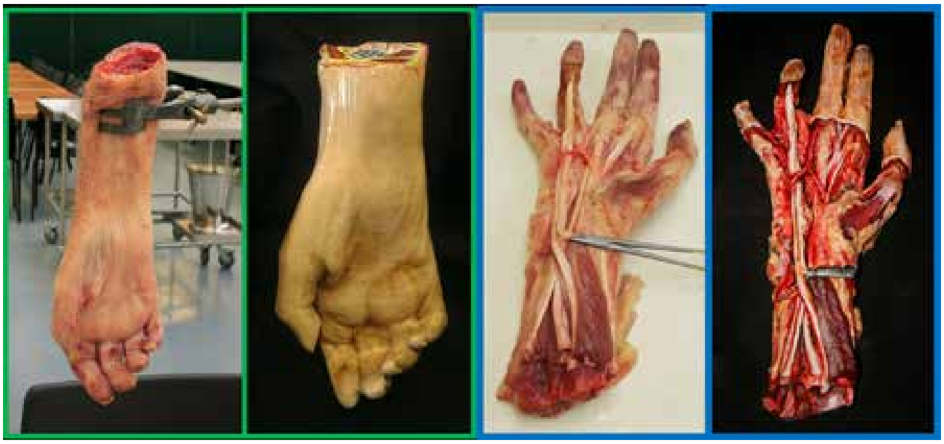
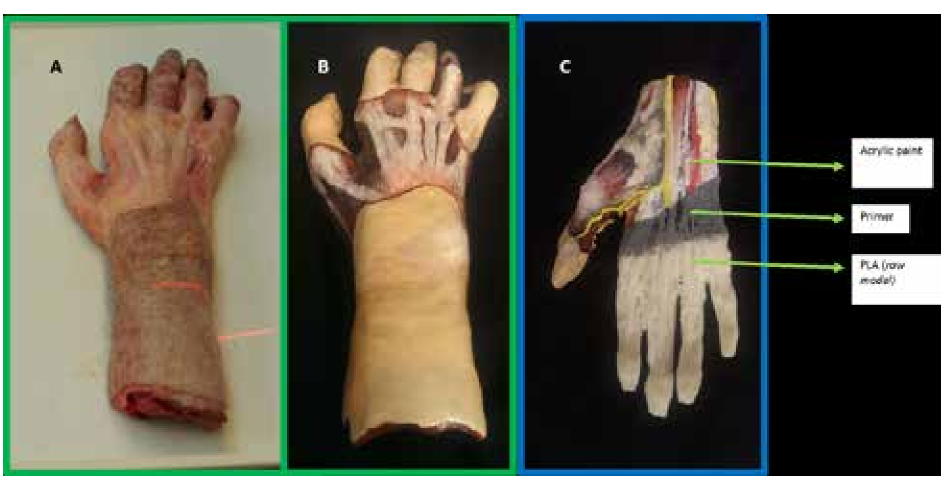


Figure 3 Trial whole hand scan (left); first model made of trial scan; superficial dissection showing superficial palmar arch and strained tendon of *flexor digitorum superficialis* on digit 4; model of same (right).

Figure 4 Deep dissection (left); model displaying tendon of *flexor pollicis longus* and oblique and transverse head of *adductor pollicis*; intermediate dissection showing *flexor digitorum superficialis* and *flexor digitorum profundus* tendons, medial nerve and branches, superficial palmar arch and branches, and superficial muscles of thenar eminence; model displaying this anatomy (right).



RESULTS

A total of six hand models were produced. The models depicted an array of anatomy appropriate for undergraduate medical education (Figures 3, 4 and 5). A detailed timeline was established to understand the feasibility of producing 3D printed models: dissection took 3–5 hours, scanning time was 10 minutes, printing 18–20 hours, filing and painting (including drying times) around 48 hours, making a total of less than 70 hours.

Prices were compared to carry out a cost analysis of model production, using Edinburgh and Warwick University approximate expenditure on current anatomy teaching resources. Cost of dissection were £20 for the dissection set and £150 for the hand (cadaver costs of £1,500/cadaver include staff salaries, maintenance of building, transport, equipment, lighting, heating, storage facilities, chemicals, cremating and coffins).[8] Comparative costs for a typical manufactured anatomy models would be £8,000 for 4–6 models (2015–16)[8] and £400,000 for 200 plastinated models.[14] Costs for the scanner would be £70,000 to purchase or rent £100/hour (these costs not included in our comparison, owing to collaboration) and no consumables were used. Primer, acrylic paint and lacquer cost approximately £3/hand and artist labour/model (optional) approximately £60. The two costs of the two printer types (Table 1) and the overall financial efficiency of producing anatomy models using 3D printing over purchasing standardised manufactured models were compared.

DISCUSSION

This study revealed the enormity of the task facing anatomy education. With the declining presence of cadaver-related dissection classes in medical schools and the coincidental emergence of 3D printing as production technology, this study aimed to understand the capabilities of 3D printing in overcoming current issues in anatomy education. To date, there have been few publications examining the potential role of 3D printing in medical education. We have piloted, designed and trialled innovative methods of producing suitable anatomical teaching and learning resources, showing particular economic advantages.

Anatomy education

The models designed in this pilot study have wide applications within anatomy education – with results suggesting the feasibility of producing such teaching and learning resources in most medical institutions when collaborating with engineering departments offering technical expertise and equipment. The short time span recorded in producing these models offers the possibility for departments to use these methods and produce their own 3D anatomy teaching resources. Such investment in 3D printing technologies will save money being spent on traditional anatomy models in the long term. If financial resources did not impede development, medical institutions could also provide specific models for their students relevant to their stage of training throughout their anatomical studies throughout the course of a medical degree. For example, undergraduates studying the thoracic cavity could be provided with accurate 3D printed lung models, increasing their learning potential. The key aims being targeted in the fabrication of new models were accuracy, affordability, durability, portability and replicability.

Accuracy

From descriptive results obtained by comparing the painted hand models with the pictures of relevant dissections, a high degree of correspondence and accuracy is achievable. The concerns of Chan and Cheng[4] about low-fidelity models as 'external representation systems' swamping anatomy education have been mitigated to a large extent with our results. The greatest criticisms were regarding shape and surface detail of anatomical structures but, with the use of the Hexagon Metrology 3D laser scanner, these obstacles have been overcome. The topographical contours allow for 3D comprehension of spatial relationships, with surface detail being mirrored to the original prosection. The print accuracy of up to 4 microns can eradicate previous concerns from surgical colleges regarding lack of correct anatomical spatial relationships in anatomy models. Each print displayed the desirable surface anatomy, although finer structures were compromised owing to their small size. Manipulating the scale of the print object may allow this issue to be overcome.

The models are limited to surface accuracy only, although developments in 3D printing and scanning technology may see this rapidly advance to internal accuracy as well. McMenamin *et al* highlighted the capabilities of 3D printed models produced from patient magnetic resonance and computed tomography images. Although these images offer a wider degree of accuracy, adding internal accuracy to their make-up, their surface-scanning resolution is less comparable to fixed or hand-held surface scanners such as the Hexagon Metrology ROMER Absolute Arm.[5] A future combination of both technologies may provide highly accurate internal and external features of reconstructed plastic anatomy for medical education.

The models are understandably textually inaccurate and this drastically reduced the similarity of the models to real human tissue. Although most anatomy can be learned visually, it is widely accepted that kinaesthetic approaches to anatomy learning are highly beneficial, especially for deeper processing and longer memory retention.[6] As advances are made in material science and steps are made to improve 3D printing materials, more accurate textures could be applied to improve this factor.

Table 1 Printer cost comparison

Activity	Printer (£)	
	Wanhao Duplicator-4	Stratasys uPrint
Polylactic acid	9.90[a]	200.00[b]
Hand (100–140g)	1.00–1.40	8.66
Approximate additional costs	30.00[c]	250.00[d]
Charge rates/gram	0.30	2.00
Total cost/hand	30.00–40.00	260.00

[a]1-kg roll
[b]3-kg roll
[c]Wear and tear, failed models, wasted material, maintenance
[d]Non-reusable printing bases, chemical wash to remove support material

Clinical relevance

Concerns with a lack of 'pathological authenticity' in anatomical models have been overcome with successful prints displaying biological anomalies.[7] These 3D prints offer further scope for providing examinable tools or mobile learning devices. For instance, the initial whole-hand print (Figure 3b) accurately replicated the surface features of the specimen, visually demonstrating a Dupuytren's contracture in the fifth digit (confirmed by a consultant hand surgeon), as well as atrophy of the thenar eminence. These examples highlight the potential of the models for teaching hand pathology from superficial characteristics with which a patient could commonly present in a clinical setting.

Portability and durability

The models are lightweight and durable because of the characteristics of the polylactic acid printing filament. These attributes mean the models can be used outside of educational establishments, increasing the learning potential of the student beyond the classroom. For medical students studying over the course of a five-year undergraduate degree with limited time for the study of anatomy, the ability to take models home for further study will provide proportionally larger benefits for medical education establishments. The durability offered by polylac-

Figure 5 Superficial dissection of dorsum of hand (A); model of dorsum of hand showing tendons of extensor digitorum (B); this model was printed with the Stratasys uPrint to compare print quality with the cheaper Wanhao Duplicator-4 (C); production has been halted at the various painting stages to illustrate the layers applied post printing (D).

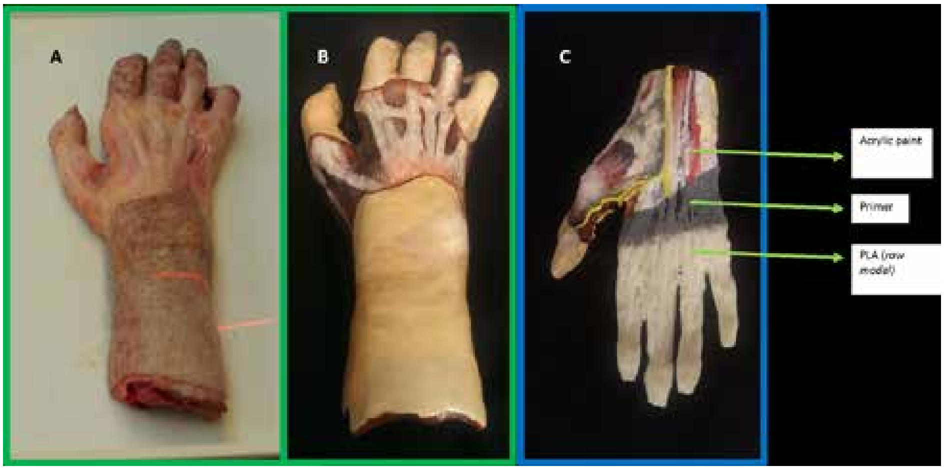


Figure 6 Adam Rouilly models are ubiquitous across UK medical schools: (a) surgical hand model, £1,184 (excluding VAT); (b) dorsum of hand with base of forearm, £455 (excluding VAT).

tic acid, together with a lasting surface finish provided by the acrylic lacquer, render the models resistant to general wear and tear from rough use.

Affordability and accessibility

The cost benefits from producing 3D printed models using this methodology have shown to be significant. As shown from the University of Edinburgh's data, a sum of £8,000 can cover the relevant costs for approximately five whole cadavers.[8] This is a substantial quantity of additional quality resources that time and professional anatomists have suggested offers the most reliable method of learning anatomy.[9] Warwick University were one of the first institutions to start teaching using plastinated specimens[7] and these incur costs far greater than 3D printed counterparts. They also offer longevity and durability similar to 3D printed models and this may be a pivotal attribute in winning the favour of teaching institutions. A sizeable disparity in cost can be seen when comparing the Adam Rouilly models used by Edinburgh University (Figure 6) with the 3D printed alternatives. With an average cost of £35 for the 3D printed model (Table 1), the difference of £420 (when comparing our dorsal hand scan with the Adam Rouilly 'Muscles of the Hand with Base of Forearm' model, Figure 6) is noteworthy.

Economic advantages can be established using our method of collaboration for producing anatomy teaching resources, offering individual students the potential to afford their own models; this cannot be said for current models on the market (Figure 6). Even though initial costs may seem high, increased quantity production and experience would bring costs down dramatically in the long term.

A final trial model was fabricated with the Statasys uPrint 3D printer (Figure 5) to compare quality of print and price with the models produced with the Wanhao Duplicator-4. The results emphasised the capabilities of the far cheaper Wanhao Duplicator-4 in producing models of equal accuracy, with the Stratasys uPrint necessitating disproportionate expenses. Visually, the models were identical (Figures 3, 4 and 5) but the Stratasys uPrint provided the additional benefit of its support material being able to be dissolved away rather than cut off, thus leaving the finer features intact. Considering a difference of approximately £220, we do not believe this to be a suitable method for future model development attempts, being only marginally cheaper than some of the existing models on the market (Figure 6).

Wider benefits of 3D printed models

Exploiting the use of digital files used to transfer scanning data to printers will allow broader access to the same models. The use of digital print files will improve the accessibility to anatomy education tools and could help with the issues of restricted cadaver use in many countries,[9] as 3D anatomy models circumvent compounding social, cultural and ethical factors associated with the use of the deceased.[5]

Another potential use of 3D printed anatomical models lies with patient education. As recently trialled by Bernhard *et al*,[10] personalised anatomy that has been 3D-reconstructed can be used by physicians in the medical environment to educate their patients. A set of 3D printed models that do not necessarily need to be personal to the patient but would be representative of their own anatomy could be owned by surgical personnel to demonstrate visually the procedure they are to carry out. This process has been shown to improve patient understanding of their surgery, resultantly reducing levels of anxiety and improving the overall healthcare experience.[11]

Limitations

There are, of course, many limitations of using 3D printing technologies to mimic human tissue. An important consideration is that prosected specimens are required for data acquisition and printing, which means that access to cadaveric material is necessary for the initial part of the model development process. The dissection stage also offers many opportunities for human error, as any mistakes in dissection would be replicated in subsequent models and would therefore provide inaccurate learning tools. Clear restrictions are also met with the textual properties of the models, which lack compliant properties reducing their similarity to the anatomy they represent. Owing to the topographical nature of the 3D scanner, spaces such as air sinuses and ventricles would not be able to be shown in a model, although their boundaries could.[5] End-stage limitations of our methods highlight the lack of 3D-printing facilities, although their increasing availability may mean that this is only a temporary issue.

Future research

Anatomy education may benefit further from the application of 3D printing in model development, with future research targeted at obtaining independent appraisals from healthcare specialists, teachers and students. Developments in materials science should increase the pace of the appraisal process and, in turn, offer possibilities of trialling models composed of materials that offer an array of consistencies that more accurately mimic human tissue, as well as presenting moving components to aid biomechanical learning of anatomy. The effectiveness of these models may be tested by comparing the results of students who have and have not been exposed to the models throughout their undergraduate medical degree. The testing and confirmation of the efficacy of these adapted models would highlight them as breakthrough learning tools in medical education.

CONCLUSION

Overall, this investigation has underlined the many expected benefits to be obtained from introducing 3D-printing technologies to the education sector, particularly medical education. Its recent uses in medical training and the engineering industries have highlighted the economic gains to be achieved, particularly through long-term use.

As unpredictable issues arise, such as lack of bequeathed bodies and increasing financial implications associated with the use of human tissue, the vast benefits presented by 3D-printing technology mean that it may still be used to facilitate anatomy learning in the future, particularly as we see further developments in material science and 3D printing technologies.

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