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ORIGINAL PAPER

Utilising 3D-printed ex vivo biomimetics to improve open reduction and internal fixation (ORIF) simulation training for hand fractures

Theodora Papavasiliou[1] · Gemma Batten[1] · Oliver Bloom[1] · Jeffrey C. Y. Chan[1] · Charles J. Bain[1] · Lauren Uppal[1]

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Abstract

Background Surgery for hand trauma accounts for a significant proportion of the plastic surgery training curriculum. The aim of this article is to create a standardised simulation training module for hand fracture fixation on open reduction and internal fixation (ORIF) techniques for residents in order to create a standardised hand-training framework that universally hones their skill and prepares them for their first encounter in a clinical setting.

Methods A step-ladder approach training using three-dimensional (3D)–printed ex vivo hand biomimetics was employed on a cohort of 15 plastic surgery residents ($n=15$). Assessment of skills using a score system (global rating scale) was performed in the beginning and the end of the module by hand experts in our unit.

Results The overall average score of the cohort pre- and post-assessment were 22.08/50 (44.16%) and 41.54/50 (83.08%) respectively. Significant ($p<0.01$) difference of improvement of skills was noted on all trainees. All trainees confirmed that the simulated models provided in this module were akin to the patient scenario and noted that it helped them improve their skills with regards to ORIF techniques including improvement of their understanding of the 3D bone topography.

Conclusion We demonstrate a standardised simulation training framework that employs 3D-printed ex vivo hand biomimetics proven to improve the skills of residents and which paves the way to more universal, standardised and validated training across hand surgery. This is, to our knowledge, the first standardised method of simulated training on such hand-surgical cases.
Level of Evidence: Not ratable

Keywords 3D printing · Simulation training · Fracture fixation

Introduction

A significant proportion of both plastic and orthopaedic surgery training is devoted to hand trauma, including the management of metacarpal and phalangeal fractures. Certification guidelines for plastic and orthopaedic surgery published by the Joint Committee of Surgical Training (JCST) state that an indicative number of forty-five hand fracture fixation procedures as the primary surgeon are required for accreditation [1]. There has been concern that training opportunities for plastic surgery trainees have been limited in recent years due to the European Working Time Directive, a problem further exacerbated by the COVID-19 pandemic [2, 3].

✉ Theodora Papavasiliou
Theodora.papavasiliou@nhs.net

[1] Department of Plastic Surgery, Guy's and St Thomas' Hospitals, Westminster Bridge Rd, Lambeth, London SE1 7EH, UK

The 2020 National Survey of Trainee Experiences by the Plastic Surgery Trainees Association (PLASTA UK) reported that despite the JCST quality indicators recommending that all trainees have access to simulation training in their deanery, only thirty-five percent of those who responded were provided with local cadaveric simulation [4, 5]. In response to an increased demand for adjuncts to aid surgical skills teaching outside of the operating theatre, innovations such as local three-dimensional printing of simulation models are gaining popularity [6, 7].

Traditional simulation courses such as those utilising cadaveric models have raised concerns amongst trainees regarding ethical, cost and availability implications [8, 9]. As a novel alternative, 3D modelling and printing utilising CAD/CAM software allow an individual centre to provide on-site, on-demand, reproducible made-to-order simulation models at a lower overall cost whilst avoiding the ethical issues involved with cadaveric training. Furthermore, the capability of a centre to create or download a multitude of designs gives added benefit of adjusting the fracture pattern difficulty for different levels of experience.

This study was performed with the aim of creating a validated course to enrich surgical training and ultimately improving patient safety on ORIF hand fracture techniques [6]. The aim of this course is to provide a safe and controlled environment for trainees to become familiar with the various fracture patterns and fixation techniques and to gain confidence using the equipment, whilst simultaneously undergoing objective assessment and receiving feedback from experts.

Materials and methods

All bone components and fully assembled silicone-embedded hand models with bespoke fracture patterns were designed in collaboration with Stelth, which oversaw the production of the models. Briefly, bone components were 3D-printed using HIPS-X gypsum filament (1.75 mm, Spectrum, USA). Wall thicknesses for each bone were chosen to be 2 mm, and an infill density of 10% was used. To arrive at these parameters, models of varying infill density and wall thicknesses were blindly trialed by hand experts of our unit, with the above being the most satisfactory with regard to their biomimicry [6] (Fig. 1).

Different levels of difficulty were chosen by the panel of hand experts of our unit and based on the JCST guidelines [1], and the trainees were able to practice each fracture once during the training module. All trainees regardless of their level of experience received a 2-h lecture on the fracture patterns of the simulation model and then practiced each fracture pattern under the guidance of the hand surgeons. A breakdown of the levels of difficulty is available in Table 1. The order of the levels of difficulty represents the overall curriculum provided on the day rather than a task-by-task basis (Fig. 2).

The trainees' skills were assessed in the beginning and after the completion of the module on a MC short oblique fracture for lag screw/neutralisation plate Fig. 3. This task was performed using the single MC model which can be fixated on the table allowing the trainees to perform the technique without the need for an assistant (Figs. 4, 5 and 6) A simple survey was completed at the end of the course by the trainees in order to get more data about the acceptability and the fidelity of the model (Appendix Table 4).

Table 1 Step-ladder approach, levels of difficulty of our training module

Level of difficulty (I–VI)	Fracture pattern
Level I	MC short oblique for lag screw/neutralisation plate
Level II	MC and proximal phalanx long oblique for two lag screws
Level III	MC transverse for compression plate
Level IV	Thumb MC Rolando fracture and proximal phalanx comminuted fracture for locking plate
Level V	MC base fracture for condylar plate
Level VI	5th MC neck fracture for CCS
Level VII	Middle phalanx transverse fracture for plate
Level VIII	DIPJ CCS fusion

MC metacarpal, *DIPJ* distal interphalangeal joint, *CCS* cannulated compression screw

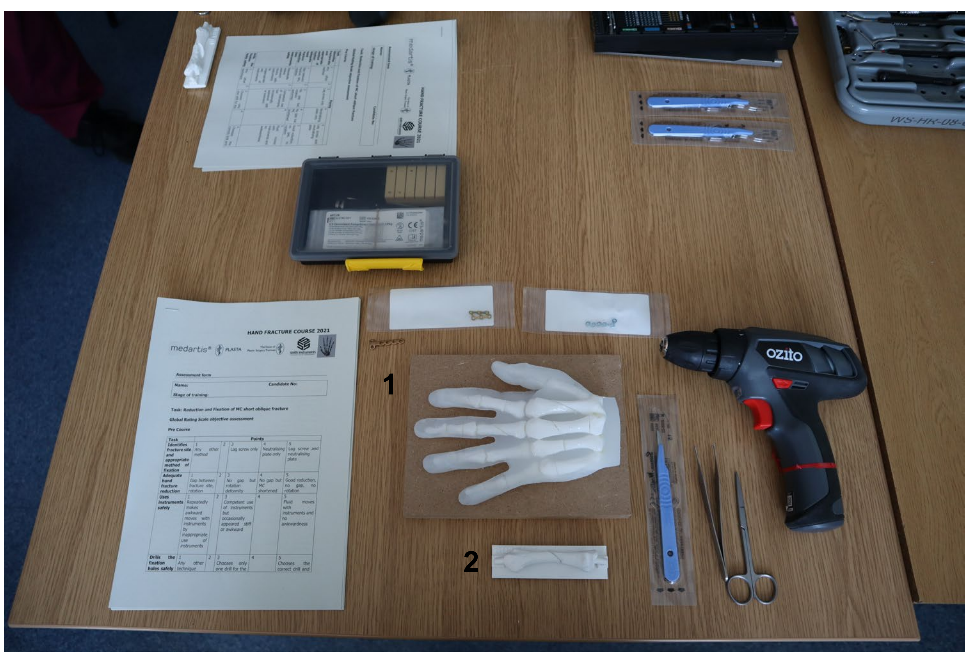

Fig. 1 The course material and setup. Including the silicone-embedded model with the customized fracture patterns for ORIF (1) and the single MC model with the short oblique fracture for the lag screw and neutralizing plate (2)

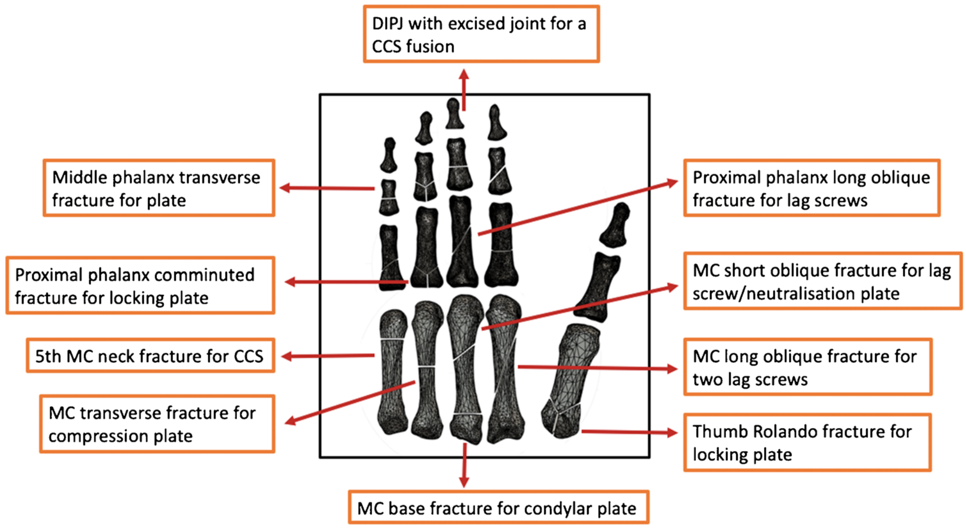

Fig. 2 Diagram providing details of the design for all the different fracture patterns and the location on the silicone-embedded hand

The cohort of trainees in this study included 15 participants ($n = 15$), 7 of which were junior residents (years 1–2) and 8 of which were senior residents (years 3–6). The individual metrics were chosen to be in line with ISCP curriculum guidelines validated and used in current practice [10]. n particular, the global assessment score used included the following criteria: (1) identifies fracture site and appropriate method of fixation, (2) adequate hand fracture reduction, (3) uses instruments safely, (4) drills the fixation holes safely and accurately having selected the appropriate drill, (5) economy of movements and appropriate pace, (6) selection of plate–neutralising non-locking plate, (7) plate positioning, (8) accurately measures screw length using depth gauge, (9) lag screw positioning and (10) time to complete a task. These criteria were chosen as they are both validated metrics and also familiar to the assessors allowing quantitative assessment [10]. Scores ranged from 1 (poor) to 5 (outstanding) in terms of the candidate's performance. The metrics and the average assessment scores per metric can be found in Table 2. Participants were assessed both prior to and post-completing the simulated hand-training module on the MC short oblique fracture for lag screw/neutralisation plate.

Results

The overall average score of the cohort pre- and post-assessment were 23.75/40 (59.4%) and 34.7/40 (86.8%) respectively. To ensure that the data are normally distributed, we performed the Shapiro–Wilk test which showed that for this level of confidence we can assert that the null hypothesis is indeed rejected. The improvement in overall performance was found to reject the null hypothesis of Student's paired *t*-test ($p < 0.01$) suggesting significant improvement in the technique of the trainees. Inspection of the individual metric category scores suggests that the simulation hand-training course had a significant impact on the candidate's ability to identify the fracture site and select the appropriate method of fixation (2.85/5 to 4.31/5, $p < 0.01$), perform adequate fracture reduction (3.69/5 to 4.92/5, $p < 0.01$), use instruments safely (3/5 to 4.23/5, $p < 0.01$), drill the fixation holes safely and accurately by selecting the appropriate drill (2.92/5 to 4.92/5, $p < 0.01$), economy of movements (2.31/5 to 3.92/5, $p < 0.01$), select the appropriate plate for fixation (1.15/5 to 4.61/5, $p < 0.01$), position the plate appropriately (0.77/5 to 3.77/5, $p < 0.01$), accurately measure the screw length (2.31/5 to 4.38, $p < 0.01$) and position the lag screw (2.08/5 to 4.54/5, $p < 0.01$).

Using the same 1–5 scale as before, the precision of the 3D-printed models scored 4.4/5 amongst the 15 trainees. Encouragingly, when asked whether the course improved the trainee's confidence in the management of fractures using these techniques, the entirety of the cohort responded with a score of 5.

Discussion

Whilst there are many practical courses that teach hand fracture management techniques and skills, there are none in the UK, to our knowledge, that utilize 3D-printed models. These anatomically accurate, low-cost (material cost 60 USD) and high-fidelity simulation models allowed the early-stage trainees to establish their basic surgical skills on ORIF techniques and the senior trainees to further hone their skills on this field.

In order to gauge the experience of each trainee prior to the course and therefore establish a baseline to monitor their training progress, the candidates were assessed on the fixation of a MC short oblique fracture for lag screw/

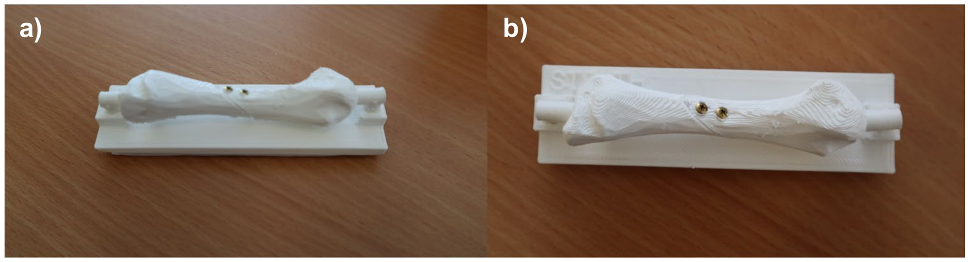

Fig. 3 The single MC model with the short oblique fracture. **a**, **b** AP and side view of the fixation with 2 lag screws

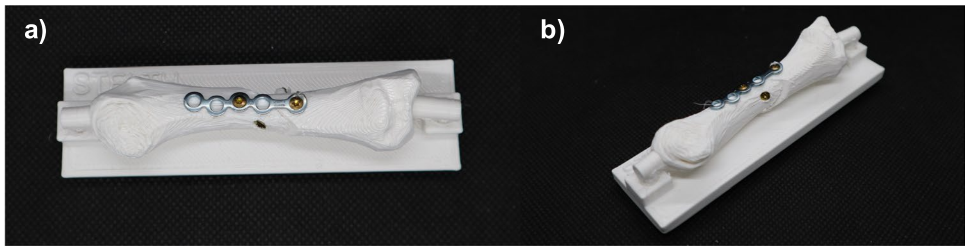

Fig. 4 The single MC model with the short oblique fracture. **a**) AP **b**) Side view of the fixation with lag screw and neutralizing plate

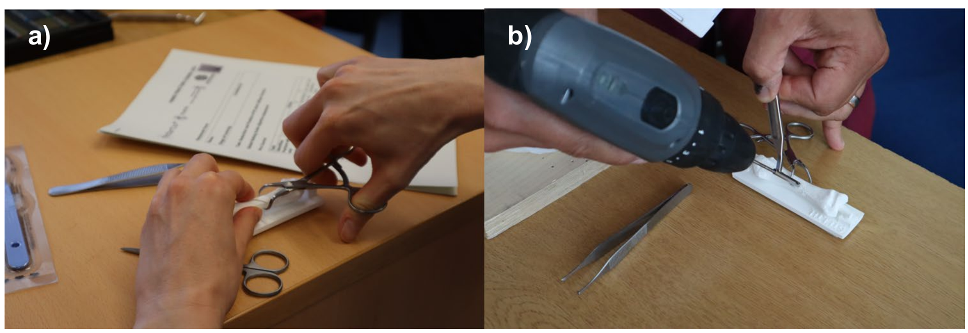

Fig. 5 Trainees practicing on the single MC model with the short oblique fracture. **a** The model allows for the use of the bone reduction forceps to perform fracture reduction which is a crucial part of the operation. **b** The trainee uses the drill and the drill guide and aims to follow a line perpendicular between the fracture line and the long axis of the bone

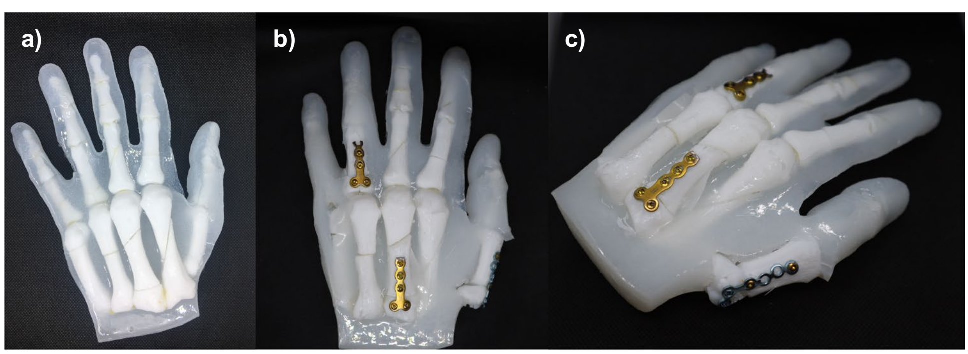

Fig. 6 The silicone-embedded model. **a** Before the fracture fixation. **b**, **c** AP and side view after the fracture fixations

neutralisation plate on the single MC model prior to the course (Figs. 3, 4 and 5). Candidates were then allowed to practice with hand simulation models under the guidance of a hand consultant. Tasks were introduced in a step-ladder approach (Table 1). We chose to adopt such an approach to formally introduce, or in the case of senior trainees, reinforce, the fundamentals of ORIF of hand fractures.

The silicone-embedded model incorporated the above fracture patterns due to the customization allowed by 3D printing technologies (Fig. 6). The silicone was used to cover the dorsal aspect of the bony components with a thin layer to mimic the periosteum. The choice of silicone cross-link ratio was chosen based on what our experience deemed as adequate biomimic. The trainees were asked to dissect prior to approaching the fracture fixation technique. This was reflected in a follow-up questionnaire filled up by the trainees post-assessment. The observed feedback sheets used to assess our course participants have been standardised using Likert scales to enable a quantitative evaluation of their individual performance [11,

Table 2 Assessment global rating system (GRS) for the MC short oblique fracture for lag screw/neutralisation plate

Task	Points				
Identifies fracture site and appropriate method of fixation	1 Any other method	2	3 Lag screw only	4 Neutralising plate only	5 Lag screw and neutralising plate
Adequate hand fracture reduction	1 Gap between fracture site, rotation	2	3 No gap but rotation deformity	4 No gap but MC shortened	5 Good reduction, no gap, no rotation
Uses instruments safely	1 Repeatedly makes awkward moves with instruments by inappropriate use of instruments	2	3 Competent use of instruments but occasionally appeared stiff or awkward	4	5 Fluid moves with instruments and no awkwardness
Drills the fixation holes safely and accurately having selected the appropriate drill	1 Any other technique	2	3 Chooses only one drill for the lag screw technique	4	5 Chooses the correct drill and performs the lag screw drilling correctly
Economy of movements and appropriate pace	1 Many unnecessary moves	2	3 Efficient time/motion but some unnecessary moves	4	5 Clear economy of movement and maximum efficiency
Selection of plate–neutralising non-locking plate	1 Any other plate/screw	2	3	4	5
Plate positioning	1 Plate positioned but reduction not maintained	2	3	4 Applies plate securely whilst maintaining satisfactory reduction	5 Performs pre-bending of the plate and applies securely whilst maintaining satisfactory reduction
Accurately measures screw length using depth gauge	1 Screw short	2	3 Screw very proud	4	5 Screw length correct-going through both cortices but not proud
Lag screw positioning	1 Screw positioning not performing compression	2	3	4	5 Screw positioned perpendicular between the fracture line and the long axis of the bone
Time needed to complete task	1 > 5	2	3	4	5 < 4 min

12]. They also reported that the 3D-printed models had been an important part of this fast improvement. Several candidates also commented that the 3D-printed devices emulating the human hand anatomy allowed them to gain a deeper understanding of the structures and the fixation process compared to saw bones or other standalone plastic models.

We acknowledge that a limitation of this study is the fact it was conducted in a single centre and with a small sample size of trainees using the GRS scoring to evaluate the results. We hope in the future to expand the number of trainees by repeating this course both at the local and the national level. We also hope to introduce new fracture patterns which will provide more refined didactic opportunities and better demonstrate a step-ladder approach thus enabling a task-by-task assessment of the trainees (Table 3).

Conclusion

This study has demonstrated the implementation of a standardised hand fracture fixation course for ORIF techniques using 3D-printed simulation models that incorporated complicated fracture patterns. This is a step towards creating a framework of training for the assessment of trainees' skills in a simulated environment. Our study showed that residents, both early and late stage, improved in their technique, with early-stage residents showing more notable improvements

Table 3 Metrics of the GRS and *p* values

	Average scoring prior to completion of course (1–5)	Average scoring (1–5) after completion of course	*P* value
Identifies fracture site and appropriate method of fixation	2.846153846	4.307692308	1.45767E – 05
Adequate hand fracture reduction	3.692307692	4.923076923	4.25594E – 05
Uses instruments safely	3	4.230769231	8.81183E – 05
Drills the fixation holes safely and accurately having selected the appropriate drill	2.923076923	4.923076923	0.000164667
Economy of movements and appropriate pace	2.307692308	3.923076923	0.000708558
Selection of plate–neutralising non-locking plate	1.153846154	4.615384615	0.002032756
Plate positioning	0.769230769	3.769230769	0.006453838
Accurately measures screw length using depth gauge	2.307692308	4.384615385	0.022403407
Lag screw positioning	2.076923077	4.538461538	0.118030586
Time needed to complete task	1	2.083333333	n/a
Total	22.08	41.54	

in the technical aspects of the techniques. The significant improvement of trainees towards these techniques shown here suggests that modules that make use of 3D-printed biomimetics can potentially become a mainstay in the training of hand surgeons, particularly for the early stages of their learning curve, improving overall patient outcomes.

Appendix

Table 4 Trainee questionnaire

What is your level of training?	Years 1–3	Year 3–5
How would you rate the small lectures?	1 2 3	4 5
How would you rate the delegate:tutor ratio?	1 2 3	4 5
How would you rate the 3D-printed models?	1 2 3	4 5
How would you rate the course overall?	1 2 3	4 5
Do you feel more confident on performing ORIF techniques for hand fractures after this practical session?	1 2 3	4 5
Please leave comments below:		

Funding No funding was provided for this study

Data Availability All data are available with this paper.

Declarations

Ethics approval No patients were involved in this study. The study was conducted complying with the 1964 Helsinki Declaration and its later amendments. No ethical approval was required for this study.

Conflict of interest Theodora Papavasiliou is a co-founder of Stelth, the company that manufactured the models described in this paper. Gemma Batten, Oliver Bloom, Jeffrey C. Y. Chan, Charles J. Bain, and Lauren Uppal declare no competinginterests.

Consent to participate All participants consented to participate in this study.

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