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Hand/Peripheral Nerve

A Standardized Hand Fracture Fixation Training Framework using Novel 3D Printed Ex Vivo Hand Models: Our Experience as a Unit

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Background: Surgery for hand trauma accounts for a significant proportion of the plastic surgery training curriculum. The aim of this study was to create a standardized simulation training module for hand fracture fixation with Kirschner wire (K-wire) techniques for residents to create a standardized 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 with 6 levels of difficulty on 3-dimensional (3D) printed ex vivo hand biomimetics was employed on a cohort of 20 plastic surgery residents ($n = 20$). Assessment of skills using a score system (global rating scale) was performed in the beginning and at the end of the module by hand experts of our unit.

Results: The overall average scores of the cohort before and after assessment were 23.75/40 (59.4%) and 34.7/40 (86.8%), 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 regard to K-wire fixation techniques, including improvement of their understanding of the 3D bone topography.

Conclusions: We demonstrate a standardized simulation training framework that employs 3D printed ex vivo hand biomimetics proved to improve the skills of residents and that paves the way to more universal, standardized and validated training across hand surgery. This is, to our knowledge, the first standardized method of simulated training on such hand surgical cases. *(Plast Reconstr Surg Glob Open 2021;9:e3406; doi: 10.1097/GOX.0000000000003406; Published online 15 February 2021.)*

INTRODUCTION

Surgery for hand trauma constitutes a large component of the plastic and orthopedic surgery training curriculum. Notably, the Joint Committee of Surgical Training stipulate that in order for surgeons to be accredited with the title of Plastic Surgeon, a trainee needs to have performed at least 150 hand trauma procedures, with 50 being fracture fixations.[1] Hand surgery necessitates that the trainee surgeon acquires a skillset in a very diverse repertoire, which, amongst others, includes small bone fixation, microsurgery, arthroscopy, joint replacement, and reconstruction of skin, nerves, vessels, muscle tendons, and bone. Trainees in this sub-specialty are thus met with operations demanding strong foundations not only in hand anatomy knowledge across all tissue structures but also honed pattern-recognition capabilities that can only be acquired with consistent practice and exposure to hand trauma operations.

Small-bone fixation via Kirschner wire (K-wire) internal fixation is often regarded as an entry level operation for junior trainees. However, despite the perceived simplicity of the technique, a soaring body of evidence

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suggests that the technique is associated with a large number of complications, the majority of which being a consequence of imprecise technique. For instance, Sharma et al in their meta-analysis study noted a 32.3% complication rate for K-wire fixations postoperatively. The group noted that 2 of the predominant reasons for wire loosening and pin tract infections were associated with K-wires being left outside the skin or not having traversed both cortices.[2] It is therefore becoming evident that a more robust training framework ought to be established for the K-wire internal fixation technique.

Simulated training is often employed to accelerate the growth of skill in early-stage trainees for K-wire fixation.[3,4] Traditionally, the hand fracture fixation training model makes use of human cadaveric hands.[5] This, in turn, requires, in addition to the cadaver itself, access to accredited cadaveric laboratory spaces equipped with the necessary instruments able to produce the fractures of interest. Furthermore, specialized personnel are necessary to ensure that infection control measures are put in place.

To circumvent the above, training centers alternatively employ ex-vivo models, such as animal bones, to simulate fracture patterns.[6] The anatomy, of course, is drastically different than a human hand. Such courses are therefore best suited for the "first encounter" of the trainee with the technique.[3] Nonetheless, the instatement of frameworks such as the 3Rs (Reduction, Refinement, Replacement) insinuates an overall shift away from cadaveric and animal models and a move toward the use of artificial ones for the early-learning curve of trainees.[6]

Recent technological advances have rendered bespoke manufacturing techniques such as 3D printing both very accessible and very precise. The above render such techniques ideal for the production of artificial biomimetic models for hand trauma simulation, with several studies emerging in the literature in the recent years.[7–10] Although the aforementioned studies have limited themselves in predominantly the production aspect of models, it is becoming apparent that the above technological advancements present a unique opportunity for the development of standardized, validated frameworks for simulated training in hand fracture fixation. Unlike most present-day models which form fractures in situ with, for instance, oscillating saws, 3D printing technologies allows the explicit and on-demand design of fracture sites as prescribed for the technique of interest and the level of training needed. The above can be produced at a much lower cost compared with the that of cadaveric models.

In this study, we have developed a step-ladder training module that employs simulated 3D printed artificial biomimetic models at its core, intended for early- and mid- stage trainees. Our course, which featured a cohort of 20 trainees in our department, employed hand models exhibiting radio-opacity and cortex strength akin to human ones, as validated by hand experts in our unit. Crucially, the manufacturing capabilities of 3D printing allowed for the precise placement of fractures of various types, including Bennett's, reverse-Bennett's, proximal phalanx, metacarpal neck, and mallet finger. This allowed our cohort of trainees to perform the fracture fixation while being evaluated in a quantitative manner by senior hand consultants. We proceeded to assess this approach in its ability to provide a standardized training framework for K-wire fixation.

MATERIALS AND METHODS

All bone components and fully assembled silicone embedded hand models with bespoke fracture sites were designed in collaboration with Stelth, which oversaw the production of the models (Figs. 1 and 2). Briefly, bone components were 3D printed using HIPS-X gypsum filament (1.75 mm, Spectrum, USA), which was found to be sufficiently radio-opaque for this application. 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. Although higher infill choices ranging between 20% and 30% were found to improve contrast to a small extent, they did so at the cost of the precision of the models (Fig. 3). In particular, we found the chosen infill setting

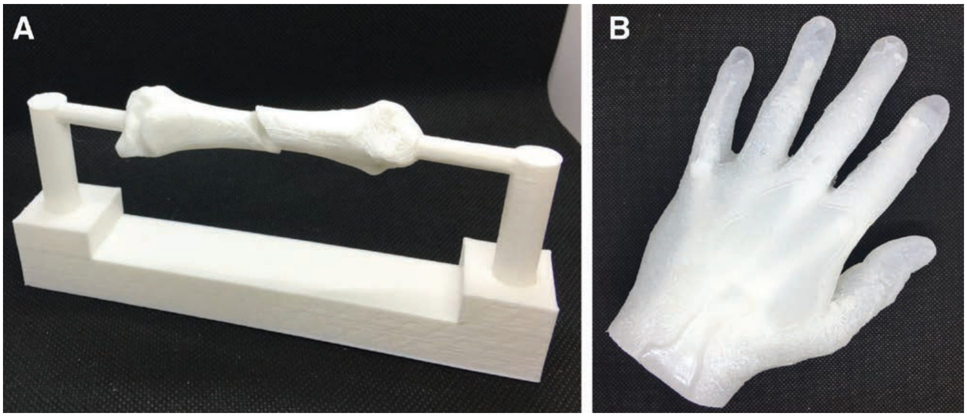

Fig. 1. All the models used: A, The MC on the stand device, fracture short oblique through the shaft. B, The silicone-embedded 3D printed biomimetic model.

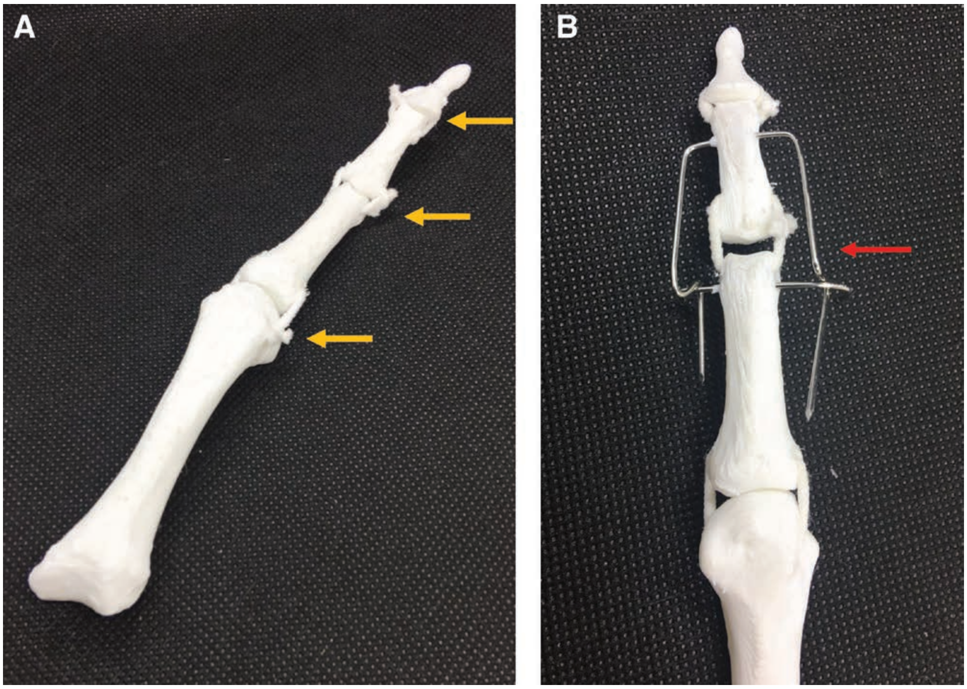

Fig. 2. A, The single finger bone construct for dynamic frame fixation. Orange arrows indicate the elastic bands that mimic the collateral ligaments. B, External fixator. The red arrow indicates the ability to increase the joint space.

to better simulate the medullary cavity and its contrasting strength to the cortices.

For level II training, single metacarpal bones with short spiral shaft fractures were 3D printed as above and positioned on a standing device. This allowed the trainees to practice K-wire insertion without the need of an assistant (Figs. 1 and 2).

Level III training required the placement of a dynamic external fixator. This was achieved by assembling single finger constructs using elastic bands that mimicked the collateral ligaments (Figs. 1 and 2).

For the remaining levels of training, owing to the customization abilities of 3D printing, different fracture patterns were designed in silico, 3D printed on the hand skeleton and then embedded in silicone. This consisted of fracture fixations of the 5th Metacarpal (MC) neck fracture, Bennett's and Reverse Bennett's fracture, transverse proximal phalanx, and mallet finger deformity (Fig. 4).

RESULTS

The cohort of trainees in this study included 20 participants (n = 20), 10 of which were junior residents (years 1–2) and 10 of which were senior residents (years 3–6). The individual metrics were chosen to be in-line with ISCP curriculum guidelines used in the current practice.[11] In particular, the global assessment score used included the following criteria: (i) instrument handling, (ii) hand model manipulation, and (iii) efficiency

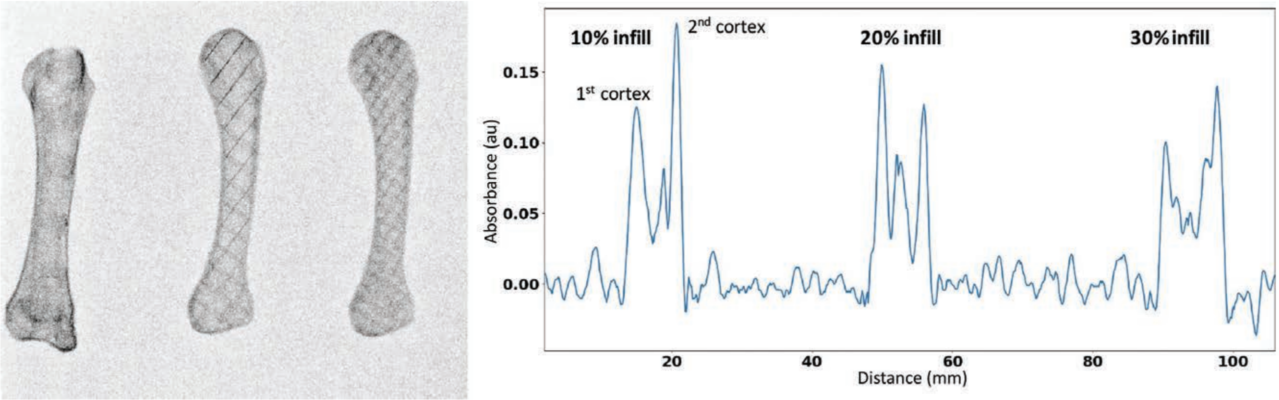

Fig. 3. A, X-ray radiograph using a mini C-arm as obtained for 3 different infill settings of a single MC model. From left to right: infills of 10%, 20%, and 30%. B, Image analysis suggested the relative radio-opacities calculated from 3 different regions of interest to be (100 ± 1.7)%, (99 ± 2.0)%, and (97 ± 1.9)%, respectively, suggesting no significant difference with regard to the 3 different infill settings.

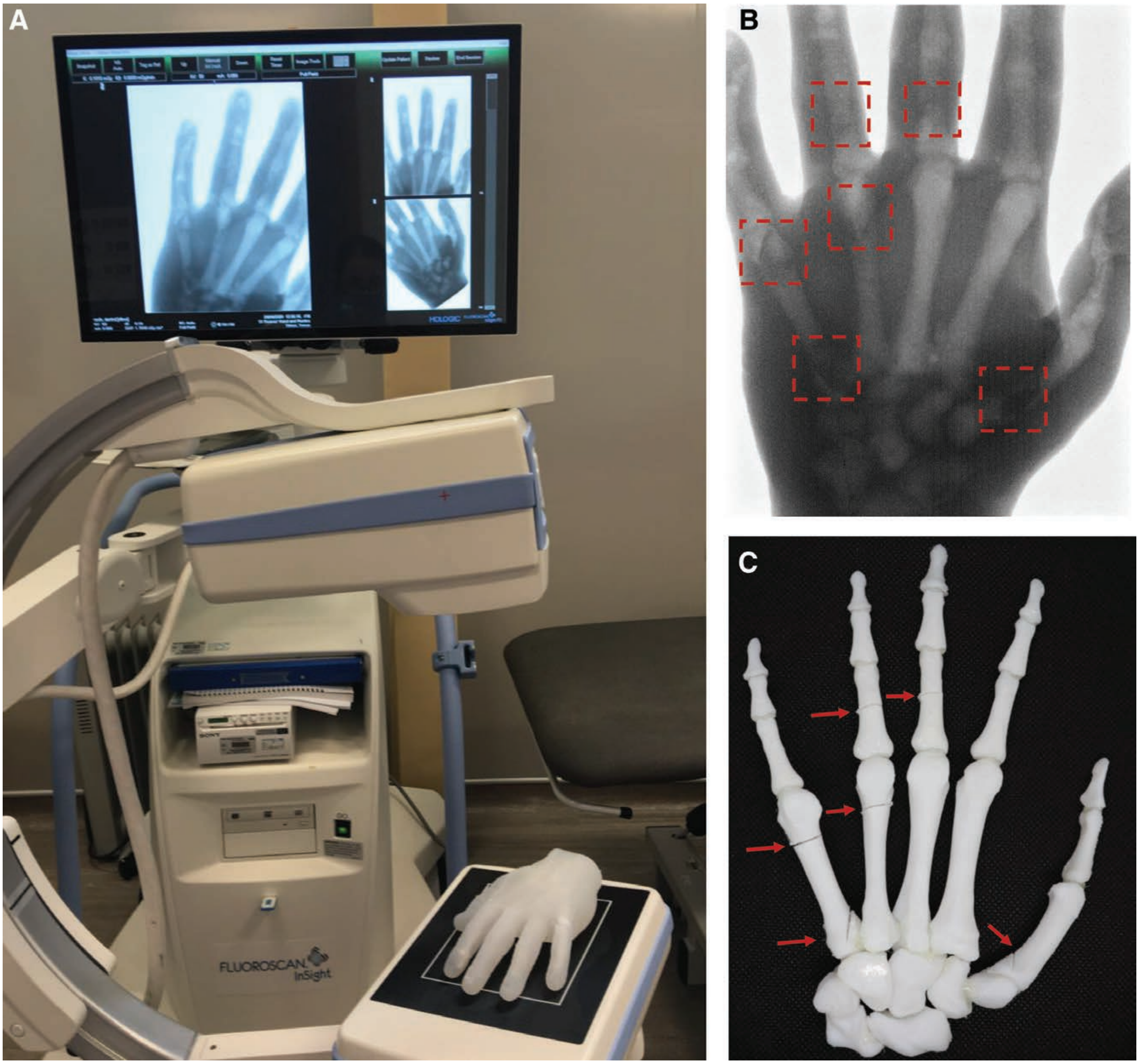

Fig. 4. A, The silicone embedded 3D printed biomimetic model with the fracture patterns. B, The radiograph taken with mini C-arm provides evidence of significant contrast to mimic a normal hand radiograph. C, The 3D printed bone parts with the fracture patterns.

in completing the task, (iv) use of C-arm with economy of movements, (v) final position of K-wires, (vi) number of K-wire insertion attempts, (vii) satisfaction of fracture reduction without rotation deformities, and the (viii) adequate use of the assistant. These criteria were chosen, as they are both validated metrics and also familiar to the assessors allowing quantitative assessment[11] (Table 1). Scores ranged from 1 (poor) to 5 (outstanding) in terms of the candidate's performance (Fig. 5). The metrics and the average assessment scores per metric can be found in Table 1. Participants were assessed both before and after completing the simulated hand training module on the crossed K-wire fixation of the 5th MC neck fracture.

The overall average score of the cohort pre- and post-assessment were 23.75/40 (59.4%) and 34.7/40 (86.8%) respectively. 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 position the K-wires correctly (2.65/5 to 4.25/5, $P < 0.01$), with instrument handling (2.9/5 to 4.2/5, $P < 0.01$), hand model manipulation, (2.9/5 to 4.2/5, $P < 0.01$), completing the task within a reasonable timeframe (3.2/5 to 4.55/5, $P < 0.01$), use of C-arm with economy of movement (3 to 4.45/5, $P < 0.01$), minimal attempts on K-wire insertion (2.7/5 to 4.25/5, $P < 0.01$), satisfactory reduction with no rotation deformity (3.5/5 to 4.6/5, $P < 0.01$), and adequate use of the assistant surgeon (2.95 to 4.2/5, $P < 0.01$).

Table 1. Scoring System (Global Rating Scale Objective Assessment)

Task	Average Scoring (1–5) before Course	Average Scoring (1–5) after Completion of Course	*P*
Instrument handling	2.9	4.2	<0.01
Hand model manipulation	2.9	4.2	<0.01
Efficiency in completing the task	3.2	4.55	<0.01
Using C-arm with economy of movements	3	4.45	<0.01
Final position of K-wires	2.65	4.25	<0.01
Minimal attempts for K-wire insertion	2.7	4.25	<0.01
Satisfactory reduction with no rotation deformity	3.5	4.6	<0.01
Adequate use of the assistant	2.9	4.2	<0.01
Total	23.75	34.7	

Average scoring on each task is shown. Score breakdown: 1—resident required guidance for most of the task, 2—resident required guidance in part of the task, 3—resident performed task without guidance but lacked fluency, 4—resident performed task fluently, 5—resident performed the task with outstanding fluency and efficiency of time.

K-wire: Kirschner wire.

Table 2. Levels of Difficulty of Our Training Module Using a Step-ladder Approach

Level of Difficulty (I–VI)	Fracture Pattern	Simulation Model
Level I	Mallet finger fracture	Finger bone model
Level II	MC shaft fracture	Individual MC bone model
Level III	Dynamic Ex-Fix	Finger bone model
Level IV	MC neck fracture/ Proximal phalanx fracture	Hand embedded in silicone
Level V	Reverse Bennett's	Hand embedded in silicone
Level VI	Bennett's fracture	Hand embedded in silicone

MC, metacarpal; Ex-Fix, external fixator.

DISCUSSION

To gauge the experience of each trainee before the course and therefore establish a baseline to monitor their training progress, the candidates were assessed on the fixation of a 5th MC neck fracture on the silicone-embedded hand models before the course. 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. We chose to adopt such an approach to formally introduce or, in the case of senior trainees, reinforce the fundamentals of K-wire placement and fixation. Six levels of increasing difficulty, as agreed upon by 3 of our unit's hand experts were chosen. These were, in ascending order of complexity, mallet finger, MC shaft fracture, dynamic external fixator, metacarpal neck fracture/proximal phalanx fractures, and Reverse Bennett's and Bennett's fracture on the silicone embedded hand model (Table 2).

When junior and senior resident cohorts were treated as distinct groups, improvements across all aspects were found ($P < 0.01$). Comparison of the p-values obtained across each metric category for the 2 groups provides a way of quantifying which aspects of the procedure improved more for trainees depending on their training stage. In particular, it was found that early stage trainees improved at a more significant rate than their senior counterparts in instrument handling, hand model manipulation, efficiency in completing the task, final position of K-wires, and satisfactory reduction with no rotation deformity. This is likely due to senior residents already being adept at the more technical aspects of the K-wire fixation techniques; therefore, improvements in those aspects would be expected to be marginal for that group, as opposed to early-stage trainees. The senior resident group, on the other hand, was found to become distinctly more adept at making adequate use of their assistants ($P_{junior} = 2.6 \times 10^{-3}$, $P_{senior} = 2.6 \times 10^{-4}$). Both groups appeared to be improving at the same rate with regard to C-arm coordination (Table 3).

The silicone-embedded hand models, in addition to simulating the cortex and medullary canal strengths accurately, also exhibit flexibility of the fingers, allowing the

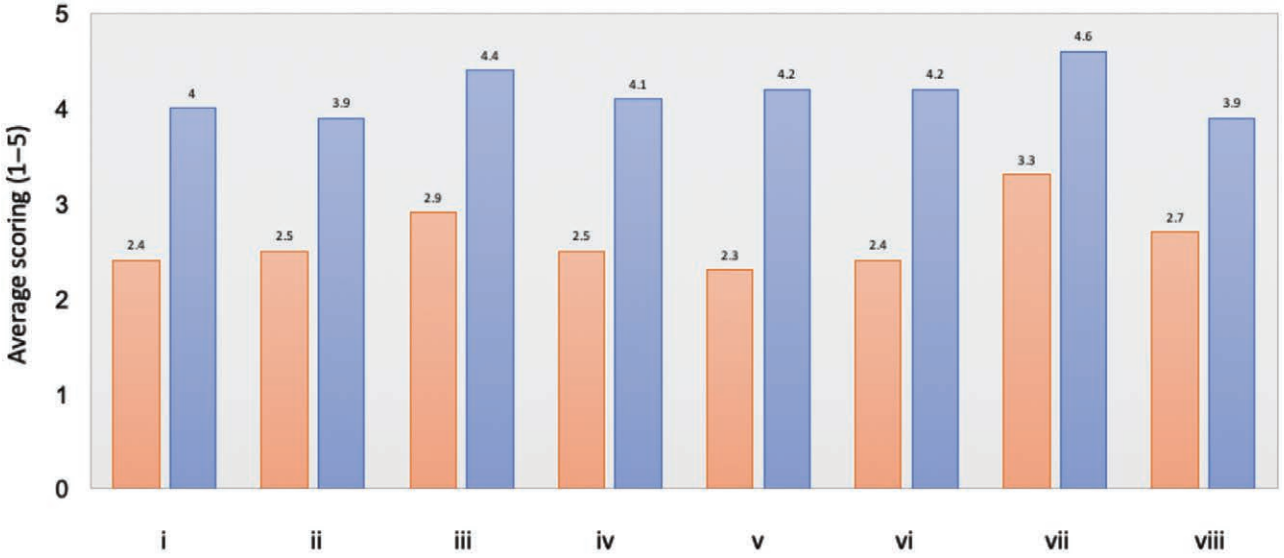

Fig. 5. Bar plot showing the average score on each task before (orange bars) and after (blue bars) the completion of the module.

Table 3. Tabulated *P* -values per Assessment Criteria for the Junior and Senior Trainee Cohorts

Task	P_{junior} (n = 10)	P_{senior} (n = 10)
Instrument handling	2.1×10^{-6}	5.3×10^{-4}
Hand model manipulation	6.8×10^{-5}	1.0×10^{-4}
Efficiency in completing the task	3.3×10^{-3}	6.5×10^{-3}
Using C-arm with economy of movements	1.0×10^{-4}	9.1×10^{-5}
Final position of K-wires	2.0×10^{-4}	9.5×10^{-4}
Minimal attempts for K-wire insertion	1.9×10^{-4}	9.5×10^{-4}
Satisfactory reduction with no rotation deformity	3.1×10^{-3}	5.0×10^{-3}
Adequate use of the assistant surgeon	2.6×10^{-3}	2.6×10^{-4}

K-wire: Kirschner wire.

The last column indicates the ratio of *P* values across each metric.

trainee to perform the Jahss maneuver when performing 5th MC neck cross K-wiring fixation. (**See Video [online],** which details cross K-wire insertion for 5th MC neck fracture.) This was reflected in a follow-up questionnaire filled up by the trainees post-assessment. Using the same 1–5 scale as before, the precision of the 3D printed models scored 4.6/5 amongst the 20 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, suggesting that the trainees' mindfulness was reinforced from their experience with the hand-simulated models.

CONCLUSIONS

In this study, we have demonstrated the implementation of a hand training course for K-wire fixation using simulated 3D printed hand models that reproducibly recreate complex fracture patterns. This was completed as a step moving toward creating a standardized framework of practice and assessment for early stage trainees. Our study showed that residents, both early and late stage, improved in their technique, with early stage residents showing more notable improvements in the technical aspects of the techniques. Late stage residents, in addition to reinforcing their techniques, showed a significant improvement in their ability to make adequate use of an assistant, a skill typically honed in the later stages of training. The significant improvement of trainees toward 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.

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