A standardised hand fracture fixation training framework using novel 3D printed ex-vivo hand models: our experience as a unit.

Theodora Papavasiliou MD[*1]; Stelios Chatzimichail PhD[2]; Jeffrey C.Y Chan FRCSI (Plast), PhD[1]

Charles J Bain FRCS (Plast)[1]; Lauren Uppal FRCS (Plast)[1]

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

[2] Department of Surgery and Cancer, Imperial College London, White City Campus, 80 Wood Lane, London W12 0BZ

***Corresponding author:**

Theodora Papavasiliou, MD

Guys' and St' Thomas Hospital

Westminster Bridge Rd, Lambeth

London SE1 7EH

Theodora.papavasiliou@nhs.net

Twitter handle: @DocTheodora

Keywords

3D printing; hand trauma; simulation training; fracture fixation

Financial disclosures/commercial associations

Theodora Papavasiliou and Stelios Chatzimichail own Stelth, the company that manufactured the models described on this paper. The rest of the authors have nothing to declare.

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 standardized simulation training module for hand fracture fixation with Kirschner wire (K-wire) techniques for residents in order 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 six levels of difficulty on three-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 the end of the module by hand experts of our unit.

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. 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 K-wire fixation techniques including improvement of their understanding of the 3D bone topography.

Conclusion: We demonstrate a standardized 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, standardized 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: III

Introduction:

Surgery for hand trauma constitutes a large component of the plastic and orthopaedic 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, 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 as well as 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 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 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 post-operatively. The group noted that two 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's 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 lab spaces equipped with the necessary instruments able to produce the fractures of interest. Furthermore, specialised personnel are necessary in order to ensure infection control measures are put in place.

To circumvent the above, training centres alternatively employ ex-vivo models, such as animal bones, to simulate fracture patterns[6]. The anatomy, of course, being drastically different to 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 towards 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[7,8,9,10]. While 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 standardised, 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 much lower cost compared to the cadaveric models.

In this study, we have developed a step-ladder training module which 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 standardised 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. (Figure 1) 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 while an infill density of 10% was used. To arrive at these parameters, models of varying infill density and wall thicknesses were blindly trialled by hand experts of our unit with the above being the most satisfactory with regards to their biomimicry. While higher infill choices ranging 20% and 30% were found to improve contrast to a small extent, they did so at the cost of

the precision of the models. (Figure 2) In particular, we found the chosen infill setting to better simulate the medullary cavity and it's 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. (Figure 1)

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

For the remaining levels of training, owed to the customisation 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. (Figure 3)

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 current practice. [11] In particular, the global assessment score used included the following criteria: i) Instrument handling, ii) hand model manipulation, iii) efficiency 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 2). Scores ranged from 1 (poor) to 5 (outstanding) in terms of the candidate's performance. (Figure 4) The metrics and the average assessment scores per metric, can be found in table 2. Participants were assessed both prior- and post-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, $p < 0.01$).

Discussion

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 5th MC neck fracture on the silicone embedded hand models prior to 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 three 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, Reverse Bennett's and Bennett's fracture on the silicone embedded hand model. (Table 1)

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 two 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 showed to becoming distinctly more

adept at making adequate use of their assistant ($p_{junior}=2.6 \times 10^{-3}$, $p_{senior} =2.6 \times 10^{-4}$). Both groups appeared to be improving at the same rate with regards 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 trainee to perform the Jahss manoeuvre when performing 5th MC neck cross K-wiring fixation (Video 1: Supplementary Information). 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.

Conclusion

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 towards creating a standardised 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 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 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.

References

1) Joint committee of surgical training. Certification guidelines and checklists, 2017/18. https://www.jcst.org/quality-assurance/certification-guidelines-and-checklists. last accessed on 10/8/20
2) Sharma H, Taylor GR, Clarke NMP. A Review of K-wire Related Complications in the Emergency Management of Paediatric Upper Extremity Trauma. Ann R Coll Surg Engl. 2007, 89(3): 252–258.
3) Akhtar KSN, Chen A, Standfield NJ, and Gupte CM. The role of simulation in developing surgical skills. Curr Rev Musculoskelet Med. 2014, 7(2): 155–160.
4) Dawe S R, Pena G N, Windsor J A et al. Systematic review of skills transfer after surgical simulation-based training. Br J Surg. 2014,101(9):1063-76.
5) Kang PS, Horgan AF, Acheson AG. Laparoscopic surgery training. Try fresh frozen cadavers. *BMJ.* 2009, 338: b2426.
6) Guerreschi P, Qassemyar A, Thevenet J, Hubert T ,Fontaine C, Duquennoy-Martinot V. Reducing the number of animals used for microsurgery training

programs by using a task-trainer simulator. Laboratory animals. 2013, 48(1): 72-77.

7) Maier J, Weiherer M, Huber M, Palm C. Optically tracked and 3D printed haptic phantom hand for surgical training system. Quant Imaging Med Surg. 2020, 10(2):340-355.
8) Brichacek M, Diaz-Abele J, Shiga S, Petropolis C. Three-dimensional Printed Surgical Simulator for Kirschner Wire Placement in Hand Fractures. Plastic and Reconstructive Surgery – Global Open. 2018, 6(3):e1706.
9) Matter-Parrat V, Liverneaux P. 3D printing in hand surgery. Hand Surg Rehabil. 2019, 38(6):338-347.
10) Papavasiliou T, Lipede C, Chatzimichail S, Sivakumar B. The development of customized three- dimensional printed paediatric hand retractor for patient-precise dimensions and enhanced surgical autonomy. Journal of Hand Surgery (European Vol). 2020
11) Intercollegiate Surgical Curriculum Programme. Procedure based assessment for closed reduction of hand fracture and K-Wire fixation, 2020 https://www.iscp.ac.uk/forms/pba.aspx , last accessed on 10/8/20.

Legends to Figures

Figure 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. c) The single finger bone construct for dynamic frame fixation, orange arrows demonstrate the elastic

bands that mimic the collateral ligaments d) External Fixator, red arrow demonstrates the ability to increase the joint space.

Figure 2- a) X-ray Radiograph using a mini C-arm as obtained for three 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 three different regions of interest to be 100 ± 1.7%, 99 ± 2.0% and 97 ± 1.9% respectively, suggesting no significant difference with regards to the three different infill settings.

Figure 3- 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 in order to mimic a normal hand radiograph. c) The 3D printed bone parts with the fracture patterns.

Figure 4: Bar plot showing the average score on each task before (orange bar) and after (blue bar) the completion of the module.

Video Supplementary information: Cross K-Wire insertion for 5th MC neck fracture.