RESEARCH ARTICLE

3D Printed Models of Periarticular Fractures of the Shoulder and Elbow Improve Surgical Decision Making in Orthopedic Trainees

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Received: 3 August 2024 *Accepted: 28 December 2024*

Abstract

Objectives: Periarticular fractures of the shoulder and elbow are spatially complex injuries that may be challenging to interpret on radiographs and advanced imaging. As three-dimensional (3D) printing technology has become less expensive and more available, 3D printed fracture models have gained attention for use in surgical preparation. In this study, we evaluated the effects of 3D printed fracture models on orthopedic trainee surgical planning and injury understanding for injuries of the shoulder and elbow.

Methods: Models of periarticular fractures of the shoulder and elbow were manufactured by 3D printing at the medical school design lab. Eleven Orthopedic trainees viewed X-rays and computed tomography (CT) scans for each injury, and completed a preoperative questionnaires. They were then given access to the 3D model of each injury, in addition to the previously viewed imaging. They again completed a preoperative plan and questionnaire. Preoperative plans were graded for feasibility by a preestablished template. Results were compared for each participant with and without the 3D models.

Results: Within all trainees and fractures, trainees were more likely to have feasible preoperative plans when given a 3D model, compared to access to x-rays and CT scans alone (74% vs. 62%). In all cases where preoperative plans were changed after handling the 3D models (46/77 changed, 60%), they stayed static or improved in feasibility. Participants reported significantly improved understanding of injury anatomy (P<0.0001), increased confidence in choosing operative positioning and surgical approaches (P<0.0001), desired implants (P=0.011), and better conceptualization of how to perform fracture reduction (P=0.0038).

Conclusion: Orthopedic trainees benefit from 3D printed fracture models when performing preoperative planning of complex periarticular shoulder and elbow injuries. Given the rarity and difficulty of these injuries, use of this technology could allow for shortened learning curves and improved surgical results in the field of orthopedic fracture care.

Level of evidence: IV

Keywords: 3D printing, Education, Elbow fracture, Orthopedic surgery, Preoperative planning, Proximal humerus fracture

Introduction

Periarticular fractures of the shoulder and elbow can be spatially complex injuries, even for experienced surgeons. These present complicated patterns that may be challenging to interpret based on radiographs or even advanced imaging. Further, they are less common surgical procedures for the orthopedic surgeon.[1,2] Because of this, trainees may see a limited number of these operations before entering practice. Once in practice,

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THE ONLINE VERSION OF THIS ARTICLE ABJS.MUMS.AC.IR

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novice and even senior surgeons may find aspects of these surgeries difficult, such as patient positioning, fluoroscopic imaging, and fracture reduction – particularly in comminuted fractures. This creates a need to maximize the preparation for and learning from each case, in part through preoperative planning. Preoperative planning has historically been performed using tracing paper and radiographs of the injured, or sometimes the contralateral, limb. According to the AO Principles of Fracture Management, "The ability to shift the tracings around, to superimpose one on the other, to lengthen, to shorten, to angulate or displace, all aid in developing a 3D image of the problem, of its associated soft-tissue implications, and of the ultimate solution."[3]

However, with the advent of three-dimensional (3D) printing technology, we are now able to render palpable preoperative models of complex pathologies from computed tomography scans (CTs) or magnetic resonance imaging (MRIs) for use in surgical planning. Orthopedic surgeons have utilized this technology in areas including trainee education, patient education, pre-operative understanding of complex fracture morphologies, bone lesions, and pediatric deformities, templating for arthroplasty, shoulder and spine surgeries, and pre-contouring and selecting specific implants to reduce surgical times and blood loss in fractures of the acetabulum, elbow, tibial plateau and distal tibia/ankle.[4–22]

We therefore sought to evaluate the effects of visualization and handling of 3D printed models on trainee surgical planning and perceived understanding in complex periarticular upper extremity fractures. Primary outcomes included differences in participant confidence and in reviewer-assigned preoperative plan scores when templating with x-ray and CT only vs. when templating with the addition of 3D printed models. Further analyses were performed by training level, fracture location, fracture difficulty, and by category of preoperative planning. The purpose of this study was to determine if 3D printed models can improve trainee confidence and performance when preparing for these surgeries. If our hypothesis that this method aids successful surgical planning is correct, widespread use of this technology has the potential to improve training in orthopedic fracture care.

Materials and Methods

We obtained Institutional Review Board approval prior to commencing the study. This study was a collaboration between the orthopedic surgery department and the multidisciplinary clinical 3D print lab located in the Health Design Lab at our institution. The orthopedic team reviewed a fracture database and selected 7 periarticular fractures involving the shoulder or elbow. These fractures varied in complexity and are listed in [Table 1]. In order to be included, fractures required injury radiographs and dedicated extremity CT with 3D reconstruction, as well as post-operative radiographs and operative report. After selection, de-identified CT DICOM (Digital Imaging and Communications in Medicine) images were obtained and reviewed with the 3D printing team.

The 3D printing team used 3D Slicer 4.9.0 (open-source software, www.slicer.org) for DICOM display and segmentation. The initial 3D mesh was then processed in Meshmixer (Autodesk Inc., San Rafael, CA)After this, slicing of the standard tessellation language (STL) file was done using Ultimaker Cura 3.5.0 software (Ultimaker B.V., Waltham MA). Fracture models were printed on Ultimaker 3 printers (Ultimaker B.V., Waltham MA) by fused deposition modeling (FDM), also known as fused filament fabrication (FFF). This was done using polylactic acid polymer (PLA) with 100% infill. Water-soluble polyvinyl alcohol (PVA) support material was used in a dual extruder setup to preserve complex fracture geometry. Each fracture was printed in two formats: 1) with the fracture fragments and remainder of bone as one solid piece held together by added supports, such that the in-situ position of the fracture at the time of CT was replicated 2) with the fracture fragments each as separate pieces, such that the fragments could be manipulated in relation to one another and to the remainder of the surrounding bone(s) [Figure 1].

Table 1. Periarticular Shoulder and Elbow Fractures Utilized in the Study

Fracture #	Body Part	Difficulty	Description
1	Shoulder	Medium	Proximal humerus fracture: Neer 4-part with comminuted greater tuberosity, simple lesser tuberosity, and surgical neck fracture with intact medial hinge
2	Shoulder	High	Proximal humerus fracture: Neer 4-part with comminuted greater tuberosity and lesser tuberosity, and surgical neck fracture with disrupted medial calcar
3	Shoulder	Low	Proximal humerus fracture: Neer 3-part with comminuted greater tuberosity and surgical neck fracture with intact medial calcar
4	Elbow	High	Intraarticular short oblique supracondylar distal humerus fracture with medial condyle fragment
5	Elbow	Medium	Radial head fracture with two small fragments and long oblique extension into radial neck
6	Elbow	Low	Transverse simple olecranon fracture through bare area
7	Elbow	High	Open Monteggia fracture: comminuted fractures of the radial head and the proximal ulna involving the coronoid, with radiocapitellar joint dislocation

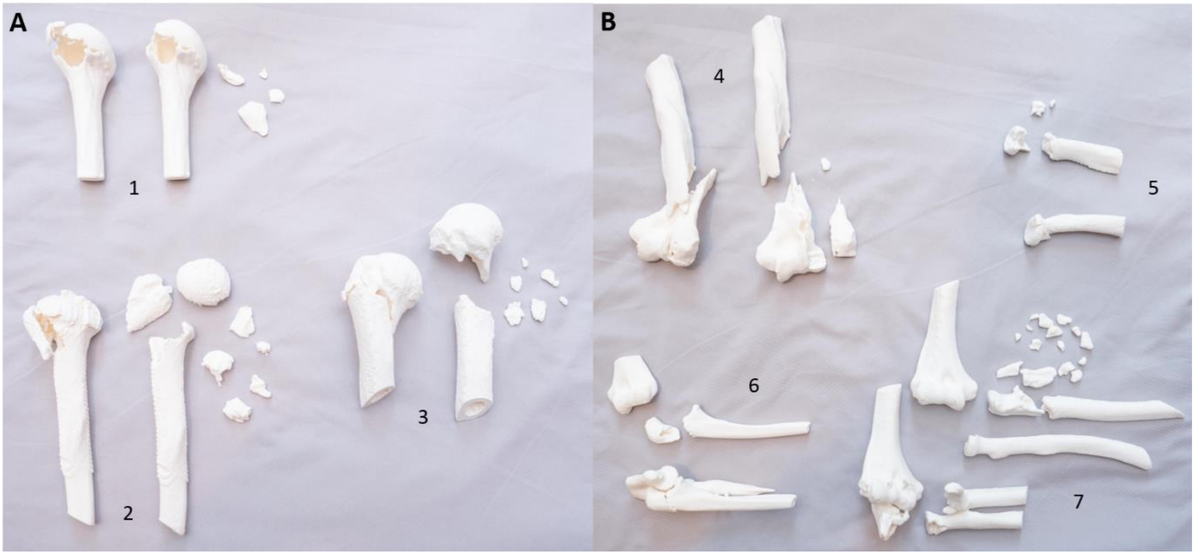

Figure 1. 3D printed models

We then recruited 11 orthopaedic trainees in various training levels: 6 junior trainees (defined as 4th year medical students with a secured residency position in orthopedics, current orthopedic interns, and 2nd year orthopedic residents), and 5 senior trainees (3rd, 4th, and 5th year orthopedic residents)). Each participant served as their own internal control, and was tested on all 7 fractures. First, they were shown the x-rays and CT scan for the injury (Condition A). They were asked to complete a templating sheet with a list of predetermined choices detailing patient positioning, surgical approach (es), desired available implants, and desired reduction tools [Supplemental Figure 1]. They were then asked to complete a questionnaire on their confidence in deciding patient positioning and operative approach, their ease of understanding the fracture anatomy, their confidence in implant selection and their fracture reduction strategy, and the overall ease of templating an operative plan [Supplemental Figure 2]. This was scored from 0-50, with 50 points indicating maximal ease and confidence. They then repeated the process for the same fracture, but this time were given access to the 3D printed models in addition to the x-rays and CT (Condition B). They again developed a surgical plan and completed a questionnaire regarding the templating process. Two attending orthopedic surgeons who were blinded to the participant's training level and available imaging then graded the surgical plans as either "feasible" or "not feasible".

Data was collated in Microsoft Excel 2016 and analyzed using GraphPad Prism version 8.0 for Windows (GraphPad Software, San Diego CA). Preoperative template scores between conditions A and B were compared by Fischer's Exact Test or Chi Square analysis. Additionally, it was noted whether the trainee modified their preoperative plan from condition A to condition B. Numeric scores from trainee-completed questionnaires were compared by paired Student's T-test. P<0.05 was defined as statistically significant.

Results

Preoperative Plans

When taking all trainees and fractures together, 48/77 (62%) of preoperative plans were feasible when trainees had access only to X-rays and CT imaging (condition A). This increased to 57/77 (74%) when trainees were additionally provided with the 3D printed fractures (condition B) (P=0.119, not significant). Forty-six of 77 (60%) preoperative plans changed from condition A to condition B. More junior trainees changed their preoperative plan choices than seniors (p=0.0058, significant). In all cases of changed preoperative plans, the plans remained static in or improved in feasibility.

By training level, 16/42 (38%) junior trainee plans were feasible for condition A vs. 23/42 (55%) for condition B (p=0.126, not significant). Thirty-one of 42 (74%) junior trainee preoperative plans changed from condition A to condition B. For senior trainees, 32/35 (91%) preoperative plans were feasible for condition A vs. 34/35 (97%) for condition B (p=0.303, not significant). Fifteen of 35 (43%) senior trainee preoperative plans changed from condition A to condition B. Junior trainees were significantly more likely than senior trainees to change their preoperative plan based on the 3D printed fractures (p=0.0058).

When analyzed by low, medium, and high fracture difficulty, there was no significant difference in percentage of feasible preoperative plans from condition A to conditions B (low difficulty p=0.709; medium difficulty p=0.340; high difficulty p=0.204). For low difficulty fractures, 10/22 (45%) of preoperative plans were changed from condition A to condition B, for medium difficulty fractures, 13/22 (59%) were changed, and for high difficulty fractures, 23/33 (70%) were changed. The percentage of preoperative plans changed from condition A to B did not differ significantly by fracture difficulty (p=0.199).

When analyzed by anatomic area of shoulder or elbow, there was no significant difference in percentage of feasible preoperative plans from condition A to condition B (shoulder p=0.099; elbow p=0.39). For shoulder fractures, 23/33 (70%) of preoperative plans were changed from condition A to condition B, and for elbow fractures, 23/44 (52%) of plans were changed. The percentage of preoperative plans changed from condition A to B did not differ significantly by fracture anatomic area (p=0.123).

Trainee Surveys

When taking all trainees and fractures together, participants gave significantly higher scores in all 5 categories when they had access to the 3D models (condition B), compared to when they only had access to X-rays and CTs (condition A) [Table 2]. This was also true for senior trainees, while junior trainees perceived that the 3D models were most helpful for deciding operative setup, understanding anatomy, and choosing reduction techniques [Table 3]. When analyzed by low, medium, and high fracture difficulty, trainees perceived the 3D models as more helpful for the higher difficulty fractures [Table 4]. By anatomic area, trainees perceived the 3D models as helpful for deciding operative setup, understanding anatomy, and for choosing reduction techniques, and for implant choice for shoulder fracture but not elbow fracture [Table 5].

Table 2. Survey Responses by All Trainees

	N=77 fractures, 11 trainees		
	No 3D	**3D**	**P**
Setup	6.7 (1.5)	7.4 (1.4)	<0.0001*
Anatomy	6.8 (1.6)	8.0 (1.6)	<0.0001*
Implant	6.0 (2.2)	6.4 (2.4)	0.011*
Reduction	5.8 (2.1)	6.4 (2.3)	0.0002*
Overall	5.8 (2.2)	6.3 (2.5)	0.0038*
Total	31.1 (8.7)	34.6 (9.0)	<0.0001*

*statistically significant. Values given as mean (SD)

Table 3.Survey Responses by Training Level

	Senior Trainees (N=35 fractures, 5 trainees)			Junior Trainees (N=42 fractures, 6 trainees)		
	No 3D	***3D***	***P***	***No 3D***	***3D***	***P***
Setup	7.7 (1.2)	8.2 (0.8)	0.0032*	5.9 (1.2)	6.8 (1.5)	0.0006*
Anatomy	7.6 (1.3)	8.1 (1.6)	0.031*	6.1 (1.5)	7.8 (1.6)	<0.0001*
Implant	7.6 (1.2)	8.0 (1.0)	0.024*	4.6 (1.9)	5.1 (2.5)	0.11
Reduction	7.4 (1.1)	7.9 (1.4)	0.024*	4.5 (1.8)	5.2 (2.3)	0.0028*
Overall	7.5 (1.2)	8.1 (1.2)	0.0066*	4.4 (1.9)	4.8 (2.4)	0.15
Total	37.7 (5.5)	40.3 (5.6)	0.0047*	25.6 (6.9)	29.8 (8.6)	0.0002*

*statistically significant. Values given as mean (SD)

Table 4. Survey Responses by Fracture Difficulty

	Low (N=22 fractures, 11 trainees)			Medium (N=22 fractures, 11 trainees)			High (N=33 fractures, 11 trainees)		
	No 3D	***3D***	***P***	***No 3D***	***3D***	***P***	***No 3D***	***3D***	***P***
Setup	6.9 (1.7)	7.6 (1.3)	0.026*	6.8 (1.7)	7.6 (1.4)	0.006*	6.6 (1.3)	7.2 (1.5)	0.010*
Anatomy	7.3 (1.7)	8.1 (1.5)	0.030*	6.8 (1.7)	8.3 (1.2)	0.0005*	6.4 (1.3)	7.6 (1.7)	0.0001*
Implant	6.4 (2.3)	6.7 (2.6)	0.090	6.0 (2.6)	6.4 (2.6)	0.31	5.7 (1.8)	6.3 (2.3)	0.060
Reduction	6.4 (2.2)	6.9 (2.3)	0.11	5.8 (2.3)	6.3 (2.4)	0.094	5.5 (1.9)	6.2 (2.3)	0.0029*
Overall	6.4 (2.3)	6.6 (2.5)	0.49	5.9 (2.5)	6.4 (2.6)	0.12	5.3 (1.9)	6.1 (2.5)	0.017*
Total	33.4 (9.4)	36.0 (8.7)	0.022*	31.3 (10.0)	34.9 (9.4)	0.015*	29.4 (7.0)	33.4 (9.1)	0.0011*

*statistically significant. Values given as mean (SD)

Table 5. Survey Responses by Fracture Anatomic Region

	Shoulder (N=33 fracture, 11 trainees)			Elbow (N=44 fractures, 11 trainees)		
	No 3D	*3D*	*P*	*No 3D*	*3D*	*P*
Setup	6.8 (1.3)	7.8 (1.0)	<0.0001*	6.6 (1.6)	7.1 (1.6)	0.024*
Anatomy	6.7 (1.5)	8.1 (1.4)	<0.0001*	6.8 (1.6)	7.8 (1.7)	0.0007*
Implant	5.7 (2.3)	6.1 (2.6)	0.030*	6.2 (2.1)	6.7 (2.3)	0.094
Reduction	5.6 (2.1)	6.3 (2.4)	0.002*	6.0 (2.1)	6.6 (2.3)	0.0158*
Overall	5.6 (2.2)	6.1 (2.7)	0.051	5.9 (2.2)	6.5 (2.4)	0.0337*
Total	30.4 (8.2)	34.4 (8.6)	<0.0001*	31.6 (9.1)	34.7 (9.4)	0.0079*

*statistically significant. Values given as mean (SD)

Discussion

Periarticular fractures of the upper extremity can be challenging to treat. These fractures are rare and it is sometimes difficult to fully appreciate these injuries with plain radiographs and even CT scans. This makes it more important for trainees and surgeons to maximize their learning potential and preoperative preparation for each of these cases. We have shown here that providing orthopedic trainees with 3D printed models of periarticular fractures of the shoulder and elbow led to improved reported understanding of the injury anatomy, increased confidence in choosing operative positioning, surgical approaches, and desired implants, and better conceptualization of how to perform fracture reduction. These effects were most pronounced in higher difficulty fractures. Further, we have shown that access to 3D printed models resulted in higher rates of feasible operative plans than access to injury x-rays and CT scans alone. This was most pronounced in junior trainees and in higher difficulty fractures, though it failed to meet statistical significance.

There is growing evidence that 3D printed models can enhance learning experiences of medical trainees. Recent studies have shown 3D models increase the percentage of knowledge gained by learners who are otherwise provided the same information.[6,8,23] From a more hands-on perspective, these models can be used to simulate surgical procedures that attending surgeons may not feel comfortable letting trainees perform on patients, such as percutaneous acetabular fixation.[24] Further, evidence is growing that surgeons find 3D printed fractures helpful in the practice of medicine: from patient education to implant selection and pre-contouring, to surgical simulation in advance, to intraoperative decision making.[12,20,25] Yang et al found surgeons gave 3D trimalleolar ankle fracture prototypes an average score of 8.9/10 for usefulness in preoperative planning.[21] Patients in their study found the prototypes helpful in understanding their condition and had a strong preference for their surgeon to use a 3D prototype to counsel them.[21] Compellingly, multiple groups have now demonstrated decreased operating times, blood loss, and fluoroscopy time when using patient-specific 3D printed models for preoperative planning of fractures ranging from humeral shaft fractures to intercondylar humeral fractures, trimalleolar ankle fractures, acetabular fractures, tibial plateau fractures, and calcaneal fractures.[9,11,16–20,26]

Our study has several limitations. We used internal controls to account for baseline differences in resident knowledge base. However, due to a hypothesis that the 3D models would improve fracture understanding and preoperative planning, participants were always shown the x-rays and CT first, and the 3D model was added second. This could have skewed our results, as trainees were revisiting their initial plan after being shown the 3D models. Further, we used a variety of fractures types, which could be perceived as both a strength and a fault. Finally, we had only 11 participants. Testing on all seven fractures took over 1 hour per subject, which we feel contributed to difficulty recruiting. With regards to 3D printing technology, it too has remaining limitations. The quality of models is limited by the slice thickness of source CT scans, with the volume between slices filled by extrapolation. The ideal format for fracture printing for a given application is not clear; this is why we choose to print each fracture with the fragments "in-situ" and a second time, with them as separate pieces allowing manipulation. Additionally, medical students were included amongst the junior trainee group. While these medical students had secured a residency position in orthopedics, it is possible that their understanding of anatomy and surgical approaches was limited by their experience with orthopedics.

Conclusion

We have shown here that orthopedic trainees benefit from 3D printed fracture models when performing preoperative planning of complex periarticular shoulder and elbow injuries. Trainees were more likely to have feasible preoperative plans when given a 3D models, compared to access to x-rays and CT scans alone. They also reported improved understanding of injury anatomy, increased confidence in choosing operative positioning, surgical approaches, and desired implants, and better conceptualization of how to perform fracture reduction. We suspect that novice and even senior surgeons might benefit from these 3D models as well. Given the rarity and difficulty of these injuries, and the increasing availability and decreasing cost of 3D printed models, we feel widespread use of this technology could allow for shortened learning curves and improved surgical results in the field of orthopedic fracture care.

Acknowledgement

N/A

Authors Contribution: Authors who conceived and designed the analysis: Pedro Beredjiklian, Brianna Fram, Jason Core, Joshua I. Ng, Robert Pugliese, Stephanie A. Kwan, Michael Rivlin/ Authors who collected the data: Brianna Fram, Jason Core, Joshua I. Ng, Robert Pugliese/ Authors who contributed data or analysis tools: Brianna Fram, Jason Core, Joshua I. Ng, Robert Pugliese/ Authors who performed the analysis: Brianna Fram, Jason Core, Joshua I. Ng, Robert Pugliese/ Authors who wrote the paper: Pedro Beredjiklian, Brianna Fram, Jason Core, Joshua I. Ng, Robert Pugliese, Stephanie A. Kwan, Michael Rivlin

Declaration of Conflict of Interest: Author BF declares no conflicts of interest/ Author JC declares no conflicts of interest/ Author JN declares no conflicts of interest/ Author RP declares no conflicts of interest/ Author SK declares no conflicts of interest/ Author MR declares stock ownership in and is a board member of Dimension Orthotics LLC, and has a patent pending for "3D printing of bone models for mechanical testing"/ Author PB declares stock ownership in and is a board member of Dimension Orthotics LLC, and has a patent pending for "3D printing of bone models for mechanical testing"

Declaration of Funding: The author(s) received NO financial support for the preparation, research, authorship, and publication of this manuscript.

Declaration of Ethical Approval for Study: This study was approved by our institutional review board with ethical code number# 153.

Declaration of Informed Consent: Informed consent was obtained from all individual participants included in the study.

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Supplemental Figure 1. Participant Preop Template Final

TEMPLATING SHEET

Training Status: Junior (MS4, PGY1/2) Senior Trainee (PGY3/4/5)

Fracture ID code: _______

Please circle all imaging you viewed for this injury: X-rays CT 3D Model

Instructions: Please circle your choice(s) for each fracture.

- Patient position (circle 1):
    - beach chair
    - supine with shoulder bump
    - supine with arm across chest over pillows/bump
    - lateral decubitus with arm over pain roller
    - supine with arm board
- Surgical Approach (may circle multiple):
    - Deltopectoral
    - Anterolateral approach to proximal humerus
    - Anterolateral extensile approach to humeral shaft
    - Posterior approach to humeral shaft
    - Posterior approach to elbow – triceps sparing
    - Posterior approach to elbow – olecranon osteotomy
    - Direct (posterior) approach to proximal ulna
    - Lateral approach to elbow (Kocher or Kaplan)
    - Medial approach to elbow (Hotchkiss "over the top", FCU split, or Taylor and Scham elevation of entire flexor-pronator mass from posterior to anterior)
- Implants Available (may circle multiple):
    - Heavy suture (#5 Ethibond, Fiberwire, etc)
    - Proximal humerus locking plate 3.5 mm
    - LCP extra-articular distal humerus plate 3.5mm

    - LCP distal humerus plate, medial 3.5mm
    - LCP distal humerus plate 3.5mm, lateral, with or without tab
    - Radial head arthroplasty
    - Mini frag plates (2.0mm)
    - LCP Olecranon Plates
    - Olecranon tension band materials (1.0 flexible wires, 1.6mm k-wires)
    - Suture anchors
- Reduction Devices (may circle multiple):
    - Schantz screws
    - K-wires
    - Dental pick
    - Pointed reduction clamps
    - Lobster claw reduction clamps
    - Steinmann pins
    - Cortical Strug allograft

Supplemental Figure 2. Participant Survey Final

3-D Upper Extremity Fractures: Participant Survey

Training Status: Junior (MS4, PGY1/2) senior trainee (PGY3/4/5)

Fracture ID code: _____

Please circle all imaging you viewed for this injury: X-rays CT 3D model

How confident were you in deciding on patient positioning and operative approaches for fixation of this injury?

Not at All **Very**
1 2 3 4 5 6 7 8 9 10

How easy was it for you to understand the anatomy of this injury?

Not at All **Very**
1 2 3 4 5 6 7 8 9 10

How confident were you in your implant selection for fixation of this injury?

Not at All **Very**
1 2 3 4 5 6 7 8 9 10

How confident were you in deciding how you would go about reducing this injury?

Not at All **Very**
1 2 3 4 5 6 7 8 9 10

Overall, how easy was it for you to template an operative plan for this injury?

Not at All **Very**
1 2 3 4 5 6 7 8 9 10

Total Score: __/50