3D Printed Anatomically Correct Hand Analog for Surgical Training - Design Proposal

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Abstract

3D printing is becoming more and more commonly used in the medical field for the creation of medical device testing models and surgical training models. This paper provides an overview of ongoing work towards the development of a 3D printed and anatomically correct surgical training model of the hand for bone pinning procedures. Our team is aiming to make this model personalized, affordable, and reusable for many bone pinning procedures of the 5th metacarpal. As of the end of the fall semester, we have produced a number of 3D printed 5th metacarpals through FDM and PolyJet printing, created formulas for density-accurate prints for accurate tactile feedback, and have begun testing small scale casting methods of the 5th ray of the hand. The feedback gained from our project contacts has been largely positive, and changes such as lower density printing in the medullary canal, as well as printing fractured 5th metacarpals, is ongoing. Our current bone models have served us very well for formulating our density profiles and print settings, as well as for testing casting methods, but going forward we also plan to replace these models with ones generated from CT imaging segmentation for the creation of bone and hand models of the correct size to be used together.

***Keywords**: 3D printing, additive manufacturing, metacarpal fractures, surgical training model*

1 Introduction

Fractures to the hand are some of the most common orthopedic injuries that occur in the U.S patient population. The primary means of training the basic motor skills needed to restore function to fractured hands have been through shadowing attending surgeons in the operating theater and using cadaver models. Several forces have made it difficult for surgical residency curricula to incorporate operating room experience including financial constraints and ethical concerns tied to training basic skills on patients. In response to these pedagogical concerns, alternative training models such as animal, cadaver, and simulation models have been sought after [1]. 3D-printed biomimetic models have been of primary interest for their ability to serve as high fidelity models for surgical training that can be developed at low costs.

Our project focuses on the creation of a 3D-printed anatomically correct hand for use in surgical training. Specifically, this hand will assist surgeons in the training of bone pinning for metacarpal fractures, which is the practice of using pins to set fractured bones in place to heal properly. Surgeons will be able to practice bone pinning techniques on a hand that has similar tissue, bone, and muscle densities, allowing them to be better prepared for live procedures. This increases patient outcomes and lowers the risk of complications for procedures that may be more invasive. While the creation of anatomical models for training use is not revolutionary, 3D printing technologies have emerged as a means to develop models of greater detail and specificity.

In 2003, the Accreditation Council for Graduate Medical Education (ACGME) set work hour limitations on surgical training. D. J. Anastakis, an expert in the field of surgical training, found that this change decreased resident exposure to the skills and procedures necessary to perform on live patients [2]. The reform was the impetus for a shift towards cadaver and simulation-based teaching models. Training models hold a significant role in health care, serving as the introduction to the basic skills needed by resident surgeons that ultimately translate to successful live-patient operations. Current teaching and patient planning models using live patients and cadavers are limited by availability, financial constraints, and ethical concerns. Alternative approaches have explored the viability of using animal models, virtual simulation, and bench models. Innovations in the development of 3D printed anatomical models could replace the need for the aforementioned training solutions while also being more specialized.

Surgical training is highly dependent on socioeconomic status. In lower-income countries, existing training solutions such as cadavers can be hard to come by unharmed and in a state appropriate for training [3]. Even when cadavers are available, they can cost around $2000 and the necessary storage humidors cost $4000 each [4]. Some teaching hospitals recoup this investment by charging patients more than non-teaching hospitals [5]. Anatomical models are important in medical training because they ensure training can occur independently of economic hurdles faced with organic training solutions.

Reduced training on cadaveric models and exposure time in the operating room directly impacts the performance of surgeons post-residency, having a negative compounding effect on patient care. The diminished time allocated to training on live patients and cadavers has been found to impact all areas of medicine, but according to John Older, an expert in orthopedic surgery, none were affected as much as the surgical disciplines [6]. Given the increased risk associated with surgery, imparting a greater experience and knowledge on anatomical landmarks and indicators is of utmost importance when training surgical residents. The ramifications of reduced practical training on the prowess and performance of surgeons can be best reflected by legal action taken by patients post-surgery. About 32% of compensation litigation post-surgery involves unintentional damage to the surrounding region of surgery [7].

The development of novel training models for metacarpal fractures would impact various populations in healthcare. 3D printed models can serve a dual purpose and directly benefit resident trainees and practicing surgeons, answering the deficiency of anatomically correct, cost-effective, and risk-free training models needed to train residents [1,8]. The use of these simulatory models could prove useful past pedagogical use for preoperative planning for practicing surgeons [9]. Developing new models for surgical training benefits our primary surgeon population, but also has a trickle-down effect on the indirect population - the patients themselves who tend to skew younger in age and male in gender [10]. Patients also benefit from their surgeon's training in the form of lower healthcare costs following their procedure. Studies have shown that increased surgical training has lowered the healthcare costs of patients undergoing pancreaticoduodenectomy, and states that other procedures show similar correlations [11].

The hand is divided into three regions: the carpals, the metacarpals, and the phalanges (**Figure 1**). Eight smaller bones make up the carpal region and the phalanges are also known as the fingertips. The metacarpals are five large bones that resemble the phalanges, they form a transverse arch that supports the palm and allows the thumb and fingers to be manipulated 12].

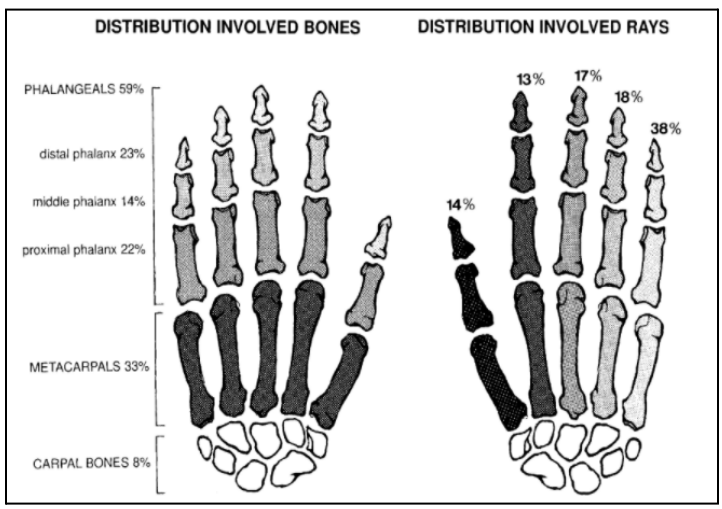

Figure 1: Breakdown of hand fractures by involved bones and involved rays of the hand (n = 786). Figure from source [10]

Anyone is at risk of fracturing a bone, but hand dominance, history of prior injuries, occupation, and athletic participation all play a significant role in contributing to a metacarpal fracture [13]. Kathleen Kollitz, MD, elucidated the prevalence of metacarpal fractures accounting for around 40% of all hand fractures, with the fifth metacarpal being most commonly broken [12]**.** Sports injuries are a common cause of metacarpal fractures in children and adolescents, while work-related injuries are the main avenue to injury for middle-aged adults [13]. According to Michael Nakashian, MD, an expert in disorders of the shoulder, elbow, wrist, and hand, metacarpal fractures predominantly occur in the male population [14].

In a study assessing 4,718 occurrences of metacarpal fractures, 82.3% of fractures occurred with men [14]. The most common type of metacarpal fracture is a fifth metacarpal neck fracture, also known as the “boxer fracture.” Fifth metacarpal fractures typically occur due to trauma being applied to a clenched first [15].

Metacarpal fractures have different classifications such as neck, shaft, and base fractures. The type of fracture line can be further categorized into transverse, oblique, spiral, or comminuted [16]. They also tend to have an angular position due to the flexors, which are assessed radiographically. The most common type is dorsal angulation, which results from the pull of interosseous muscles [17]. Symptoms of a boxer fracture include ecchymosis, swelling, pain, bent fingers that look out of alignment, and a limited range of motion of the fourth and fifth phalanges [18]

The type of treatment varies depending on if the fracture is open or closed, the number of metacarpals that are fractured, the displacement of the bone, the stability, and the rotational malalignment. If it isn't possible to position the bone back into place, surgical fixation is the next recommendation [13]. Metacarpal shaft fractures typically require surgical fixation, which includes intramedullary pinning, plates, or screws. Metacarpal neck fractures can also be fixed via intramedullary pinning, transverse pinning, while metacarpal head fractures require Kirschner wire fixation [12]. Surgery is also required if there are neurovascular injuries to surrounding arteries and nerves [15]. If the fracture is not correctly addressed, myriad issues could occur. Possible complications include; extension lag, pseudoclawing, malrotation, and stiffness, all of which inhibit a patient's ability to do daily activities. A significant contributor to surgical complications is the lack of surgical preparation, which can be avoided given the surgeons are provided with proper training and training materials. Infection and tendon ruptures are two serious complications that arise due to metacarpal fracture surgery [12].

Montgomery sought to determine if 3D printed fracture models can help improve orthopedic trainee education. The study pulled imaging from 7 separate calcaneus fractures to create 3D models which were then printed using polylactic acid (PLA), a rigid plastic. These models were not designed to be perfect anatomical analogs but rather serve as accurate prints to visualize the fracture. Researchers then compared the accuracy of fracture diagnosis when using medical images versus 3D printed models of the fracture. Accuracy of diagnosis trended higher as residency year increased (69% in first-year trainees, to 90% in fifth-year trainees) [19]. Accuracy of diagnosis also trended higher in the experiments that contained a 3D printed model, but the difference in diagnostic accuracy (69% without, 84% with) was not enough to be statistically significant ($p=.087$). Despite this, trainee understanding was improved, especially in lower-level residents. One key knowledge gap in this study was the size of the trainee group as well as the number of fracture cases reviewed and followed through upon. Furthermore, the trauma center where this study was conducted had begun to change its surgical techniques towards percutaneous and minimally invasive approaches. These larger systemic changes in treatment may be the cause of similar diagnoses by residents training under this changing system. This is the first study that the authors are aware of to assess the confidence and accuracy of 3D printed fracture models with a focus on the level of training [19]. This study showed evidence of increased training knowledge through hands-on model use, but our solution aims to create a 3D model that is more anatomically significant and surgically applicable than Montgomery's study.

One attempt to create a low-cost 3D printed surgical training model was developed by Wu et al. at Carnegie Mellon University. Hand bones were printed with links between the bones and a fracture in the 5th metacarpal. By lowering the infill density, the porosity of cancellous bone was mimicked. The skeletal hand was then cast in ballistic gel and the links between bones were broken, allowing the hand to be flexible while still holding the bones in the proper position. To finish the model, silicone was brushed on to simulate skin. Surgeons in charge of resident training tested this device and all agreed that it would be a valuable teaching aid. Junior residents can receive hands-on experience without working with cadavers. These standardized models cost only $150 compared to more expensive cadaver specimens [20]. While the surgeons were overwhelmingly positive about this model, they still had suggestions for improvements. The skin was unrealistic, which could affect binding with the pin when performing bone-pinning procedures. Due to being printed vertically, the cancellous bone structure depended on print orientation. This might affect some training depending on the level of accuracy required. The surgeons also desired more customization, both in the fractures presented and the joint mobility to allow more bone-pinning options [20].

Prisc et al. created a 3D model of a healthy hand to allow plastic surgery residents to practice percutaneous wire fixation of various hand fractures. This model allows for the bones to be individually printed and swapped out, allowing the residents to practice basic and complex fixation of fractures. The model also allows the residents to practice bone pinning without fluoroscopy and orthopedic tools; this model can be worked on with a home power drill. The total cost was under $50, but the 3D printers and materials were of no cost to the user [21]. One shortcoming of the previous attempt was that not everyone has access to a 3D printer, especially not for free, meaning-making this model under $50 is not feasible for everyone. The bones can also only handle about six to eight holes before they form one giant hole. Brown's 3D printed model uses bones encased in a silicone "skin," but it does not incorporate any other anatomical aspects. The model needs to be as realistic as possible; surgeons will not only come into contact with skin and bones in surgery, but they will also have to navigate around tendons, muscles, ligaments, vasculature, nerves, cartilage, etc [21].

Brichacek et al. looked to develop a 3D printed model hand model to be used by junior surgical residents to train closed reduction and percutaneous pinning (CRPP). The model incorporated several common hand fractures including Bennett's fracture, transverse 5th metacarpal neck fractures, and transverse 2nd proximal phalanx fractures. The model was designed to be anatomically accurate, used flexible silicon for the dorsum to allow for mobile joints and bone palpitations, contain radiopaque bones, and have realistic haptic feedback when drilling the bones. The bones were created with polyurethane foam mixed with iron powder. The addition of iron powder rendered the bones of the model radiopaque for training fluoroscopy. Soft tissues were mimicked using silicone of varying viscosities. Since the silicone was opaque, the underlying iron-doped bones were visible. This visibility would be beneficial for training novices, but to increase the difficulty for training more experienced residents a surgical glove was placed over the model to impair visibility. Despite positive responses to the 3D printed model from attending surgeons and residents, several limitations on it were elucidated. Brichacek et. al strived for anatomical accuracy but was unable to include joint capsules, collateral ligaments, and volar oblique ligament of the thumb [22].

Similar to the Brichacek, Wu, and Prsic models, Farrell et. al took a computed tomographic scan of a subject's hand to 3D print an anatomically accurate hand model. The model bones were printed using polylactic acid supported with dissolvable polyvinyl support. Fractures were simulated in the bone models before printing using fracture bridges. These fracture bridges were temporary connections between bone fragments that would keep them in place until the simulation began. The model found success in mimicking proprioceptive feel necessary for training pinning and plating. In addition, the silicone used provided the necessary matrix needed to mimic soft tissue. It had proper malleability and stability to simulate the Jahss maneuver and allow for training with the use of forceps. The authors estimate a cost of between $200 and $300 for each model but cite large batch quantities to lower production costs. They noted the desirable reproducibility of the models to fit specific educational needs. The primary setback faced in the study was truly replicating the anatomy of the hand. Much like the Brichacek model, ligaments proved to be a difficult structure to replicate and print [23].

Our model looks to build upon the framework set by the prior discoveries and studies on 3D printed orthopedic models for surgical training. Our primary goal is to make our model as anatomically relevant as possible by incorporating anatomy beyond just bones and outer tissues. By including cartilage, tendons, and vasculature, residents can receive more accurate training and be better prepared for what they will encounter in a human body. A secondary goal is to allow for more customization with regard to fractures presented. While some models already feature removable metacarpals, we aim to increase the number of bones that are interchangeable to allow for more complicated fractures and surgical procedures.

2 Statement of the Problem

Physicians are currently using a variety of devices to practice percutaneous bone pinnings, such as 3D printed models, cadavers, and Sawbone® models. Cadavers are a less preferred option due to the cost, with the national average cost of a cadaver being $2,000. Cadavers require stainless steel humidors for storage, which range from $4,000 to $8,000 [4]. The physicians would only be able to use each cadaver hand a few times before it needs to be discarded, meaning cadavers would have to be purchased frequently. In short, cadavers can be a very costly option for surgical training, which causes physicians to look elsewhere for surgical training models. There are 3D printed models available for physicians to use, but most of the models must be discarded after so many uses due to the accumulation of damage. Currently used 3D printed models are typically a couple of hundred dollars, sometimes more, but they can be customized for each patient. Physicians also use models such as the Sawbone® hand model, but that model can also be used only so many times before it needs to be discarded. Models such as the Sawbone® are also not an accurate depiction of the hand, the densities do not match the densities of bone. The Sawbones® typically takes about 21 days before it's ready to be shipped, but now it's currently taking 6+ weeks to be shipped. This is an issue because the physicians could easily run out of Sawbone® models and have to wait over 6 weeks for a new model, meaning they need to order a lot of them ahead of time which is inconvenient.

Our team searched through the US Patent and Trademark Office Database for any existing patents that are similar to this project. Using the keywords ‘3D print’, ‘medical training device’, ‘medical training model’, ‘silicone casted hand’ and others, we were unable to find any existing devices similar to our project. This could pave the way for patent filing in the future for our device and process. Since this device is a model not being used on patients, but rather as a training device, this device currently does not need FDA approval, although regulations on medical training models are a near certainty in the future.

3 Solution

Our solution is to 3D print an anatomically correct model of the hand that has interchangeable fifth metacarpals. This allows the physicians to have a 3D model to practice bone pinning on, but they don't have to discard the model after so many uses. Instead, they can swap out those parts that need to be replaced over time, this allows for a much lower cost product. Physicians are also able to 3D print a patient's specific fifth metacarpal fracture, place that fracture into the model, and practice pinning. Our design will consist of a 3D printed hand that will be encapsulated with a skin-like material, this will allow the bones to be set in place correctly and it will also allow the physicians to practice on a more life-like model. Our model seeks to address the issue of high costs associated with existing models while maintaining a high level of fidelity. Our model will be much more affordable and will only require specific parts to be replaced over time, as opposed to the entire model. Our model will also be more realistic than models such as the Saw Bone, which is essentially a skeleton model, it does not feature any ligaments, tendons, vasculature, or skin. We are trying to incorporate skin and ligament-like structures to make this training model as similar to a patient's hand as possible.

4 Plan of Action

With the primary use within pedagogical settings, a high level of reusability must be achieved and serve as a cheaper alternative to existing models, while maintaining anatomical fidelity. Of utmost importance are the mimicry of bone structures and density in order to simulate the haptic feedback and surgical landmarks associated with percutaneous pinning of the metacarpal bones. One such important landmark is the haptic feedback a surgeon experiences when initially piercing through the outer layer of cortical bone, entering the medullary cavity, and piercing through the terminal cortical layer. Additionally, skin and flesh must be modeled with synthetic material analogous to the anatomical properties of the tissues respectively. In order to improve the reusability and customization of the model, the interchange of individual 3D printed bones must be possible. This would allow for a single model to be used multiple times and for the pinning of differing fracture forms. This must all be done with proper respect to anatomical

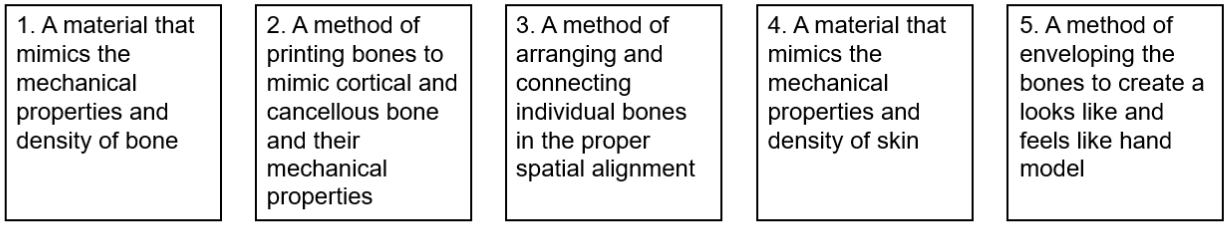

Figure 2: Diagram of functional blocks relevant to this project

structure and alignment to provide the end-user with experience performing percutaneous bone pinning on an anatomically correct hand model.

Given the need to closely mimic hand anatomy, the properties and material characteristics of in vivo structures are the primary constraints guiding project specifications. In terms of bone structure, important distinctions have to be made between a dense outer cortical layer and, porous cancellous cortices, and a hollow medullary cavity. The material chosen to print these structures would also need to be analogous to the properties and density of anatomical bones. These bones would then need to be aligned in the proper anatomical arrangement and be enveloped by a material that mimics the properties of the flesh and skin that encapsulate the hand. These specifications are defined within five functional blocks as shown above (**Figure 2**).

The main focus of the first half of the 2021-2022 academic year has been determining the best method of fabricating structurally analogous synthetic bones for the model and the ideal material used in conjunction with said method. Two concepts were considered for the fabrication methods: bone model casting and additive 3D printing. The first method would involve the creation of molds and resin casting to create bone models. The second involved exploring different additive manufacturing techniques for the creation of bones. 3D printing manufacturing concepts were further subdivided into fused deposition modeling (FDM), stereolithography (SLA), and PolyJet^{TM} printing.

Both overarching fabrication methods, casting and 3D printing, garnered their own individual advantages and disadvantages. The method of casting bone would be most similar to methods followed by Brichacek et. al which involved the pouring of polyurethane foam into a bone mold. Following this method would allow for the use of materials that would better mimic the density of bone at a better price point compared to materials available for 3D printing. Despite the promise of casting, a glaring concern lay in the inability to create distinct densities between different cross-sections of the bone, as a cast will create a solid and homogeneously dense model. 3D printing methods, specifically FDM, proved to be the more desirable for the level of detail needed to create differentiable anatomical structures. These methods proved to be more viable when compared to casting when considering fractures and bone structure could be more readily customized with the software associated with 3D printers. Moreover, clinical imaging data could be more easily segmented to create patient-specific bone models of high fidelity.

Considerations on customizability, fidelity, and importantly affordability guided the decisions on which additive manufacturing method to pursue. FDM is likely the most well-known additive manufacturing method, involving the extrusion of thermoplastic onto a build platform layer-by-layer to fabricate a three-dimensional object. Rather than extruding material, SLA utilizes guided lasers to cure a vat of resin in predetermined spatial points. The most robust method, PolyJet™ printing developed by Stratasys, ejects small drops of liquid plastic that are immediately cured with a UV light functioning in a way analogous to a traditional InkJet printer. PolyJet™ printing would allow for the creation of the most biomimetic synthetic bones to be fabricated, with a high level of mechanical and structural accuracy afforded by materials such as BoneMatrix™ and highly detailed print settings. An entire hand could simply be printed with accurate bone structure with a mimetic material with flesh and skin being printed in concert using TissueMatrix™, but with a high price point being a pronounced caveat. SLA resin printing would serve as a more affordable alternative to PolyJet™ printing that could mimic the density of bone, but it would not be feasible to print cancellous bone and a hollow medulla would with this method. Although mimicking the density and properties of anatomical bone would be more difficult with FDM printing methods, its affordability and accessibility made it the most viable method to be explored.

Table 1
Design Constraints - Bone Printing Materials

Component	Density	Young's Modulus	Cost per kg
Cortical Bone	1.85 g•cm-3	18.6 GPa	n/a
Cancellous Bone	n/a	10.4 GPa	n/a
PLA	1.24 g•cm-3	3.4 - 3.6 GPa	\$20 - \$28
ABS	1.04 g•cm-3	1.8 - 3.2 GPa	\$20 - \$ 28
Polycarbonate	1.3 g•cm-3	2.0 - 2.4 GPa	\$30 - \$ 95
Nylon	1.52 g•cm-3	2.6 GPa	\$70 - \$90

Various FDM filaments were explored and compared to the density and Young's moduli of in vivo cortical and cancellous bone. These filaments included: PLA, ABS, Polycarbonate, and Nylon. Unit costs per kilogram for each filament were also compared along with the comparison made to density and Young's moduli (**Table 1**). Material comparisons were made to the density and Young's modulus of in vivo cortical bone, 1.85 g·cm-3, and 18.6 GPa respectively [24, 25]. Due to the highly variable density of cancellous bone throughout the body, no direct comparisons were made to it. Nylon showed the most promise in being the most similar to the density of cortical bone but was significantly more expensive compared to other filaments [26]. Similarly, the higher price range and smaller Young's Moduli of polycarbonate made it a less viable option for use [27]. Although having a smaller density than Nylon, PLA had the greatest Young's Moduli and its affordability motivated its use in the prototyping process [27]. PLA is also much more resilient when printing, requiring no enclosures or special chemical releasing agents, making it more straightforward to work with. Furthermore, PLA is magnitudes less abrasive than denser materials, like nylon or carbon fiber reinforced nylon, which means the inner diameter of brass extruder nozzles when printing, lowering quality over time.

In order to replicate the soft tissues in the hand, different casting materials, such as silicone, were considered. Some of the selected materials include Dragon Skin™, Ecoflex, ballistic gel, and food-grade gelatin. Ballistic gels are widely used to simulate shooting soft tissues but may be less accurate for low-velocity tests. A material with similar mechanical properties to soft tissues at low-velocity impacts is ideal for a surgical training model. To evaluate the selected options, we looked at the metrics shown in Table 2.

Table 2
Design Constraints - Skin Casting Materials

Component	Hounsfield Units	Needle Force	Shore Hardness	Cost per lb
Soft Tissue	-150 - 73 HU	3 - 5 N	10 - 50 A	n/a
Dragon Skin (1:0:1)	165 HU	22.56 N	10 A	$16.11
Dragon Skin (3:4:3)	123 HU	4.39 N	10 A	$36.90
Ecoflex 30	131 HU	10.70 N	30 A	$25.36
Ballistic Gel 4	-182 HU	1.53 N	3.3 A	$31.81
Food Grade Gelatin	9 HU	0.21 N	n/a	$19.99

The metrics examined include Hounsfield Units, Shore hardness, and the amount of force required for an 18-gauge needle to puncture the surface of the material. Soft tissues have Hounsfield Units within the range of -150 to 73 HU, Shore hardness of 10 to 50 A, and needle force of 3 to 5 N [29]. Food grade gelatin was the only material to fall within this HU range but had a needle force of only 0.21 N and no measured Shore hardness [29]. Ballistic gel is close to soft tissue in HU, but below the desired ranges for needle force and Shore hardness [29, 30]. Ecoflex and Dragon Skin™ both have Hounsfield Units and needle force greater than soft tissue, but a Shore hardness of 30 A and 10 A respectively [29]. While none of these materials are close to soft tissue on their own, Dragon Skin™ can be modified using an additional component. This component, Slacker™, changes the mechanical properties of Dragon Skin™ to act more like soft tissue. This combined material measures 123 HU, 10 A, and 4.39 N [29]. Since Hounsfield Units are not a direct measure of density, matching Shore hardness and needle force was determined to be more important. Due to this, Dragon Skin™ with Slacker™ is the best option for a surgical model, even if it is the most expensive option.

5 Preliminary Results

As stated earlier, the bulk of our work this semester focused on designing print settings for a density-accurate 3D printed bone. We began by creating rudimentary sketches of 3D-printed bone cross-sections. We also printed a few test prints of the 5th metacarpal from files sourced from MyMiniFactory [Janson], printing the files as-is with holes for articulation as well as bones with the holes edited out using Meshmixer.

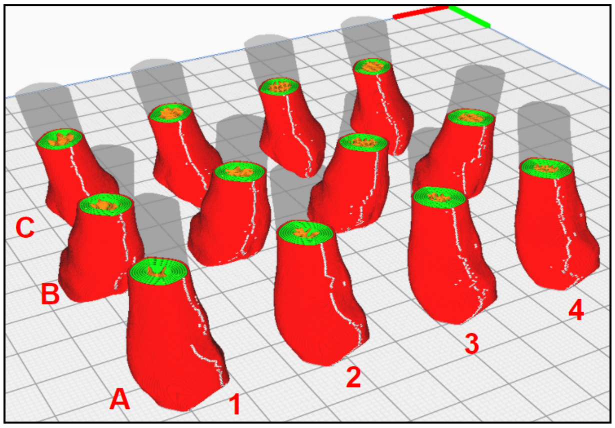

Figure 3: Screenshot of an array of 5th metacarpal 3D models in Cura

Following our initial prints and brainstorming, we started experimenting with our print settings to create an array of bones to be tested by our project contacts at the Jacobs School of Medicine and Biomedical Sciences (JSMBS). Our printed array of bones consisted of the bottom half of 12 5th metacarpals with varied wall thicknesses and infill densities. The wall thickness of the bones, seen in red and green (**Figure 3**), were tested at 2.8mm, 2.4mm, and 2.0mm as seen in rows A, B, and C respectively. The Ender 5 Pro the bones were printed on was equipped with a 0.4mm diameter extruder nozzle, so the difference between two adjacent wall thickness settings is a single layer of PLA. Columns 1, 2, 3, and 4 correspond to infill densities of 20%, 30%, 40% and 50% respectively. A higher infill density corresponds to a more solid infill, with 100% infill being completely solid. We settled on printing a gyroid infill pattern, which prints as layers of sine waves that bend into perpendicular waves as the print progresses. This pattern gave us an infill within the bone of similar geometric composition to the porousness of the cancellous bone.

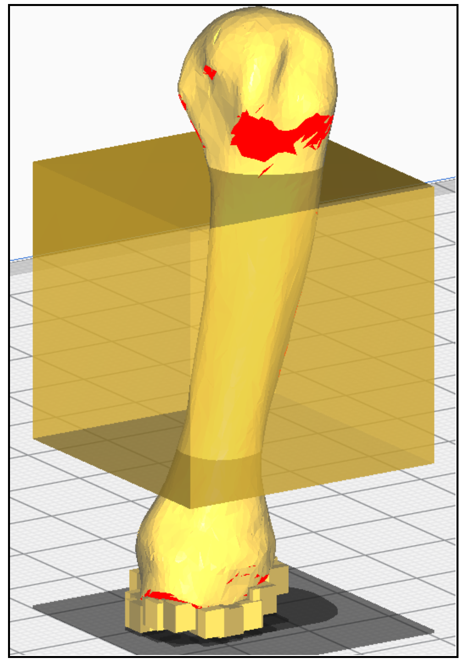

Figure 4: Screenshot of a support blocker element within a 3D model of a 5th metacarpal. View from Cura, a 3D model slicer program

This tested array was delivered to our project contacts to drill, allowing us to determine the wall thickness and infill settings that give the most realistic tactile feedback when drilling through the dense cortical bone into less dense cancellous bone. Our contacts settled on bone B2, which had a wall thickness of 2.4mm and an infill density of 30%. We also had a 5th metacarpal printed on a Stratasys ObJet printer, which prints with a VeroClear™ resin. As mentioned earlier, this bone was solid and had no differing densities. Our contacts liked the similarity to cortical bone density, but could not accept the lack of realism with the absence of cancellous bone densities. Furthermore, the resin bone cost 15$, almost the same price as 100 5th metacarpals printed with PLA. While they were very happy with the tactile feedback the PLA B2 bone delivered, especially when compared to established test methods, such as a Sawbones® model, they noted that the medullary canal of the bone should have a much lower density than the cortices to mimic the substantially lower density marrow of the bone.

In order to print the bone with two separate infill settings, we used a technique within our slicer program, Cura, called support blocking. This feature allowed us to drop a cube into our print space, causing any overlap between the cube and model to create an isolated subset of print settings (**Figure 4**). We printed a few bones with this process, allowing us to keep our wall thickness setting from earlier as well as our infill setting in the cortices, while the support blocker allows up to drop the infill density within the medullary canal. The next revision of the bones also includes printing a fractured 5th metacarpal. This process was similar to that of the array of bones earlier where only one-half of the bone was printed, however this time the fractures were much more angled.

Our group also created an assembly of the bones of the 5th ray (5th metacarpal and 5th phalanges) exposed within a 2mm offset to mimic skin coverage (**Figure 5**). A second model of just the offset 'skin' was also printed. Using the resin, a releasing agent, and our 'skin' model, we were able to create a two-part silicone rubber mold that our embedded bone model successfully slotted into. Using these models, we are able to cast into the mold and over the exposed bones to create a relief of the other half of our finger and recesses for our printed bones to be laid into place (**Figure 6**). The quality of our molds and the fit of our prints into them confirmed the validity of our plans to cast a larger scale hand next semester (**Figure 7**). One thing we need to keep in mind going forward is the curing time of our silicon rubber when planning our project timeline, as the resin we used for this section took nearly 16 hours to fully cure.

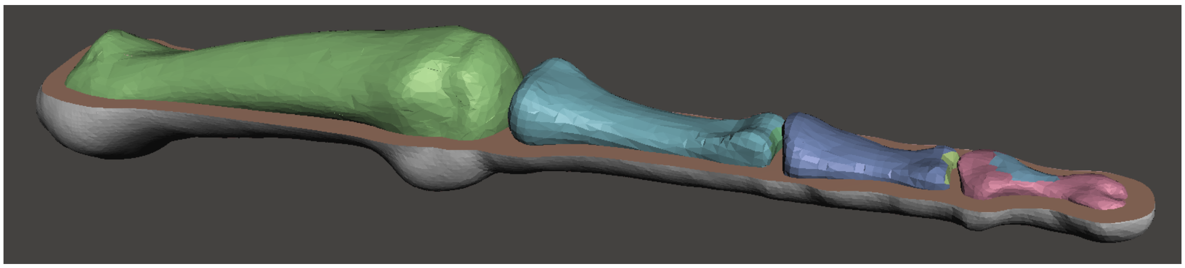

Figure 5: 3D model in Meshmixer of the bones of the 5th Ray embedded in a 2mm offset

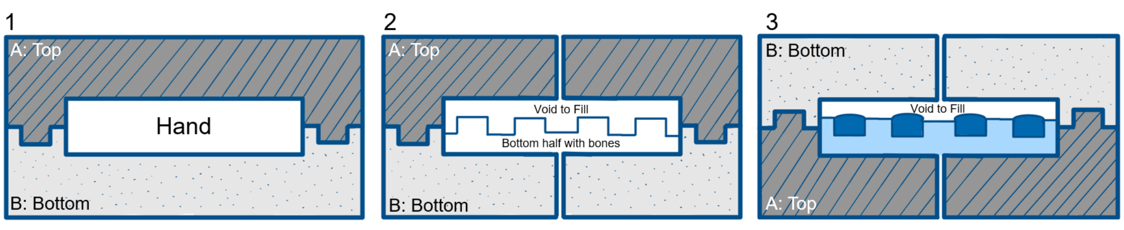

Figure 6: Schematic of casting process using 3D printed models

Figure 7: Results from preliminary tests fabricating a cast hand using a 5th digit printed based on Fig. 5

6 Management Plan

During the fall semester, we purchased Let's Resin® Silicone, Sealer, and Release, and a resin-printed bone. Manufacturers and links for all the current and planned purchases are visible in the Appendix. The resin bone was to provide our sponsors at the medical school with another material besides PLA to drill into and provide feedback on. While the tactile feeling of drilling into resin was better than PLA, the lack of different infill densities throughout the bone was a major drawback. Creating a resin bone with the desired distinct walls and variable infill density is more challenging with SLA printing than FDM. Additionally, the resin bone cost $15.37 to print at the Digital Manufacturing Lab. Since a major goal of this project is to create a low-cost model, with realistic bones, FDM printing with PLA was determined to be superior to SLA printing.

The Let's Resin® Silicone and Sealer and Release cost $24.29 and $18.88 respectively. These materials were purchased to do small-scale tests of casting the 3D printed bones in silicone. Let's Resin® Silicone is a cheaper alternative to Dragon Skin™, but will work the same way in our casting process. Sealer and Release allows a layer of silicone to be cast directly on top of cured silicone while keeping these two layers separate from each other. This is important for the casting process that was designed for the whole hand. The Sealer and Release will also work with Dragon Skin™. Using these materials, small-scale tests were performed to become more experienced casting silicone and troubleshoot any issues with the casting process.

Going forward, we are planning to purchase Dragon Skin™ and Slacker™ once the small-scale tests are finished and any encountered issues are addressed. Dragon Skin™ and Slacker™ are both Smooth-On products with the smallest available units costing $32.21 and $20.79 respectively. Using both of these materials would provide the most accurate replica of soft tissue in our surgical model. We are also planning to buy silver PLA for $21.99 since the filament we are currently using is starting to run out. Various funding avenues are being explored to supplement the $100 BME departmental budget provided to us in order to bring the project to completion. Our contacts within the JSMBS are looking to provide funding via internal research grants while our group is looking to several funding sources available to undergraduates in the University at Buffalo including the WISE fund, Lester Gerhart Experiential Learning fund, ELN fund, and CURCA Experiential learning fund.

All four group members have worked on this project an average of 5 hours a week, for 15 weeks. At $27 per hour, each member earned $2025 for a total team salary cost of $8100. Additionally, both of our contacts at the Jacobs School of Medicine and Biological Sciences should be paid $54 per hour for the 5 hours spent drilling the 3D printed bones. Altogether, $8640 should be paid to individuals involved in this project.

7 Conclusions

Additive 3D manufacturing methods have emerged as multifunctional solutions to a myriad of medical needs. The applications of 3D printing technologies within medicine are wide-reaching, spanning from device development to anatomical modeling. The ease of use, affordability, and speed of additive manufacturing are highly valuable attributes sought to be applied herein, for the use in developing alternative training models for orthopedic bone pinning. Building off an existing framework and knowledge of 3D printed training models, our model looks to provide an affordable alternative to conventional training methods. The mimicking of anatomical bone structures and flesh of the hand is of particular interest to provide haptic feedback analogous to drilling a live patient. A significant amount of progress has been made in identifying proper materials and methods for the printing of anatomically correct bones. This progress has been confirmed based on feedback from sponsors on their experiences drilling on preliminary batch samples of printed bones. The project is now moving forward to the casting and connection testing stages, with a framework for the upcoming semester set in place. The advancement of this project shows promise not only for pedagogical training but also for use in preoperative planning and patient education which are to be explored in the future.

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Appendix I

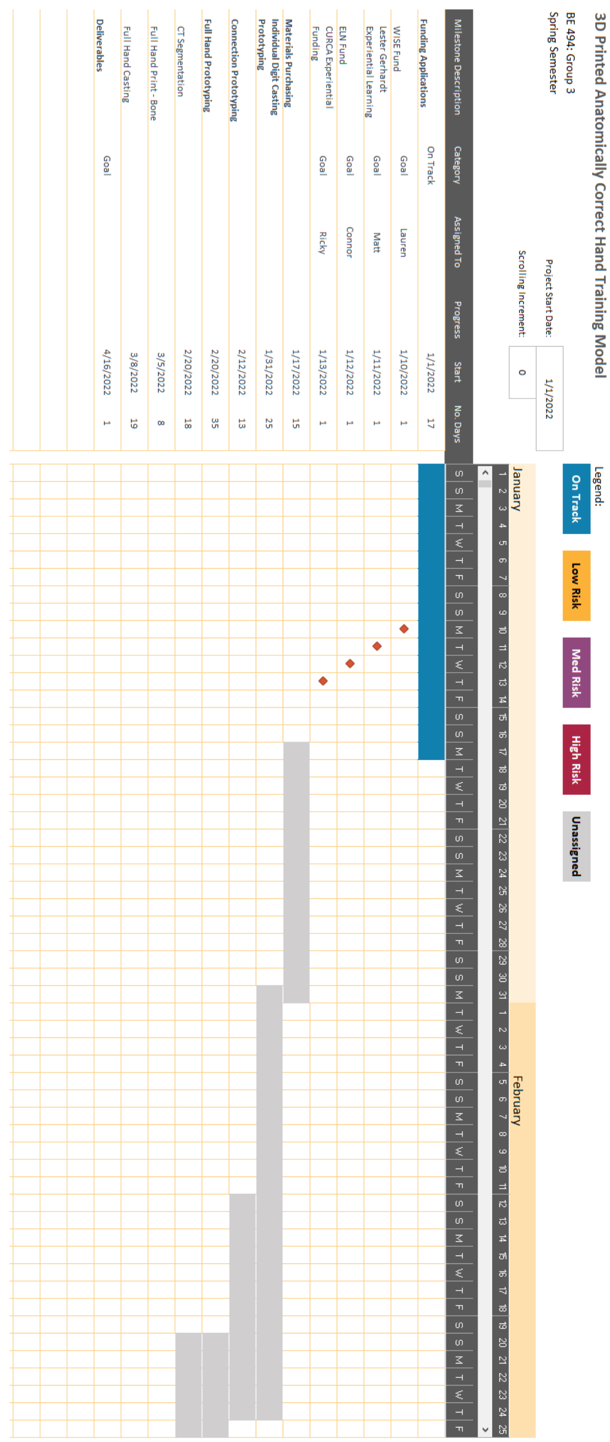
Purchased Materials

Material	Cost	Cost + Fees	Unit Price	Links	Item Type
1x VeroClear Metacarpal	$15.37	$15.37		Link	
LET'S RESIN Silicone Mold Making	$24.29	$46.95	1.15 / oz	Link	Silicone Molding
2350 SEALER AND RELEASE	$18.88			Link	Casting Sealer and Releaser

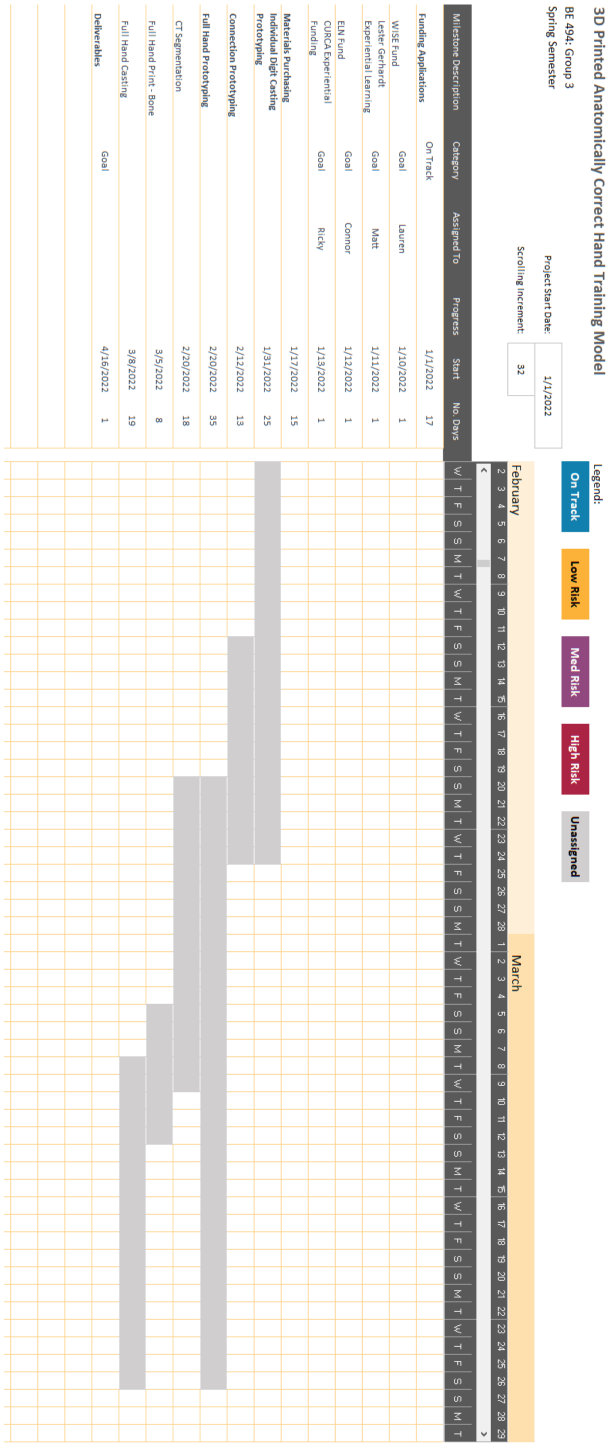
Planned Purchases

Material	Cost	Unit Price	Links	Item Type
HATCHBOX Silver PLA - 1kg	$21.99	21.99 / kg	Link	3D Printing Material
Smooth-On Dragon Skin 10	$32.21	16.105 / lb	Link	Silicone Molding
Smooth-On Slacker	$20.79	20.79 / lb	Link	Silicone Tactile Modifier

Appendix II



3D Printed Anatomically Correct Hand Training Model
BE 494: Group 3
Spring Semester
Project Start Date: 1/1/2022
Scrolling Increment: 0
Legend:
On Track
Low Risk
Med Risk
High Risk
Unassigned
Milestone Description
Category
Assigned To
Progress
Start
No. Days
January
February
Funding Applications
On Track
1/1/2022
17
WISE Fund
Goal
Lauren
1/10/2022
1
Lester Gerhardt Experiential Learning
Goal
Matt
1/11/2022
1
ELN Fund
Goal
Connor
1/12/2022
1
CURCA Experiential Funding
Goal
Ricky
1/13/2022
1
Materials Purchasing
1/17/2022
15
Individual Digit Casting Prototyping
1/31/2022
25
Connection Prototyping
2/12/2022
13
Full Hand Prototyping
2/20/2022
35
CT Segmentation
2/20/2022
18
Full Hand Print - Bone
3/5/2022
8
Full Hand Casting
3/8/2022
19
Deliverables
Goal
4/16/2022
1



3D Printed Anatomically Correct Hand Training Model
BE 494: Group 3
Spring Semester
Project Start Date: 1/1/2022
Scrolling Increment: 32
Legend:
On Track
Low Risk
Med Risk
High Risk
Unassigned
Milestone Description
Category
Assigned To
Progress
Start
No. Days
February
March
Funding Applications
On Track
1/1/2022
17
WISE Fund
Goal
Lauren
1/10/2022
1
Lester Gerhardt Experiential Learning
Goal
Matt
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ELN Fund
Goal
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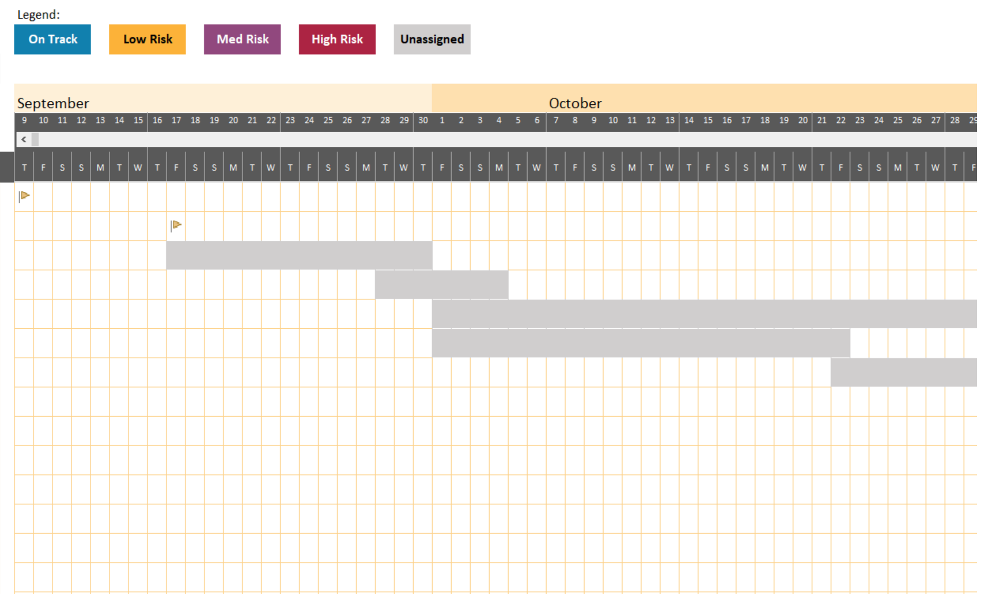
Materials Purchasing
1/17/2022
15
Individual Digit Casting Prototyping
1/31/2022
25
Connection Prototyping
2/12/2022
13
Full Hand Prototyping
2/20/2022
35
CT Segmentation
2/20/2022
18
Full Hand Print - Bone
3/5/2022
8
Full Hand Casting
3/8/2022
19
Deliverables
Goal
4/16/2022
1

3D Printed Anatomically Correct Hand Training Model

BE 493: Group 3
Fall Semester

Project Start Date: 9/9/2021
Scrolling Increment: 0

Milestone Description	Category	Assigned To	Progress	Start	No. Days
Project Topic Decision	Milestone			9/9/2021	1
Zoom Meeting	Milestone			9/17/2021	1
Disease State/Literature Review				9/17/2021	14
Intial Brainstorming				9/28/2021	7
Initial Bone Prototyping				10/1/2021	32
Material Selection & Concept Generation				10/1/2021	22
Print Matrix				10/22/2021	11
Midterm 2 - Presentation	Milestone			11/2/2021	1
Meeting with Dr. Boyko & Julia at JSMBS	Milestone			11/4/2021	1
Prototype Adjustments Based of Feedback				11/5/2021	27
Resin Bone				11/5/2021	9
Block Print/Fractured Print				11/14/2021	9
Preliminary Casting Tests				11/27/2021	14
Advisory Board Meeting	Milestone			12/2/2021	1



3D Printed Anatomically Correct Hand Training Model

BE 493: Group 3
Fall Semester

Project Start Date: 9/9/2021
Scrolling Increment: 47

Milestone Description	Category	Assigned To	Progress	Start	No. Days
Project Topic Decision	Milestone			9/9/2021	1
Zoom Meeting	Milestone			9/17/2021	1
Disease State/Literature Review				9/17/2021	14
Intial Brainstorming				9/28/2021	7
Initial Bone Prototyping				10/1/2021	32
Material Selection & Concept Generation				10/1/2021	22
Print Matrix				10/22/2021	11
Midterm 2 - Presentation	Milestone			11/2/2021	1
Meeting with Dr. Boyko & Julia at JSMBS	Milestone			11/4/2021	1
Prototype Adjustments Based of Feedback				11/5/2021	27
Resin Bone				11/5/2021	9
Block Print/Fractured Print				11/14/2021	9
Preliminary Casting Tests				11/27/2021	14
Advisory Board Meeting	Milestone			12/2/2021	1