Development and Validation of a Modular, Realistic IV Placement Training Model (PractIV)

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Abstract

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This thesis presents the development of *PractIV*, a modular peripheral intravenous (PIV) training simulator designed to improve realism, adaptability, and integration of IV placement training for healthcare professionals. The research project is a collaboration with the University of Washington (UW) Mechanical Engineering 'Engineering in Health' (EIH) Program, and the Center for Research in Education and Simulation Technologies (CREST) at UW. The goal of this work is to develop a modular IV arm trainer specifically designed to comply with the Modular Healthcare Simulation and Education System (*MoHSES*™) physical connection standards, enabling seamless integration with existing manikins such as the Advanced Joint Airway Management System (AJAMS), Both previously developed by CREST.

PractIV addresses key limitations in existing IV training tools, which often lack anatomical realism and fail to prepare learners for challenging patient scenarios. By combining insights from clinical practice, mechanical design, and additive manufacturing, this work contributes to the fields of medical simulator development and IV training.

Table of Contents

1. Introduction 1
   a. Background and Motivation 1
   b. Problem Statement 3
   c. Research Objectives 5
   d. Scope of Work 6
   e. Thesis Structure Overview 8
2. Literature Review 8
   a. Clinical Training Needs for IV Placement 8
   b. Existing IV Simulation Technologies and Limitations 10
3. Design and Development 15
   a. Design Requirements and Specifications 15
   b. Mechanical Design 21
   c. Material Selection and Fabrication 39
   d. Prototype Iterations and Improvements 40
4. Validation Methods 44
   a. Experimental Setup 44
   b. Usability Study Design 47
5. Results 50
   a. Final Product 50
   b. Usability Study Findings & Feedback 55
   Participants 55
6. Discussion 68
7. Conclusions 73
   a. Summary of Contributions 73
   b. Clinical and Educational Implications 74
8. References 76
9. Appendices 79
   I. IRB 79
   II. QQ Plots 81
   III. Raw Data from Usability Study 83

1. Introduction

a. Background and Motivation

Peripheral intravenous (IV) cannulation is the "insertion of an indwelling single-lumen plastic conduit across the skin into a peripheral vein… They allow fluids, medications and other therapies such as blood products to be introduced directly into the cardiovascular system, bypassing other barriers to absorption and reaching most target organs very quickly"[1]. As the most common invasive medical procedure in healthcare[2], over a billion peripheral intravenous catheters (PIVCs) are inserted each year in hospitalized patients worldwide[3] it is estimated that 30-80% of hospitalized patients require an IV during their stay [4]. Across all hospital settings, 35-40% of first-attempt IV insertions fail, resulting in repeated painful insertion attempts and significant treatment delays [5]. These failures place a burden on clinicians and nursing staff, reducing overall efficiency in high-stakes environments such as emergency rooms and intensive care units.

One of the most common methods for teaching IV placement relies on IV arm trainers—training devices that simulate a human arm with embedded veins. These models allow students and clinicians to practice venipuncture, catheter insertion, and related procedures in a safe, risk-free environment before working with patients. They provide a platform for skill acquisition and performance assessment without exposing patients to discomfort or complications. However, through our market analysis and interviews with subject matter experts, we identified several limitations in the current generation of IV arm trainers:

- Oversimplified vein identification by making insertion sites visually obvious rather than challenging trainees to palpate and assess veins.

- Lack of accurate fidelity of skin and veins, leading to negative training transfer for this common skill.
- Typically depict only lean, light-skinned male arms, overlooking both the diversity of patient demographics (e.g., female patients, varying body types, skin tones) and clinical scenarios involving critically ill patients.
- Lack modularity, forcing institutions to purchase multiple arms to train for different patient conditions.

Our findings suggest that current trainers may not fully prepare learners for the variability and complexity of IV placement in clinical practice. First-attempt success is strongly influenced by knowledge, hands-on practice, and confidence in peripheral intravenous catheter (PIVC) placement, while procedures performed by experienced nurses are associated with fewer patient complications [6]. Evidence also indicates that high-fidelity simulation enhances knowledge acquisition, procedural performance, and learner confidence among nursing students [7]. In response, our design emphasizes realistic, high-fidelity IV training with the ability to integrate into a full-body simulation system, providing trainees with exposure to a broad range of clinically relevant scenarios. By delivering an advanced, adaptable IV trainer, we aim to improve clinician proficiency, reduce patient discomfort, and increase hospital efficiency through more effective training.

This project originated during a visit to the Center for Research and Education in Simulation Technologies (CREST) at the University of Washington, with the Mechanical Engineering 'Engineering Innovation in Health' program (EIH). I expressed interest in contributing to a research effort that combined mechanical engineering with medical simulation, and CREST proposed the development of a new IV training arm that complies with the Modular Healthcare

Simulation and Education System (MoHSES™) physical connection standards, enabling seamless integration with existing manikins such as the Advanced Joint Airway Management System (AJAMS). Both projects previously developed by CREST were created to support clinical education through customizable, anatomically accurate modules - allowing educators and students to simulate diverse clinical scenarios by swapping out components such as limbs or organs to enhance realism and instructional flexibility. [8]

The research proposal aligned with the clinical training gaps previously identified, supported CREST's ongoing mission to advance medical simulation through innovative engineering solutions, and resonated with my personal interest in applying mechanical design to address real-world clinical challenges. In particular, the project offered an opportunity to integrate computer-aided design (CAD) tools such as SolidWorks (Dassault Systèmes, Waltham, Massachusetts) and nTop (nTopology Inc., New York City, New York) with additive manufacturing techniques to create compliant lattice structures that mimic the mechanical behavior of soft tissue. This approach enabled us to enhance the fidelity of the simulator, providing more realistic feedback during patient evaluation and IV insertion, contributing to the research and development of high-fidelity, patient-specific simulation tools done at CREST.

b. Problem Statement

Although IV insertion is one of the most frequently performed procedures in healthcare, many clinicians—including students, early-career providers, and even experienced practitioners seeking to refresh their skills—lack access to training tools that accurately reflect the range of clinical situations they may encounter.

Simulation-based training has been shown to be effective at improving IV insertion performance and confidence—one randomized trial demonstrated significantly better skill scores and self-assurance in trainees who trained using simulators[9]. However, current IV simulators remain limited: they often oversimplify anatomy, lack modularity, and fail to replicate complex or less commonly encountered scenarios. Consequently, trainees may enter clinical practice underprepared for real-world variability, contributing to higher rates of failed IV attempts, increased patient discomfort, and clinician anxiety. Reported first-attempt success rates for staff nurses range from 44% to 76.9%, while specialized and more experienced IV nurses achieve markedly higher rates between 91% and 98% [10].

To address this clinical training gap, the project followed a structured, user-centered design framework consisting of five modes—*Empathize, Define, Ideate, Prototype, and Test*—as adapted from the Hasso Plattner Institute of Design at Stanford [11] and taught by the Engineering Innovation in Health (EIH) program at UW. In the *Empathize* mode, we engaged directly with healthcare professionals through interviews, observation of IV training sessions, and tours of nursing simulation centers, following recommended practices to observe users in context, engage in open-ended conversations, and capture both explicit and latent needs[11]. Commonly reported challenges included limited access to advanced training tools, insufficient anatomical variability in simulators, and a lack of tactile realism for practicing vein palpation and needle insertion. During the *Define* mode, we synthesized these findings into a focused, actionable problem statement. With guidance from faculty mentors and clinical advisors, we developed the following validated needs statement:

"A way to address the gap in advanced IV insertion training for healthcare students so that they gain hands-on experience, build confidence, and improve proficiency in performing complex IV placements safely and effectively."

This statement became the foundation for all subsequent design and prototyping decisions, ensuring alignment with both clinical relevance and user priorities.

c. Research Objectives

The objectives of this research are to develop a clinically relevant IV training simulator that addresses current gaps in realism and modularity, and to explore novel engineering methods for medical simulator development. Specifically, this project aims to:

1. **Develop a modular and anatomically realistic IV arm simulator**
    - Create interchangeable components that simulate anatomical variation and insertion challenges.
    - Ensure external geometry, venous patterns, and tissue compliance meet predefined anatomical accuracy criteria.
2. **Validate anatomical accuracy through expert feedback and clinical references**
    - Compare anatomical features – such as vein location relative to osteologic landmarks, soft tissue feel, and needle insertion feedback - to real world scenarios.
    - Collect and analyze qualitative and quantitative feedback from clinicians and simulation experts.
3. **Compare usability to existing commercial IV training models**
    - Determine if the new model achieves significantly higher ratings for realism, usability, and training value compared to market-leading trainers.

- Identify strengths and limitations through structured user evaluations.

4. **Investigate additive manufacturing techniques for medical simulation**
    - Evaluate the use of surface modeling (SolidWorks) and implicit modeling (nTop) to generate soft-tissue-mimicking lattice structures.
    - Assess the feasibility of Fused Filament Fabrication (FFF) for producing cost-effective medical simulation devices.

d. Scope of Work

Winter 2025 – Needs Finding and Conceptual Design

During Winter Quarter, the collaborative project was initiated between the University of Washington's Department of Mechanical Engineering's Engineering Innovation in Health (EIH) program and the Center for Research and Education in Simulation Technologies (CREST). The project team consisted of myself and Courtney Cho, B.S. in Human Centered Design & Engineering.

Guided by advisors with expertise in medical device innovation, we engaged directly with key stakeholders, including clinicians, nurses, and trainees through interviews and observational studies. These activities revealed limitations in existing IV training models, particularly around realism and variability. To better understand the clinical context, we conducted a detailed cognitive task analysis (CTA) of the IV insertion procedure, mapping out both the physical actions and key decision-making steps involved.

Drawing from these early insights, we developed a set of initial design concepts and entered the Hollomon Health Innovation Challenge (HIC) just ten weeks after beginning the project. As one of 22 finalist teams out of 70 applicants, we presented the problem, our proposed

solution, and a comprehensive market analysis. The team was awarded $1,250 in prototyping funds to develop a prototype for the competition.

Spring 2025 – Initial Development and Testing

During Spring 2025, the project progressed from concept development to physical prototyping. A series of tests were conducted to evaluate design concepts, test candidate silicone materials, refine our casting techniques, and explore various 3D-printed lattice geometries to replicate the mechanical properties of soft tissue. Insights from these early experiments informed the methods of fabrication for the first complete prototype of the modular IV trainer. This initial build allowed for hands-on evaluation of form, function, and material performance. The product requirements were further refined to incorporate user feedback and adapt to technical constraints. The prototype was presented at the Engineering Innovation in Health (EIH) Spring Symposium, where feedback from clinicians, educators, and engineering mentors guided the priorities for the next design iteration.

Summer 2025 – Iteration and Validation

During Summer 2025, the project entered an intensive phase of design iteration and user-centered validation. The prototype underwent multiple refinements in response to preliminary feedback, with improvements targeting vein visibility, insertion feel, and design for assembly. A pilot usability study was conducted with a diverse group of target users, including nurses from the UWMC IV team, an anesthesiologist, an EMT, and clinical educators. Their input on insertion realism, anatomical accuracy, and usability informed rapid design modifications. Those suggested were implemented and a final model was made for a formal usability study involving eight IV team nurses, providing structured feedback to validate the model's usability in

comparison to the traditional IV arm trainers. The project was supported through the Engineering Innovation in Health Summer Incubator Program, which provided $5,000 in funding to advance prototype development and conduct formal usability validation.

e. Thesis Structure Overview

This thesis is organized into six chapters, each addressing a key phase in the development and evaluation of the PractIV intravenous (IV) training model.

- **Chapter 1** introduces the motivation for the project, the clinical need for improved IV training tools, and outlines the project objectives.
- **Chapter 2** presents a literature review covering clinical training gaps, limitations of existing IV simulation technologies, and relevant educational frameworks.
- **Chapter 3** details the methods used for user needs identification, design development, material selection, and prototyping.
- **Chapter 4** describes the usability study design, testing protocol, and data collection.
- **Chapter 5** summarizes the results of the usability evaluation and discusses their implications for simulation design and clinical training.
- **Chapter 6** concludes the thesis with a summary of findings, limitations, and recommendations for future work.

2. Literature Review

a. Clinical Training Needs for IV Placement

Successful intravenous (IV) catheter placement is a critical skill in clinical care, yet first-attempt success rates remain suboptimal, particularly among less experienced practitioners.

According to one review, first-attempt success rates for staff nurses range from 44% to 76.9%, whereas more highly trained and experienced IV nurses achieve rates between 91% and 98% [10]. This variability underscores the need for improved and standardized training approaches that effectively bridge the gap between novice and expert practitioners.

A 2021 study published in Nurse Education Today investigated the impact of combining structured simulation with on-the-job training for PIVC placement. The study found that students who participated in simulation-based practice followed by supervised clinical implementation demonstrated significantly greater proficiency and retained their skills more effectively than those who received traditional instruction alone. The integration of simulation into the clinical workflow not only improved technical performance but also enhanced learners' ability to make critical decisions under realistic conditions. [12] This layered training approach reinforces the importance of developing simulators that not only support individual skill acquisition but also translate seamlessly into team-based and real-world clinical environments. These findings further emphasize the need for anatomically and functionally accurate devices that can integrate with broader simulation systems, precisely the approach taken in the development of the PractIV model.

Another 2021 study, published in the International Journal of Caring Sciences evaluated the impact of simulation-based teaching on peripheral intravenous catheter (PIVC) placement skills using full-body patient simulators. The results showed that students in the experimental group—who trained using a high-fidelity full-body simulation—achieved significantly higher skill performance scores (44.47 ± 3.72) than those in the control group, who trained only on a plastic arm model (32.47 ± 5.55, $p < 0.001$). Additionally, the experimental group reported high levels of satisfaction and self-confidence, highlighting the value of immersive and contextually

realistic training environments. [13] These findings support the integration of anatomically accurate, modular training devices into full-body simulations to enhance learner engagement and clinical readiness. The IV arm developed in this project was specifically designed to comply with the *MoHSES*™ physical connection standards, enabling learners to experience IV placement as part of a comprehensive clinical scenario. This compatibility enhances the realism and training value of the device, aligning with evidence that context-rich simulation environments improve procedural confidence and performance.

b. Existing IV Simulation Technologies and Limitations

Traditional IV training arms have become a standard tool in intravenous catheter placement education, replacing earlier practices in which students trained on one another. These simulators offer a low-risk, tactile platform for learners to develop basic needle insertion and catheterization skills. Typically, they consist of synthetic skin layers over molded plastic or silicone substrates, with embedded tubing that simulates peripheral veins. Some models incorporate fluid reservoirs to mimic blood flashback, providing visual confirmation of successful vein access.

While these trainers offer valuable initial exposure in a controlled environment, some fall short in replicating the anatomical variability, procedural complexity, and haptic feedback of real patient encounters. Most commercial IV arms feature only a limited number of access sites and do not accommodate patient diversity—such as differences in size, skin tone, and venous distribution patterns. Additionally, they often fail to simulate common complications like vein rolling, infiltration, or variable tissue resistance. Their standardized designs are constrained by mass manufacturing requirements, further limiting adaptability and realism. As a result, learners

may gain technical familiarity in idealized settings but remain underprepared for the nuanced challenges of clinical practice.

For example, the *Simulator Intravenous ARM III* from KYOTO KAGAKU (Kyoto Kagaku Co., Ltd., Kyoto, Japan) [14] has obvious venipuncture sites within soft rectangular pad on the arm, making it straightforward for users to locate veins. However, according to clinical experts we interviewed, vein identification and selection by palpation and vision, is a critical skill in real IV insertion. Simulators that fail to encourage tactile exploration limit a learner's development of real-world technique and confidence.

Current trainers are also limited in their representation of patient diversity. Most default to a lean, light-skinned adult male arm, which does not reflect the clinical reality of many patients in emergency or critical care settings. While products like the *Simulaids™ Geriatric IV Training Arm*(Simulaids, Inc., Saugerties, NY , USA) [15] attempt to address specific patient conditions, such as aging skin, they lack modularity. Healthcare institutions must invest in separate trainers to simulate different demographics or pathologies, adding cost and logistical complexity.

These limitations are consistent with broader findings in medical simulation literature, where high-fidelity models have been shown to improve skill acquisition, clinical performance, and confidence, but their benefits depend on the learner's level of experience [16], [17], [18]. Novice trainees may risk overconfidence when introduced to overly sophisticated models too early, while advanced learners gain more from complex and realistic scenarios. Because of this, existing IV trainers often fail to align with the needs of diverse learner populations. The shortage

of realistic, inclusive, and adaptable simulation tools underscores the need for improved technologies that balance fidelity, modularity, and educational goals.

c. Patent Search

To situate the PractIV trainer within the broader landscape of IV training technologies, a targeted patent search was conducted to identify key innovations in venipuncture simulation. This search highlights the historical progression from early handcrafted models to modern modular and fluid-driven systems. Patents such as US2704897A (1955)[19], US20130078603A1 (2013)[20], and EP2577645B1 (2017)[21] illustrate recurring design priorities—realism in vein palpation and flashback, modularity to enable reuse, and durability against repeated punctures. Reviewing these patents provides a foundation for evaluating how PractIV builds upon and advances these concepts through additive manufacturing, anatomically accurate design, and integration with high-fidelity simulation systems.

The patent US2704897A[19], “Arm for teaching venipuncture and intravenous therapy”, published in 1955 describes one of the first venipuncture training arm models. The invention aimed to replicate the palpability and form of a human arm using simple, low-cost materials such as a roll of newspaper, plaster bandages, foam rubber, cotton layers, and an outer latex or plastic sleeve to represent skin. Rubber or latex tubing embedded within grooves simulated veins, which could be filled with water from a syringe reservoir. A key feature of the design was allowing the tubing to “roll” slightly within the grooves, mimicking the movement of natural veins under the skin. By adjusting the thickness of cotton layers covering the tubing, trainers could vary vein visibility and palpation difficulty to match the learner’s skill level. This incremental approach

supported progressive training—starting with visible veins for novices and advancing to hidden veins that required tactile identification.

The PractIV trainer builds on these foundational concepts while leveraging modern materials and manufacturing technologies. Unlike the early models that relied on cotton, and plaster, PractIV incorporates modular silicone skin layers, compliant Thermoplastic Polyurethane (TPU) lattice structures to enhance anatomical fidelity and functional realism. The rolling vein concept introduced in US2704897A is carried forward with PractIV, with vein channels wider than the tubing, coated in petroleum jelly designed to replicate the tactile feeling and behavior of a rolling vein. Furthermore, additive manufacturing enables consistent, reproducible fabrication of complex internal geometries such as bones and internal vein channels that were previously unattainable with handcrafted methods.

The patent US20130078603A1[20] “Arm model apparatus for intravenous injection training” describes an IV training arm model designed with a detachable skin pad containing embedded blood vessel–mimicking tubing. The skin pad is placed in a recessed groove on the top of the arm, which is twisted in orientation so that both the cubital fossa and the back of the hand are accessible for practice. A pump-driven fluid circulation system, consisting of a pump unit and a connected liquid reservoir, supplies artificial blood to the tubing. This design enables realistic flashback during cannulation and allows for repeated use through replacement of the skin pad.

The design described in US20130078603A1 emphasizes modularity and reusability by incorporating a detachable skin pad with embedded tubing, supported by a pump-driven fluid circulation system to simulate blood flashback. This approach allows targeted replacement of wear-prone components while providing learners with visual confirmation of successful

cannulation. Similarly, PractIV incorporates a closed-loop, pressurized fluid system to simulate flashback, aligning with the same goal of enhancing realism during IV insertion. However, PractIV expands upon this concept by embedding veins within vein channels in the compliant TPU lattice structure that more accurately represents the anatomical location of the veins, with full venous access from the hand through the forearm, up to above the elbow, allowing for the clinician to decide on where to perform the procedure. In this way, PractIV preserves the foundational ideas of fluid-driven realism and replaceable components, but advances them with greater anatomical accuracy, tactile fidelity, and adaptability for diverse learner needs.

The patent EP2577645B1[21] “Iv training system” describes a self-sealing, replaceable pad system for venipuncture training, designed to improve realism and reduce maintenance compared to traditional latex-tube and PVC models. The pad is injection-molded from thermoplastic elastomers or silicone rubbers with inherent self-sealing properties and incorporates integrated fluid passageways that mimic veins. These passageways can be pressurized with fluid, causing them to become visible beneath the skin-like surface and simulating vein filling under a tourniquet. The pad is shaped for compression fitting into a frame within an artificial arm or manikin, with underside connectors that provide both fluid supply and detachable fastening, enabling quick replacement after repeated punctures. The design allows for multiple training sites (e.g., cubital fossa, dorsum of the hand, pediatric variants) and can incorporate valve and accumulator systems to replicate physiologically accurate vein filling.

Compared to EP2577645B1, which focuses on a modular, self-sealing pad system with embedded fluid passageways that can be inflated to mimic vein distension, the PractIV trainer expands realism and flexibility by incorporating anatomically accurate 3D-printed lattice

structures and modular tissue layers rather than a single molded pad. While EP2577645B1 emphasizes replaceability and durability through injection-molded elastomers and simple connector-based fluid integration, PractIV prioritizes anatomical fidelity by leveraging additive manufacturing, layered silicone casting, and integration with a MoHSES compatible full-body manikin system. Furthermore, unlike the patented design where realism is primarily achieved through fluid pressurization of vein-like bores, PractIV allows for greater anatomical fidelity through full veinous access through the hand, forearm, and just above the elbow, supporting a wider range of clinical training scenarios. In this way, PractIV builds on the durability and maintenance improvements proposed in EP2577645B1 while extending functionality toward high-fidelity, customizable, and system integrated IV training.

PractIV distinguishes itself through its use of a 3D-printed lattice engineered to replicate human tissue compliance and its integration with a MoHSES™-compliant full-body simulation system, positioning it as a next-generation solution for IV placement training. Beyond its technical advancements, PractIV was designed to promote accessibility, foster academic collaboration, and support continued innovation in medical simulation.

3. Design and Development

a. Design Requirements and Specifications

User Needs Evaluation

To inform the design of the IV training arm, we conducted a comprehensive user needs evaluation in collaboration with clinicians, nurses, and trainees. This included interviews, observational studies, and a cognitive task analysis of the IV insertion procedure. Key themes that emerged were the need for:

- Improved anatomical realism that supports accurate vein identification through visual and tactile cues
- Reliable tactile feedback during palpation and cannulation, replicating the feel of a vein beneath soft tissue and providing appropriate resistance during needle advancement.
- Durable components capable of withstanding repeated needle insertions
- Simulated complications such as rolling veins, fragile tissue, and fluid leakage following improper technique, to allow learners to practice troubleshooting realistic clinical challenges in a safe setting.

Cognitive Task Analysis

A cognitive task analysis (CTA) was conducted in collaboration with clinical experts to gain a deeper understanding of the peripheral intravenous (PIV) insertion procedure and identify the cognitive and technical demands placed on learners during each stage. The purpose of this analysis was to translate complex clinical decision-making and motor skills into actionable design inputs for simulation. This process helped ensure that the IV trainer addressed not just mechanical functionality, but also the perceptual and cognitive components critical to successful IV placement.

To begin, we reviewed clinical best practices and procedural guidelines from *Introduction to intravenous therapy for health professionals* [22] to establish a baseline procedural flow. We then refined and validated this step-by-step breakdown through interviews with experienced practitioners. These discussions helped clarify the reasoning behind each action, common challenges faced by trainees, and the visual, tactile, and verbal cues practitioners rely on in real clinical settings.

The CTA focused on the most relevant phases of the procedure from a strictly clinical perspective, including vein evaluation, vein preparation, needle placement, catheter connection, and flow verification. For each step, we documented detailed information using a structured CTA framework that included:

- Scene Description (e.g., visible anatomy, hidden structures, patient factors)
- Key Decisions and Cues Required (e.g., how practitioners assess vein suitability)
- Risks and Complications (e.g., missing the vein, vein rolling, infiltration)
- Metrics (e.g., angle of insertion, number of attempts, time to successful cannulation)
- Tips, Tricks, and Common Errors (e.g., how experienced clinicians stabilize the vein or adjust for patient discomfort)
- Skills Required (cognitive, technical, and team-based)

Through this analysis, we identified several high-priority simulation needs, such as realistic skin and vein compliance for palpation, visible and variable vein anatomy for visual evaluation, and tactile feedback during needle insertion. These insights were directly translated into specific product requirements that guided the material selection, lattice design, and modular configuration of the PractIV training model.

Product Requirements

The following product requirements were developed in collaboration with our mentors in the Engineering Innovation in Health (EIH) program, the staff at CREST, and our clinical references. Each requirement addresses a core need identified during the user research phase.

1. **Compliance with MoHSES™ for Physical Connection:**

- The training arm must comply with the Modular Healthcare Simulation and Education System (*MoHSES*™) physical connection standards.

2. **Anatomical Accuracy**
    - The arm must replicate human anatomy with appropriate proportions for skin, veins, subcutaneous tissue, and osteologic landmarks.
    - The trainer must accurately reflect anthropometric data from the Modular Healthcare Simulation and Education System (*MoHSES*™) female dataset to ensure both visual realism and structural compatibility when integrated with the full-body simulation system.
3. **Realistic Tactile Feedback**
    - Skin and veins must provide lifelike compliance and resistance during palpation and needle insertion.
    - Veins must shift slightly under pressure ("rolling veins").
    - Needle insertion force must be validated by clinician feedback.
4. **Pressurized blood flow system**
    - The system must maintain fluid pressure of 5-15 mmHg.
    - Blood flashback must occur within 3 seconds of successful puncture.
    - Incorrect insertion must result in fluid leakage in the surrounding tissue, replicating a failed puncture.
5. **Compatibility with standard clinical tools**
    - The model must accommodate standard IV catheters (18–22 gauge), butterfly needles, syringes, and IV tubing.
    - The fluid system must allow for a syringe flush.

6. **Simulation of difficult patient conditions**
    - The model must support interchangeable skin and soft tissue modules to allow for the further development of skin tones and vein anatomy.
7. **Simulation Technician Experience**
    - Each module must be interchangeable within 15 minutes to maintain flow during training sessions.
    - The system must be straightforward to disassemble and clean.

Anatomical and Biomechanical Benchmarking:

To establish realistic design targets for the PractIV training model, we drew upon the female anatomical data sets available to download from the MoHSES^{TM} website [8], in combination with review of literature and consultations with clinicians experienced in IV placement. The goal was to identify the key physical parameters that influence successful venipuncture and translate them into actionable engineering requirements for simulation.

A full-body magnetic resonance imaging (MRI) data from a 37-year-old female subject (height: 168 cm, arm length: 55.5 cm, leg length: 66 cm, weight: 147 lb, BMI: 23.0) provided the anthropometric reference for anatomical boundaries. These MRI datasets were previously segmented to create detailed 3D anatomical models using 3D Slicer (Surgical Planning Laboratory, Brigham and Women's Hospital, Boston, MA, USA) and Autodesk Maya (Autodesk Inc., San Rafael, CA, USA) and subsequently converted into SolidWorks files to support computer-aided design workflows [23]. PractIV's geometry was derived directly from these SolidWorks models, ensuring anatomical accuracy and consistency with the broader MoHSES system used in full-body simulation platforms

Vein dimensions in the PractIV trainer were intentionally designed on the smaller end of the physiological range to increase training value and better prepare learners for challenging scenarios. Based on anatomical data and clinical references, the veins were constructed with an outer diameter of 4 mm ± 1mm and an inner diameter of 2 mm, closely aligned with published anatomical measurements. One study reported mean inner diameters of 1.9 ± 1.2 mm for the cephalic vein and 1.8 ± 1.1 mm for the median cubital vein, supporting the realism of this design choice.[24] This sizing reflects real-world vein variability and ensures that the model presents a moderate level of difficulty, helping users build both confidence and proficiency in locating and cannulating smaller, less prominent vessels.

Peak force required to puncture through skin and the vein wall in the forearm of human subjects were found to range from 1.25 ± 0.37N [25]to 3.2 ± 1.2 N[26] depending on needle gauge, tissue depth, and insertion angle. These values were used to guide our material testing protocols. These benchmarks allowed us to assess insertion resistance across a variety of silicone formulations and skin thicknesses. By comparing the mechanical performance of these materials to known clinical force ranges, we were able to select skin analogs that offered realistic puncture feedback, ensuring that learners receive appropriate tactile cues during insertion.

In addition to quantitative targets, we incorporated qualitative benchmarks derived from subject matter expert (SME) feedback. These included assessments of soft tissue compliance, vein mobility (e.g., rolling), and skin tension during vein stabilization—all of which contribute to the tactile realism of IV placement. For instance, the phenomenon of vein rolling—a common challenge in clinical settings—was replicated by introducing slack into the vein path and minimizing friction with surrounding tissue using petroleum jelly as a lubricant. This design feature enabled the simulation of realistic failure scenarios and promoted the teaching of

appropriate handling techniques - such as stabilizing the vein by applying skin tension with the thumb.

Together, these anatomical and biomechanical benchmarks guided material selection and physical modeling strategies, ensuring that the final prototype delivered meaningful tactile feedback and aligned with the real-world training needs of healthcare professionals.

b. Mechanical Design

This section will expand on the engineering behind the PractIV Each component will be discussed, as well as the design paths they took to get there.

i. Core Structure

To replicate the compliance and anatomical characteristics of human soft tissue, a core 3D-printed lattice structure was developed. The structure was fabricated using fused filament fabrication (FFF) with thermoplastic polyurethane (TPU) filament (95A durometer). The core geometries, comprising of skin, vein, and bone models, were derived from the open-source MoHSES™ dataset[8]. SolidWorks 2025 Student Edition was used to develop precise solid models and assemblies based on anatomical reference data. nTop (nTopology Inc.), a computational design platform optimized for advanced latticing and implicit modeling, enabled the generation of tunable internal structures that mimic the mechanical behavior of soft tissue. Meshmixer (Autodesk Inc., San Rafael, CA, USA)a mesh editing tool, was employed for model preparation, including mesh cleanup, smoothing, and integration of organic geometries.

To prepare the internal geometry, Meshmixer software was used to offset the external skin surface by 3 mm to define the shell thickness and to remove the fingers. This created a simplified core structure that allowed for the “sleeving” of a cast silicone outer layer. The

internal lattice and simplified form provided a compliant yet supportive base for the outer silicone, enhancing the realism of vein palpation and needle insertion.

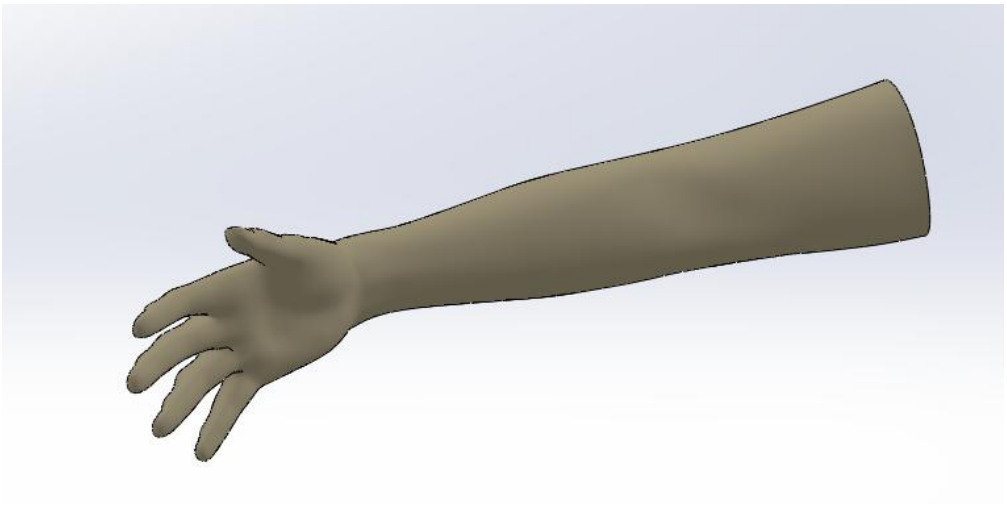

Fig. 1. Outer arm skin surface

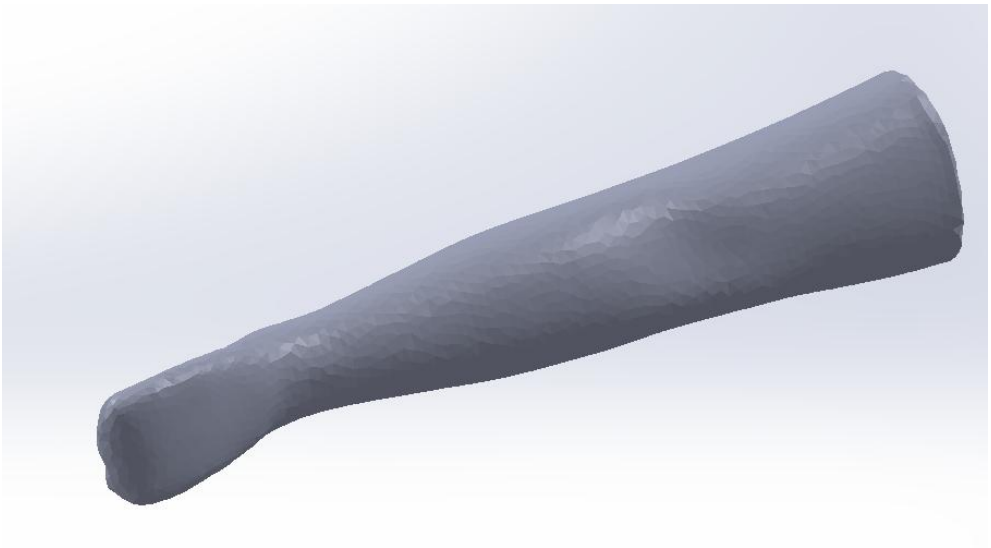

Fig. 2. Sculpted simplfied core structure

The bones from the MoHSES female dataset were modified for assembly and connection to the MoHSES segment connector, while still providing realistic compliance throughout the arm, and articulation in the joints.

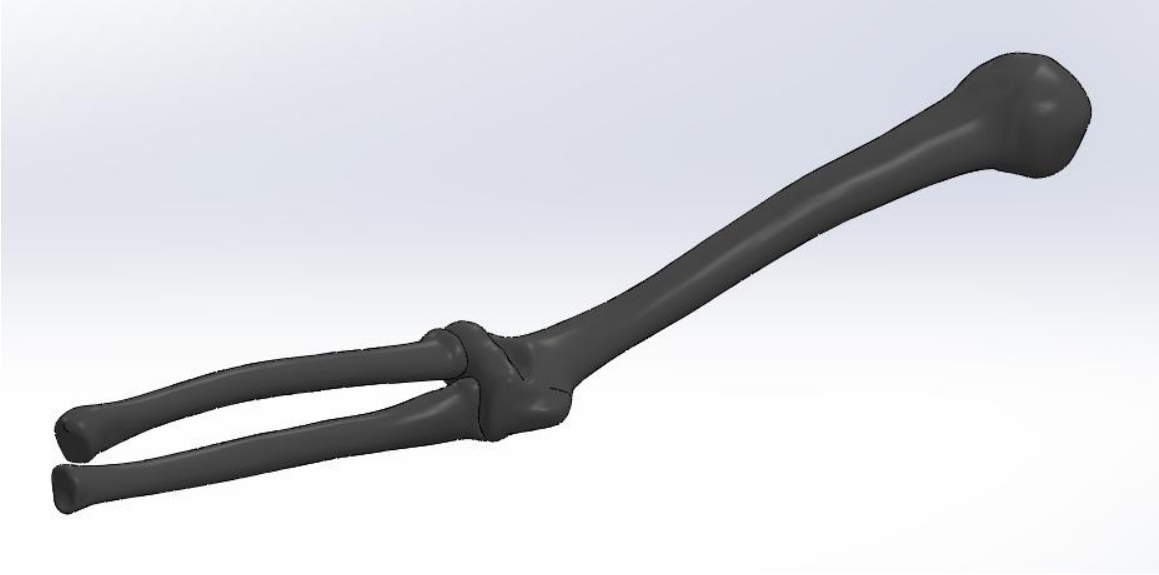

Fig. 3. Humerus, Radius, Ulna from MoHSES female dataset

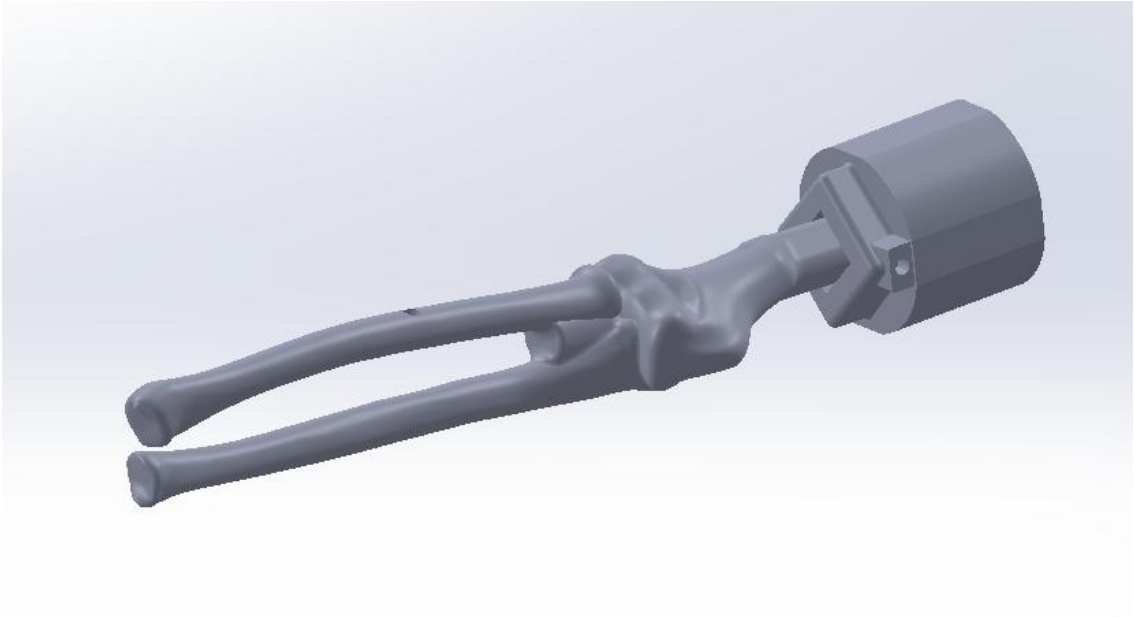

Fig. 4. Modified bone models with segment connector housing

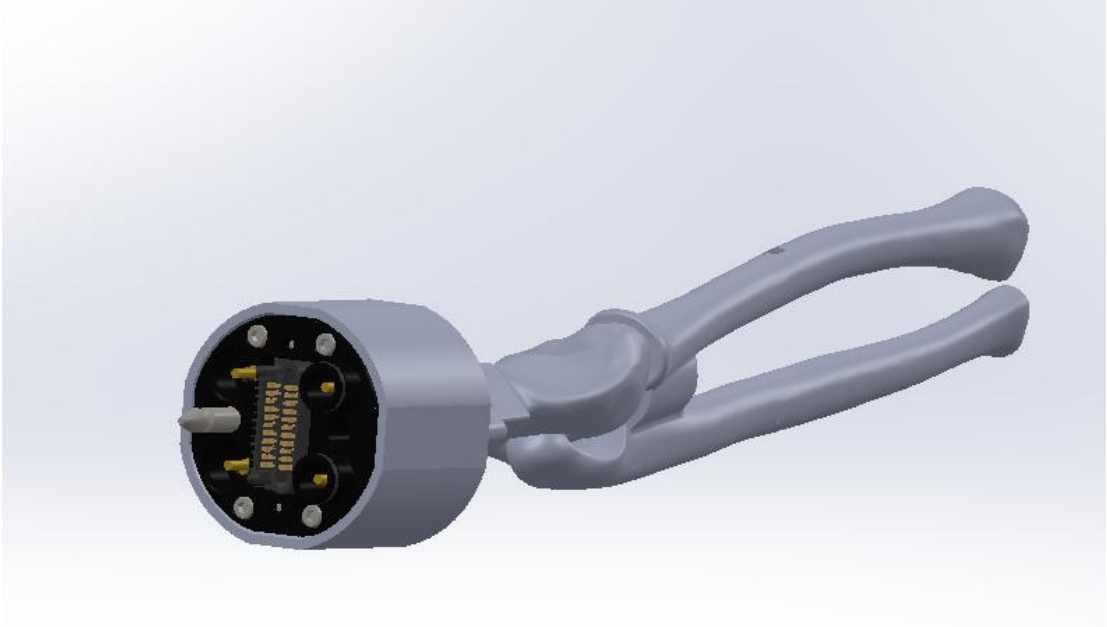

Fig. 5. Modified bone models with segment connector

Fig. 6. Segment Connector [8]

The “Segment Connector” shown above facilities a physical connection into MoHSES compatible modules. This connector was developed during the original MoHSES project as a standardized means of mechanical connection for peripheral limbs.

Vein Channels

The vein channels were created with sweeps in SolidWorks, based on the core structure geometry. These models are shown in figure 7 & 8. The volume was hollowed using the Meshmixer software, so that there was a 1mm wall thickness. A Boolean intersect command was run in nTop between the core structure and the hollowed sweeps, to get the open, C-shaped channels shown in figure 9 below.

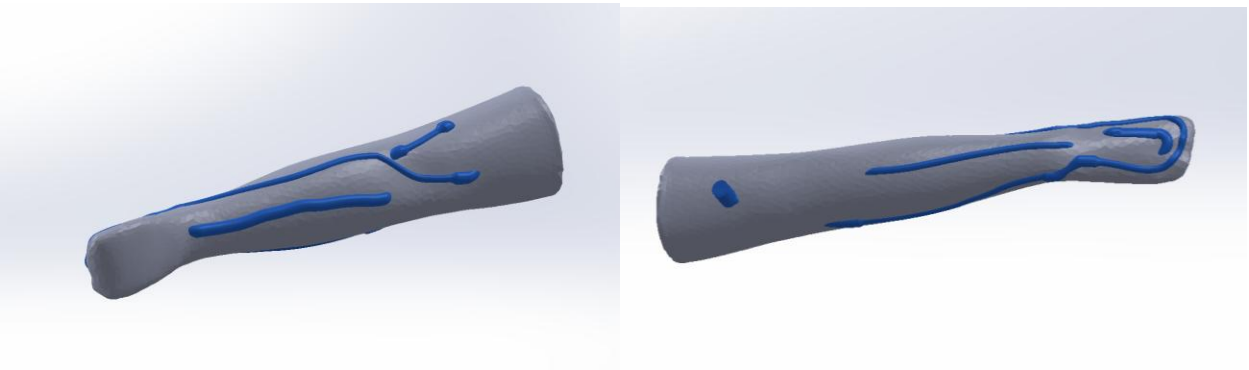

Fig. 7. Vein channels with surface of core: (a) angled view and (b) side view.

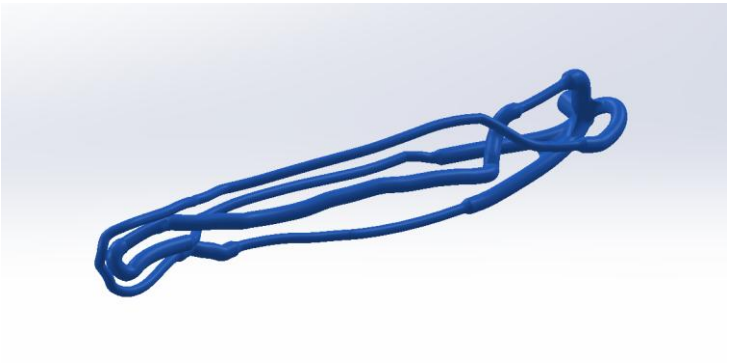

Fig. 8. Vein channels model

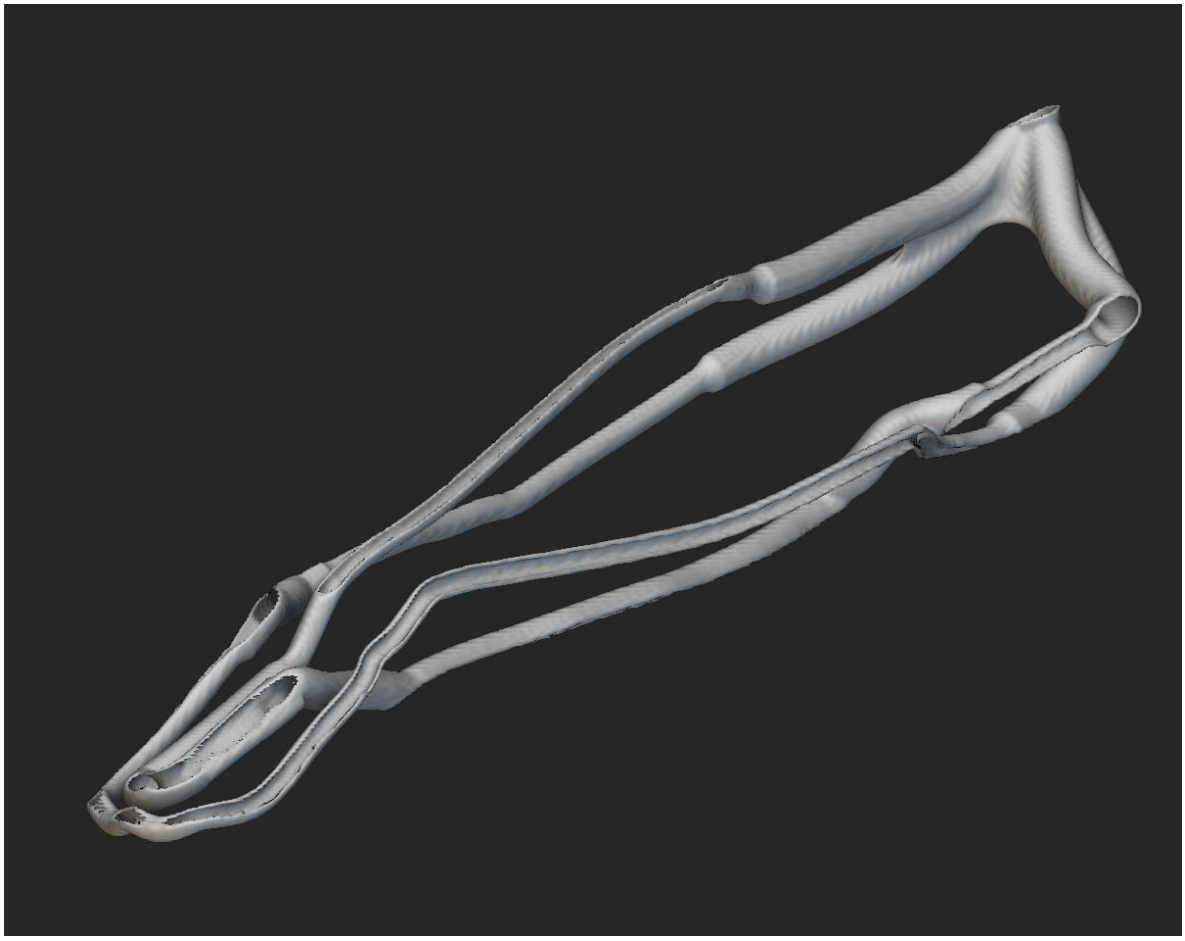

Fig. 9. Boolean Intersect of veins

In this project, nTop was used to design custom internal and surface lattice structures that mimic the compliance and anatomical characteristics of human soft tissue. The lattice geometry was defined by a diamond-shaped unit cell, which establishes the overall pattern of the lattice. A cylindrical cell map, which dictates how the unit cells are distributed over the volume, was applied to the internal volume to provide bulk mechanical support. Lastly, a Voronoi surface lattice was used to fill in the voids left by the open lattice and spread the load to feel more like cohesive tissue. The software's ability to precisely control cell size, orientation, and density allowed for fine-tuning of mechanical behavior and manufacturability, contributing to a more realistic and functional IV trainer.

The internal lattice consisted of a unit cell with the following specifications:

- Unit Cell Type: Diamond
- Orientation: UVW
- Cell Map: Cylindrical
- Cell Radius: 15 mm
- Cell Height: 15 mm
- Arc Count: 15
- Beam Thickness: 1.6 mm

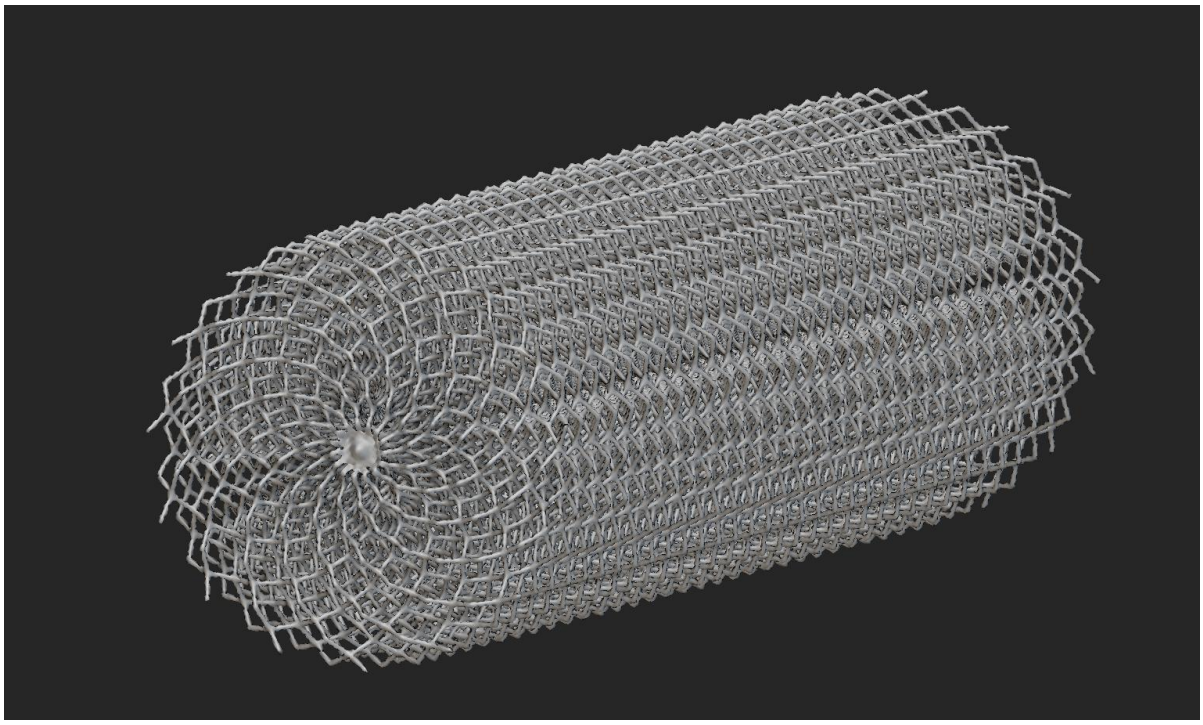

Fig. 10. Cylindrical cell map, with diamond unit cell

The ‘trim lattice’ command in nTop was used to trim the lattice shown in figure 10 with the domains shown below in figure 11. In addition with a Boolean subtract command with the model shown in figure 12, to get the resulting soft tissue lattice in figure 13.

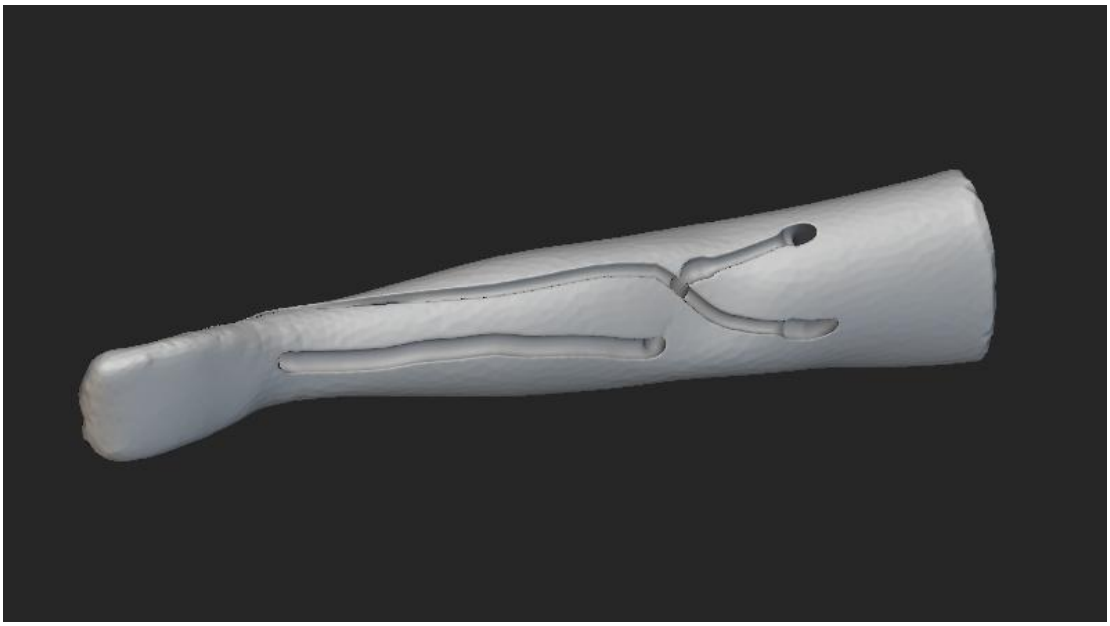

Fig. 11. Domain used for trimming the lattice

The internal bone sections were trimmed from the modified bone bodies, as well as the domain around the elbow joint was trimmed to allow for increased motion of the joint. shown in figure 12.

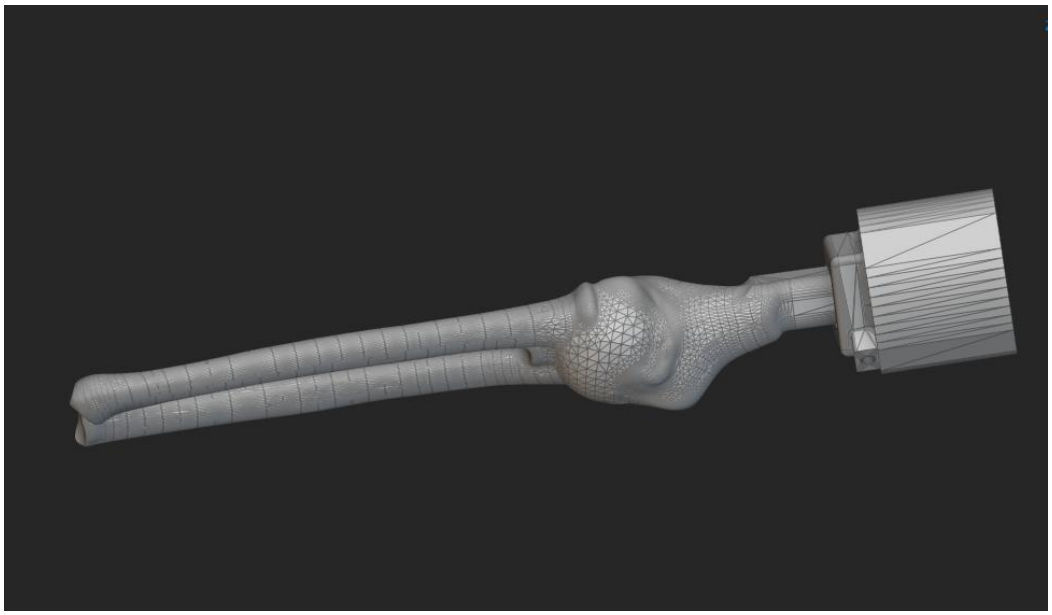

Fig. 12. Elbow Domain

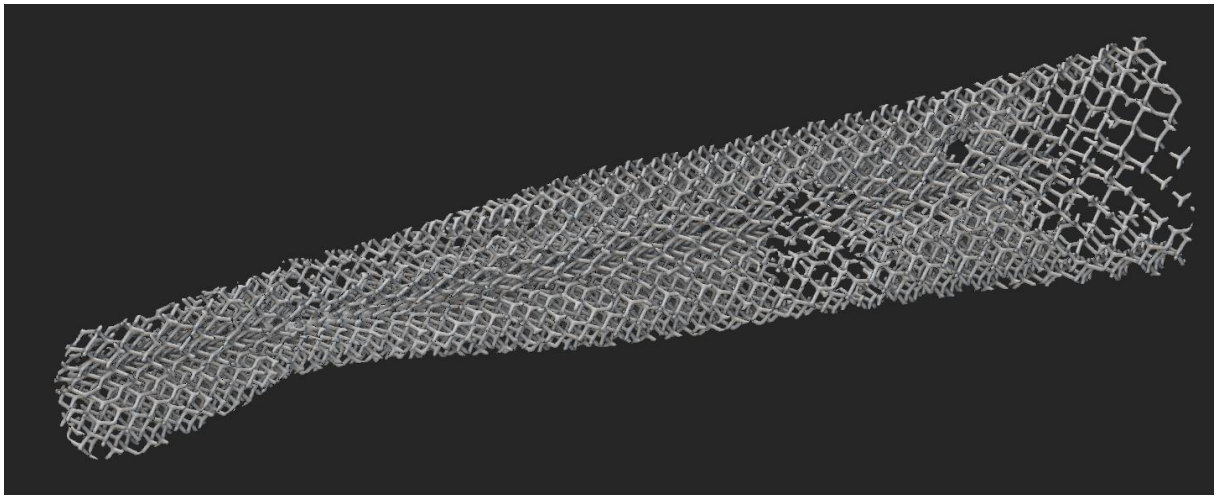

Fig. 13. Internal cell map trimmed

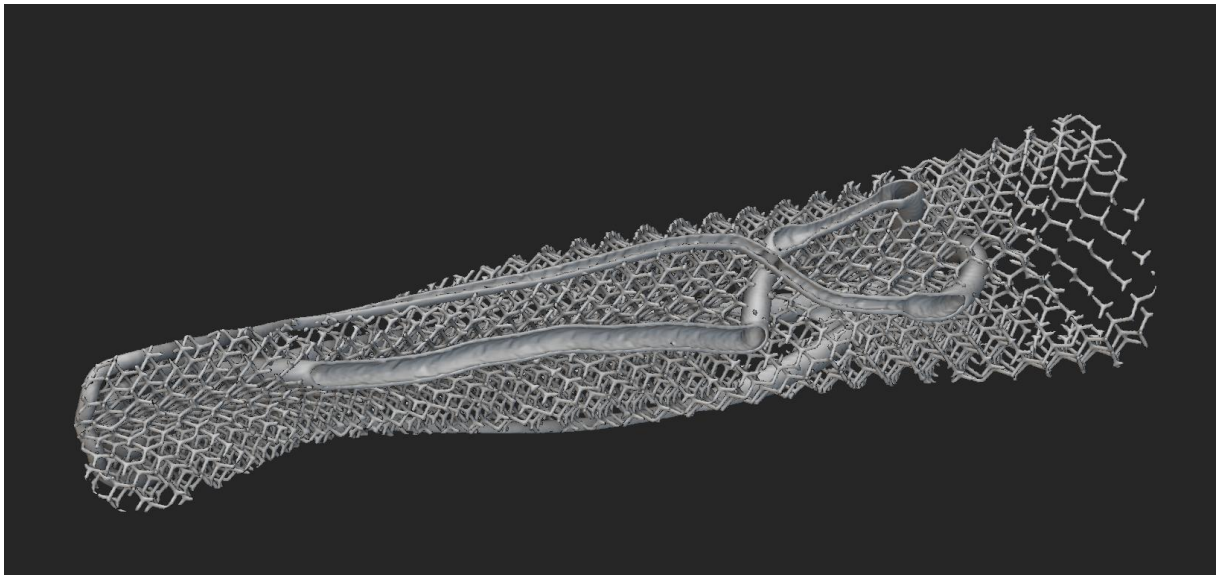

Fig. 14. Soft tissue with integrated vein channels

The Voronoi surface lattice was selected due to the inherent compliance and flexibility, as well as the ability to mitigate the inter-layer tearing observed in earlier prototype iterations. The Voronoi surface parameters were as follows:

- Point Count: 3000
- Relaxation Iterations: 30
- Random Seed: 1
- Surface Thickness: 2 mm

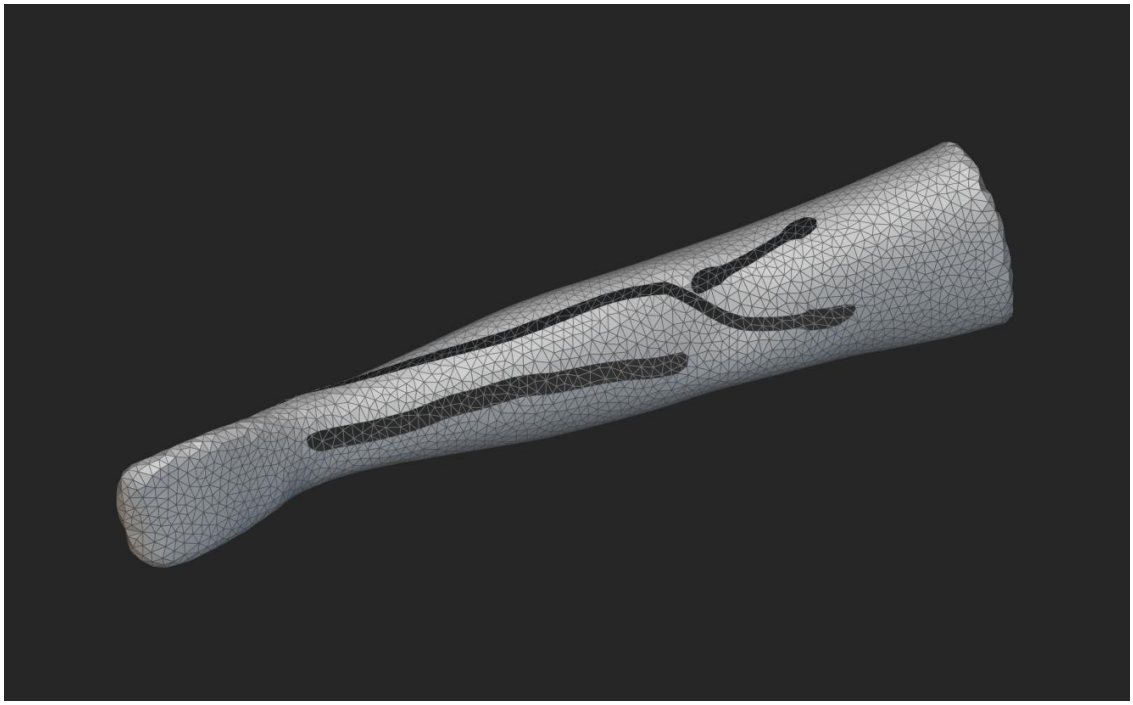

Fig. 15. Surface model for lattice generation

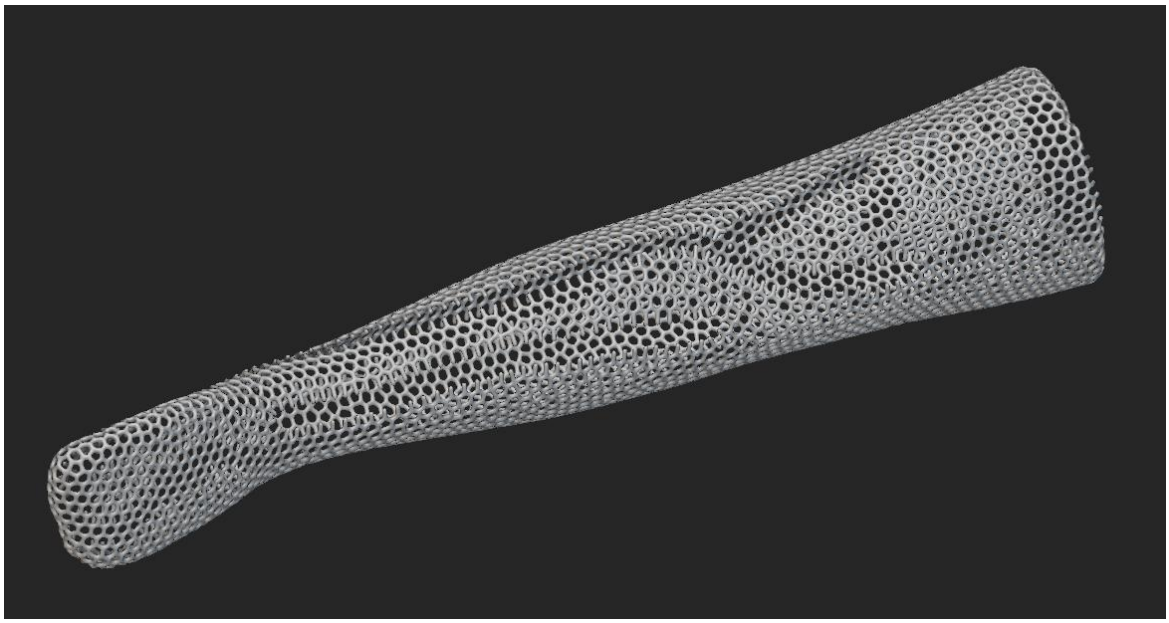

Fig. 16. Voronoi Surface Lattice

Recognizing the dimensional limitations of desktop Fused Filament Fabrication (FFF) printers, the arm model was segmented into modular sections. This allowed each part to be

printed independently and reassembled post-print without compromising the anatomical fidelity or functional integration. All lattice components were fabricated using a Bambu Labs P1S 3D printer(Bambu Lab, Shenzhen, China), chosen for its precision, reliability, and compatibility with flexible Thermoplastic Polyurethane (TPU) filament.

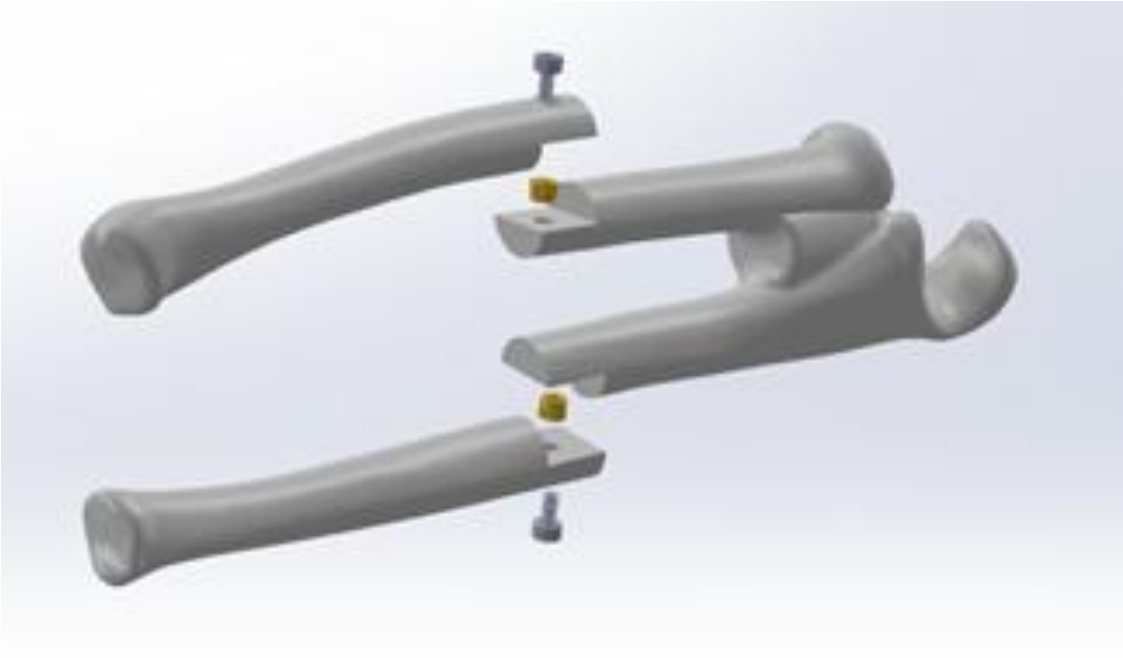

Fig. 17. Ulna and Radius attachment mechanism

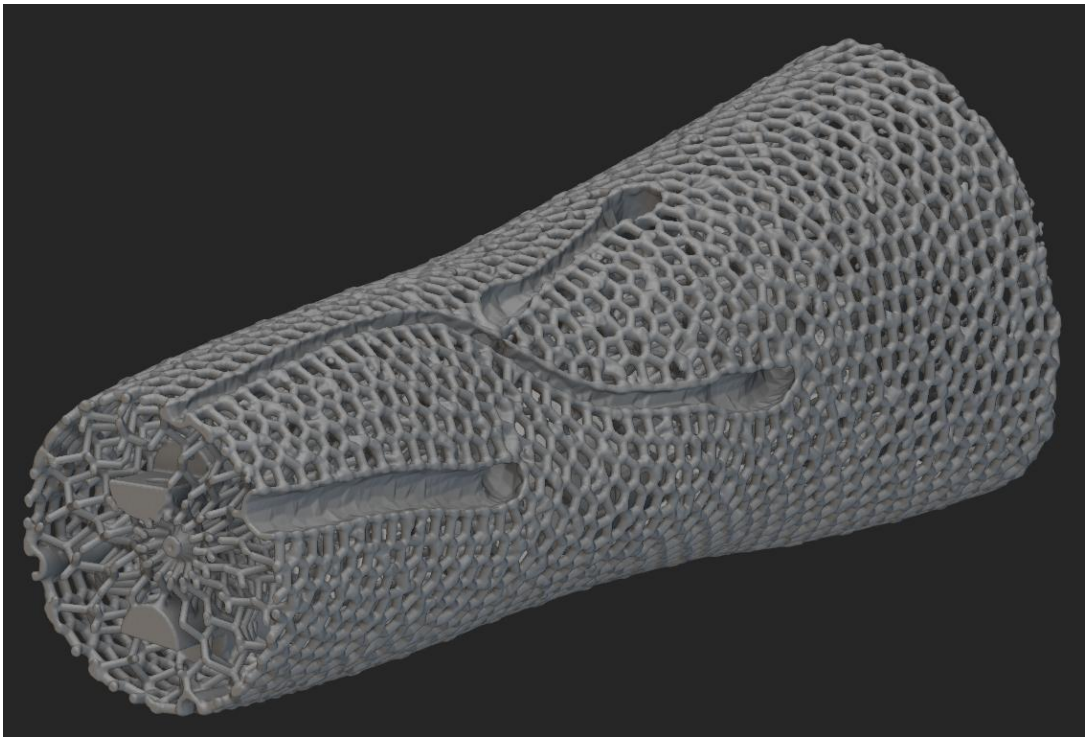

Fig. 18. upper arm and elbow printable model segment

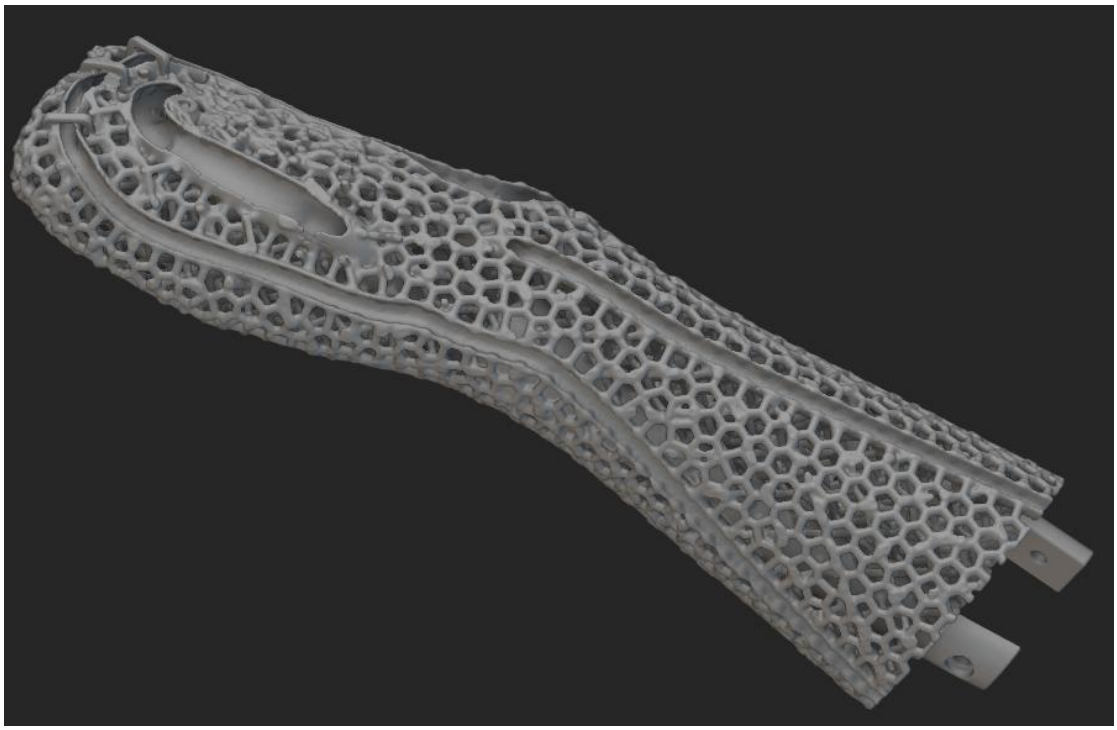

Fig. 19. Hand and forearm printable model segment

ii. Silicone skin sleeve

The silicone skin sleeves were designed to replicate the appearance, texture, and mechanical behavior of human skin for realistic IV insertion training. Each sleeve was cast using platinum-cure silicone - Smooth-On EcoFlex™ 00-30 (Smooth-On, Inc., Macungie, Pennsylvania, USA), chosen for its durability, elasticity, and pot life. Pigments and flocking were added to achieve lifelike skin tones. and the silicone was poured into a custom 3D-printed mold. The sleeves were fabricated as removable components that could slide over the lattice armature, allowing for modular replacement and easy maintenance. This design approach enabled consistent tactile feedback during vein palpation and needle insertion while also supporting repeated use in clinical simulation environments.

To fabricate the silicone skin sleeves, an eight-part mold (Figures 20 & 21) was designed with a focus on ease of demolding and compatibility with standard desktop FDM 3D printers. The mold was segmented to avoid undercuts and reduce the risk of damaging either the mold or the silicone cast during removal. Each part included mechanical alignment features (peg and holes) as well as bolt holes with standoffs to suspend the internal core evenly within the mold. Hot glue was used to seal the seams between mold segments, providing an effective yet easily removable barrier that facilitated clean demolding after the silicone had cured.

The mold design incorporated two strategically placed injection ports—visible in the cross-sectional view in figure 22—to facilitate silicone flow into both the hand and forearm sections of the sleeve. This dual-injection setup ensured complete filling of the mold's lower cavities and reduced the likelihood of air entrapment during casting. Silicone was injected using wide-nozzle paint syringes, which provided sufficient flow for the high-viscosity material. This

method enabled precise, controlled casting of the skin sleeve while maintaining a smooth internal surface finish suitable for interfacing with the underlying TPU lattice structure.

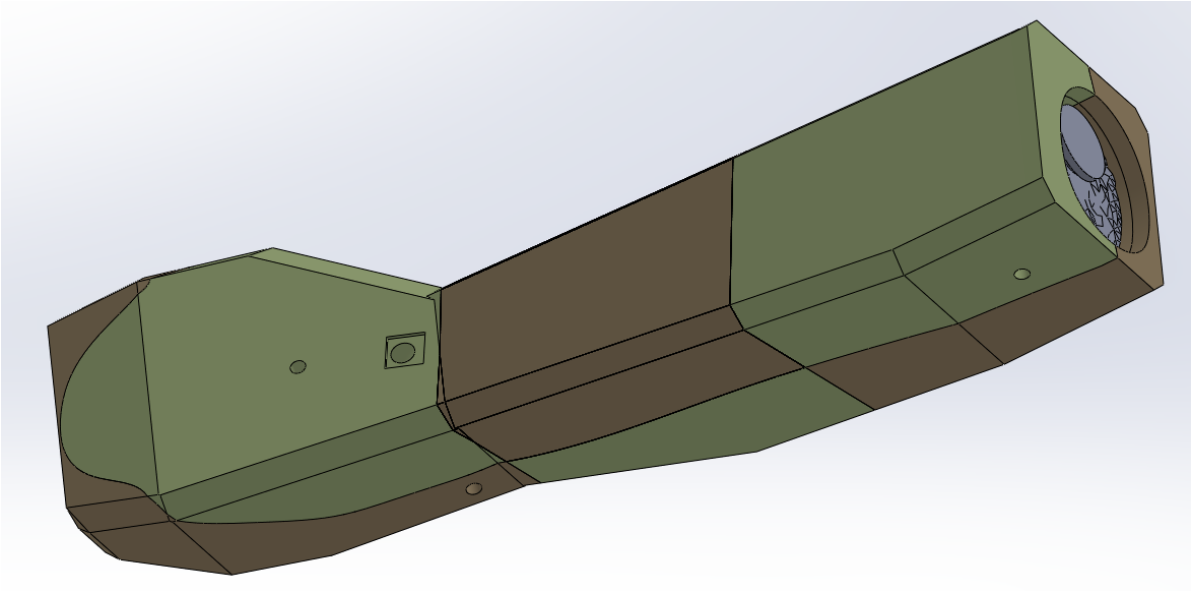

Fig. 20. Silicone sleeve mold

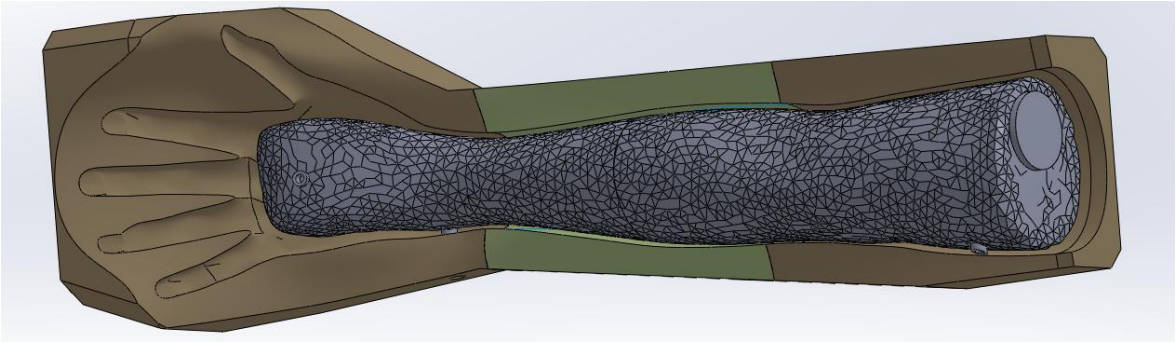

Fig. 21. Internal core of silicone sleeve mold

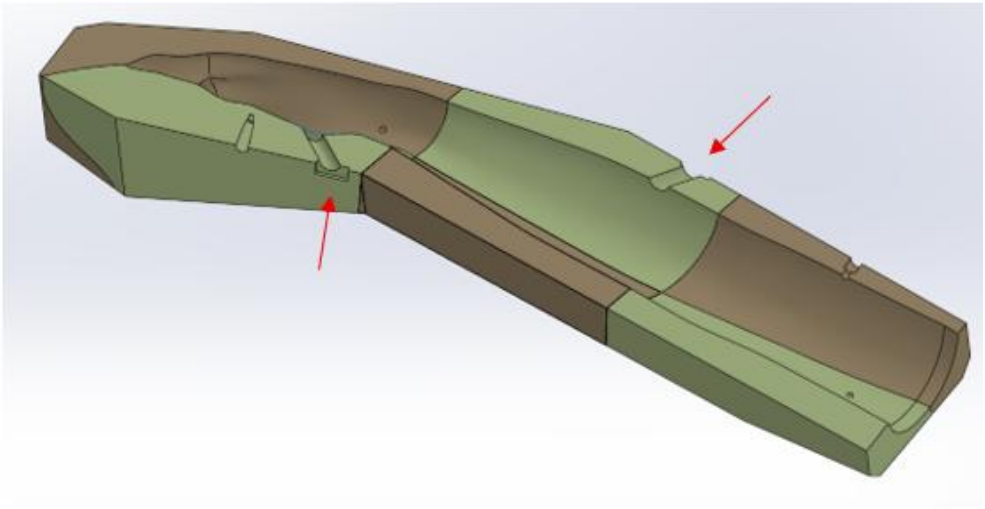

Fig. 22. Cross section view of silicone mold. Injection ports locations pointed with red arrows.

Fig. 23. Hot glue used to seal seams of mold segments

iii. Veins

The artificial veins used in the PractIV trainer were fabricated using clear silicone tubing with a co-extruded outer layer of blue-pigmented silicone to enhance visibility through the simulated tissue (figure 24). This dual-layer construction allowed the veins to maintain realistic compliance while also providing visual contrast for users during palpation and insertion.

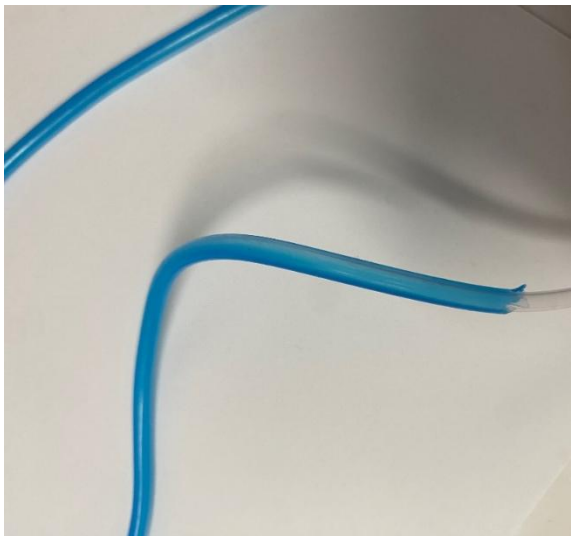

Fig. 24. Blue silicone extrusion on outside of clear tubing to create veins

Fig. 25 Modified syringe for co-extrusion (a) plunger (b) nozzle

To produce this feature, a custom extrusion method was developed using a modified syringe. A small hole was drilled into the back side of the plunger (figure 25a), with a syringe nozzle with a diameter of 4.3 mm (figure 25b). As the plunger was depressed and the syringe was pulled down the tubing, blue-pigmented silicone was extruded through the syringe tip, forming a thin coating around the clear tubing as it passed through the nozzle. This approach enabled consistent deposition of the outer layer along the length of tubing required for the trainer. The resulting structure provided a more lifelike appearance and facilitated vein identification during practice, especially under the semi-opaque silicone skin layer.

iv. Pressurized fluid system

To simulate blood flashback —the visual return of blood into the catheter that confirms successful entry into a vein—during successful vein cannulation, the PractIV trainer incorporated a closed-loop, pressurized fluid system. The setup consisted of two flexible silicone tubes (the veins) connected to IV bags at either end. One IV bag was placed inside a pressure sleeve equipped with a manual hand pump and pressure gauge (figure 26), allowing the system to be pressurized to 5–15 mmHg—a range chosen to reflect typical venous blood pressure in adult patients. The second IV bag served as a passive reservoir to initially purge air from the tubing. Once fluid was flowing steadily, the outlet roller clamp on the downstream end was closed to halt flow and allow the pressure to build within the system.

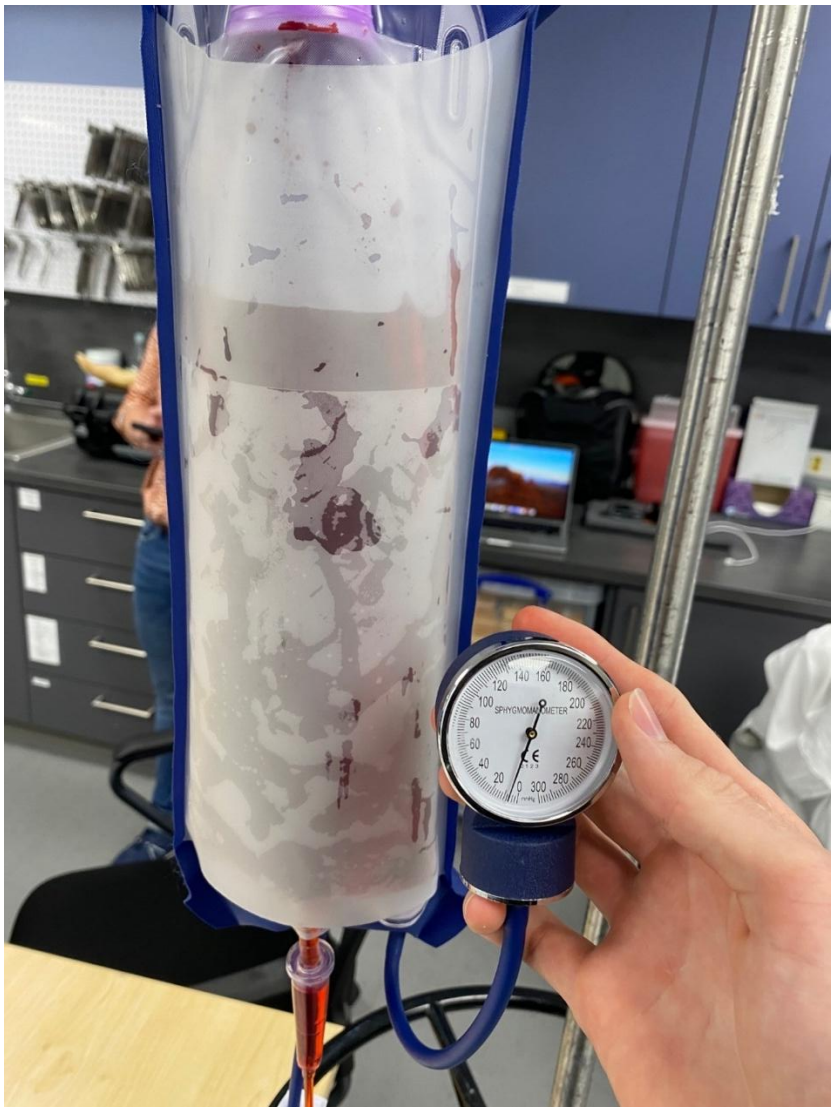

Fig. 26. Pressurized sleeve fluid system

Upon successful catheter insertion, the pressurized fluid provided a realistic flashback response, mimicking the visual cue of blood return seen in clinical settings. This feature not only reinforced proper technique but also provided immediate feedback to learners. The system was designed to be modular, refillable, and durable — supporting repeated use during training without compromising functionality or realism. By integrating this physiological feedback mechanism, the PractIV trainer offers a more immersive and clinically relevant simulation experience.

c. Material Selection and Fabrication

To characterize the depth of skin needed to provide a realistic needle insertion experience- including force, palpation of vein, etc. Various prototypes were made to understand the effect of thickness on these metrics. In our biomechanical benchmarking, our research showed that the peak needle insertion force into a vein in the forearm ranged between 1 – 4N of force[25], [26]. To match this metric in our device, we developed the prototype shown in figure 33. This included 5 silicone tubes, used as our veins placed at varying different thicknesses. From 1-5mm. this allowed testing of needle insertion forces through the skin and puncture of the vein. The peak value of the force was recorded and averaged over 10 trials. Testing was done at a 15-30 degrees insertion angle to represent procedural accuracy.

Some limitations to this prototype testing were the instrument only recorded a peak value, and we could not observe the force distribution as the catheter went through the skin and vein wall. Another limitation was that the same gauge of needle was used and was not replaced with a sharp needle. This means the needle would have dulled over the repeated insertions and caused the insertion force to increase.

Material Testing of Silicone

To replicate the mechanical properties of human skin, multiple silicone formulations from Smooth-On were tested. These materials were selected based on clinician feedback and evaluated for realism in terms of compliance, palpability, and needle insertion feel. Our initial castings were performed using Smooth-On Dragon Skin™ 30, where "30" refers to the 30 A shore hardness of the cured silicone. This material offered a balance of softness and durability, and

provided a 45-minute pot life, and 16-hour cure time. However, during our pilot usability testing, we noticed that it was too difficult for clinicians to advance the catheter through the skin.

Alternate silicone recipes were tested for our application, including:

- A mixture of 50% Smooth-On Dragon Skin™ 30 and 50% Smooth-On Ecoflex™ 00-30
- Smooth-On Ecoflex ™ 00-30 with a hardener (with a 2A:2B:1H ratio)
- Smooth-On Ecoflex ™ 00-30 with a hardener (with a 1A:1B:1H ratio)
- Smooth-On Dragon Skin™ 30 with 5% volume added of mineral oil

Ultimately, The Ecoflex™ 00-30 with the hardener at a 2A:2B:1H ratio was selected for the final prototype. This formulation provided the best combination of softness, needle pass-through feel, and durability—closely mimicking the mechanical resistance of human soft tissue while still enabling successful catheter advancement during simulated IV insertion.

d. Prototype Iterations and Improvements

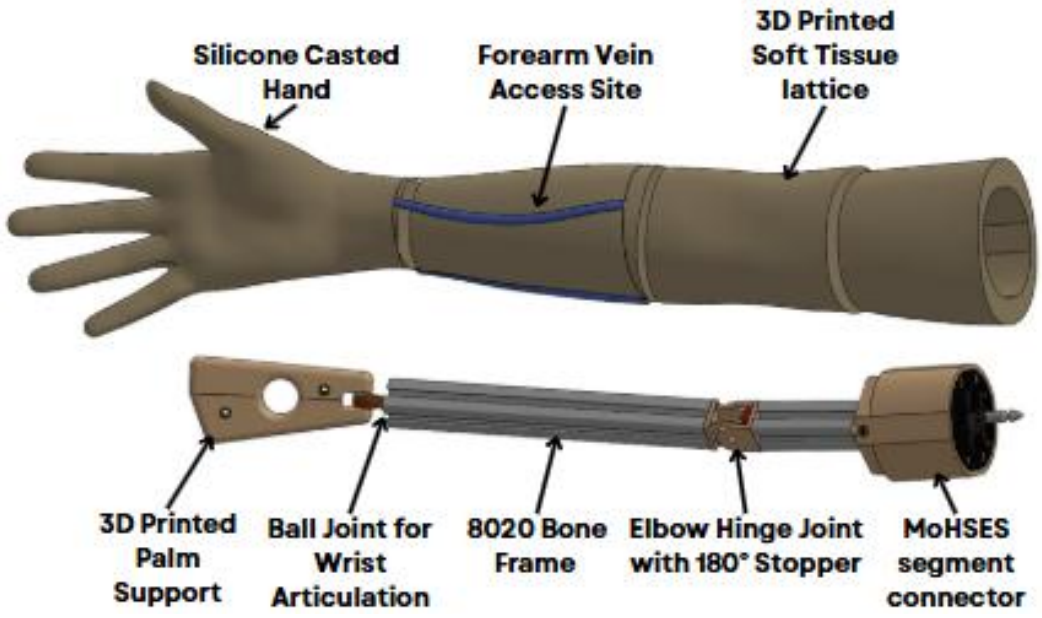

Fig. 27 Labeled exploded view of first full functional prototype

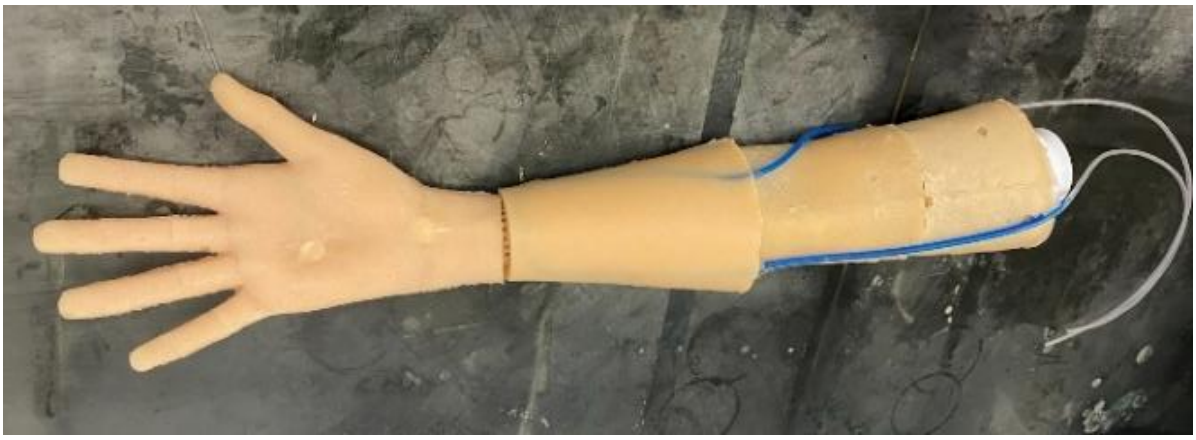

Fig. 28. Image of first full functional prototype

The first iteration of the PractIV IV training arm was completed and presented at the EIH Spring Symposium in June 2025. This prototype was modularly segmented into distinct anatomical regions—hand, forearm, elbow, and upper arm—to evaluate various fabrication strategies and material configurations. The primary goal of this version was to validate key components of the project, on a small scale. Such as the silicone casting process, vein integration, and soft tissue compliance using a 3D-printed lattice structure. It also served to assess joint articulation and compatibility with the AJAMS full-body simulation platform.

Based on internal testing and early feedback from clinicians and simulation experts, a second iteration (figures 29-31) was developed that retained the core architecture of the initial prototype while incorporating several key improvements. These included refinements in silicone formulation for better needle insertion and catheter advancement, enhanced anatomical accuracy of vein placement, and improved mechanical integration between components. Structural upgrades were also made to the 3D-printed internal lattice, elbow hinge, and wrist articulation, increasing durability and range of motion. The updated design also featured better alignment of the pressurized vein system with key access sites to improve realism and usability during training.

Fig. 29. Top view of second full functional protype

Fig. 30. Inner forearm of second full functional protype

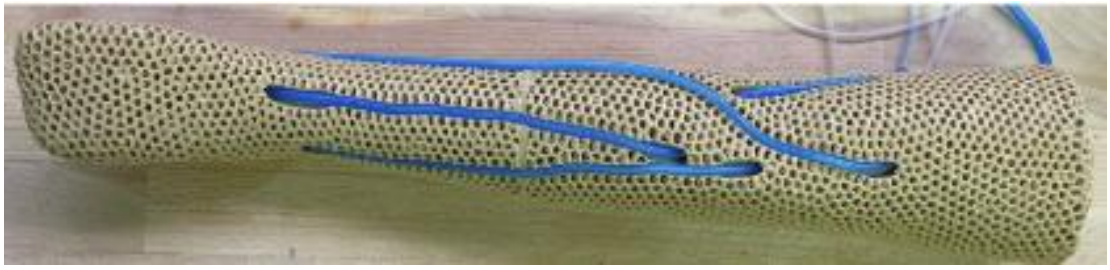

Fig. 31. Second Iteration Prototype core structure

i. Silicone molding prototypes

To evaluate surface quality and anatomical realism, we tested multiple silicone molding techniques. Each mold was designed in SolidWorks and tested for ease of demolding, surface

texture, and fidelity of anatomical detail. We used Smooth-on silicone products casted into these molds and allowed them to cure at room temperature.

3D printing our molds with Fused Filament Fabrication (FFF) allowed for fast iteration and reliable demolding but left visible layer lines that slightly reduced the realism of the final skin texture. Designs with integrated pour openings and separable components improved silicone flow and minimized tearing during demolding.

Fig. 32. Early Silicone mold prototypes (a) pour funnels integrated in mold (b) demolding of hand

These prototypes shown in figure 32 revealed several important insights for effective silicone molding: (1) molds must include dedicated pour channels and air vents to ensure complete filling, (2) multi-part mold designs are essential for clean demolding of soft materials, and (3) the short working time of some silicones require quick, coordinated pouring to avoid premature curing. While the 3D printed molds offer a practical solution for prototyping, future

improvements could include post-processing (e.g., sanding or coating) or transitioning to resin-based molds for smoother finishes and higher detail fidelity.

4. Validation Methods

a. Experimental Setup

Preliminary needle insertion force testing

Our team conducted a preliminary evaluation of a prototype with variable silicone thicknesses to test the force required for needle insertion. This test aimed to assess the realism of haptic feedback during IV placement, which is a critical usability factor for effective simulation training. Our goal was to compare the insertion force of our prototype against published data for human tissue[25][26] . Guided by early advice from simulation expert mentors, we first aimed to approximate this benchmark range, with the intention of refining the model further based on clinician feedback. This approach acknowledges that the subtle nuances of human tissue cannot be fully captured by a single force metric alone.

Methods

A digital force gauge with an IV catheter needle mounted to simulate controlled needle insertions into silicone samples of varying thicknesses (1–5 mm). A standard 20-gauge IV catheter was advanced until puncture occurred. The peak insertion force was recorded for each trial. Multiple trials were conducted per thickness to assess repeatability and determine the optimal skin depth that replicates clinical insertion forces.

We conducted 10 insertions for 5 different thicknesses on the prototype to account for material variability.

Fig. 33. Variable skin thickness prototype. A silicone skin model with embedded tubing and varying thickness regions (1–5 mm) used to evaluate needle insertion force and optimize tactile realism during venipuncture.

Results

TABLE I

EXPERIMENTAL NEEDLE INSERTION FORCE VALUES

Thickness between skin and vein	1mm	2mm	3mm	4mm	5mm
Average Force (N)	1.70	1.84	3.64	6.47	10.52

Discussion

The results demonstrate that the insertion force required by our prototype increases with silicone thickness, ranging from 1.70 N for 1 mm samples to 10.52 N for 5 mm samples. This trend aligns with expectations, as thicker layers require increases the area for drag forces to be imparted on the catheter during insertion.

When benchmarked against human data, our results show that the 2 mm and 3 mm samples (1.84 N and 3.64 N, respectively) fall between the realistic range of 1.25 ± 0.37N [25]to 3.2 ± 1.2 N[26] typically required to puncture human forearm skin using a 16G catheter needle. This suggests that our design can realistically replicate the initial puncture resistance experienced during clinical IV insertion, especially when using skin thicknesses in the 2–3 mm range.

The 4 mm and 5 mm samples (6.47 N and 10.52 N, respectively) exceed this physiological range and may lead to overly stiff or unrealistic haptic feedback. Conversely, the 1 mm sample (1.70 N) falls just below the lower bound of realistic skin resistance, which could result in insufficient tactile realism. These findings highlight the importance of tuning the skin layer thickness and material properties to replicate the target insertion force range.

Our prototype does include a distinct vessel layer with separate mechanical properties. In real tissue, a second force peak corresponding to vein wall puncture is typically observed. This embedded vein analog helps simulate this characteristic “pop” and further enhances training realism.

Overall, our testing provides objective validation that our prototype can simulate clinically realistic insertion forces under certain configurations. These results inform future

design iterations, particularly for optimizing silicone thickness and stiffness to stay within validated for needle insertion fidelity.

b. Usability Study Design

Our Prototype was evaluated alongside a commercial IV trainer (Life/form Advanced Venipuncture and Injection Arm (Light Skin))[27] to benchmark performance. We collected System Usability Scale (SUS) scores and user feedback on realism, anatomical fidelity, and ease of use. IRB (approval was secured in advance(MOD00022934), see Appendix I.

Data Collection Tools and Measures

System Usability Scale (SUS) was used to assess the usability of our device. The "SUS" is an industry standard evaluation mechanism, consisting of 10 items, which assess user's overall perception of the system. The SUS utilized was originally published by Brooke in 1996[28].

TABLE II

SYSTEM USABILITY SCORE RATING

Score	
90+	Exceptional
80+	Good
70+	Acceptable
70 >	Usability Concerns Requiring Revision

Question Prompts
I think that I would like to use this system frequently.
I found the system unnecessarily complex.
I thought the system was easy to use.
I think that I would need the support of a technical person to be able to use this System.
I found the various functions in this system were well integrated.
I thought there was too much inconsistency in this system.
I would imagine that most people would learn to use this system very quickly.
I found the system very cumbersome to use.
I felt very confident using the system.
I needed to learn a lot of things before I could get going with this system.

Questions For Clinicians
Please answer these questions using your experience with real human patients, and their anatomy as your reference point.

Educational Utility
On a slider scale from "Very Unlikely" to "Very Likely"

- In your view, does this trainer have the potential to train in IV access to a level consistent with professional competence?
- How likely are you to recommend this IV Arm Trainer for incorporation into a formal nursing or medical training curriculum?
- How does this IV Arm Trainer compare to other IV Trainers that you have used in the past?

Visual Fidelity (How Things "Look" Relative to Real Life) *on a slider scale from "Not Realistic" to "Very Realistic"*

- Consider the veins of the IV Arm Trainer. How closely does their coloring resemble real human veins?
- Consider the veins of the IV Arm Trainer. How closely does their arrangement (branching, location relative to landmarks) resemble real human veins?
- Consider the skin of the IV Arm Trainer. How closely does its color (or "skin tone") resemble real human skin?

Tactile Fidelity (How Things "Feel" Relative to Real Life) *on a slider scale from "Not Realistic" to "Very Realistic*

- How would you rate the fidelity of the vein(s) during palpation?
- How would you rate the fidelity of the needle insertion into the vein?
- How would you rate the fidelity of the soft tissue of the forearm?
- How would you rate the fidelity of the IV Arm Trainer's wrist mobility?
- How would you rate the fidelity of the IV Arm Trainer's elbow mobility?

Open Ended Questions

- In your opinion, what are the most valuable features of the prototype?
- Are there any features that make this prototype stand out, relative to other products on the market?
- In your opinion, what features could be improved or refined?
- What modifications would you make to the prototype to make it more useful in your environment?
- This prototype is built to be compatible with a full body simulation system and physiology engine that can respond to a user's actions in real time (e.g.: present accurate patient vitals in response to drug administration). How could you see this feature, if utilized, benefiting IV access training?
- Using other commercially available IV Arm Trainers as a reference point, what price would you expect to pay for this prototype?
- Is there anything else you would like to share with the research team about your experience interacting with this prototype IV Arm Trainer?

c. Statistical Analysis

For each item, we assessed the normality of the within-participant difference scores (PractIV − Commercial) using Q–Q plots. When the differences were approximately normal and there were no outliers, we used paired-samples t-tests; otherwise, we used the Wilcoxon signed-rank test. Q–Q plots are provided in Appendix II. All statistical analyses were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) and Python (v 3.10) (Python Software Foundation, Beaverton, Oregon).

d. Pilot Usability Study feedback

The second iteration arm, shown in figures (figures 29-31) was initially run through a pilot usability study with an anesthesiologist, a recently graduated Advanced EMT, and 3 Nurses – 1 who is on the IV team at their hospital. To better understand the strengths and shortcomings of the design, participants were asked to provide detailed feedback on the realism and usability of the prototype.

The feedback highlighted several areas for improvement in the second iteration prototype. Users noted that the skin felt too hard and “grabby,” making it difficult to thread the catheter, requiring the needle to remain inserted longer than normal, and preventing them from properly tensioning the skin with their fingers. Concerns were also raised about the venous anatomy: the basilic vein was slightly mispositioned, a vein was missing on the dorsal surface of the forearm, and the veins did not roll as expected in a real patient. In terms of appearance, participants felt the skin tone was overly transparent, making the veins unrealistically easy to visualize, and they remarked that hand veins are generally more visible than forearm veins in actual practice. Despite these limitations, users reported several positives, including the

durability of the skin, the quality of fluid flashback, and the realistic joint mobility of the model. Based on this feedback, design improvements were made to enhance fidelity by repositioning veins, increasing soft tissue compliance, and transitioning to a softer silicone material.

Improvements were made to increase the fidelity of the device, this included adjusting the placement of the veins, increasing the soft tissue stiffness, and a change to a softer silicone material.

5. Results

a. Final Product

The final iteration of the *PractIV* trainer is a modular, anatomically accurate intravenous (IV) insertion model designed to simulate the physical, visual, and procedural aspects of peripheral IV placement. Developed through iterative prototyping and direct input from clinicians, educators, and simulation experts, the device addresses key shortcomings of existing training models—the lack of anatomical variability, realistic tissue behavior, and meaningful feedback during needle insertion.

The completed prototype replicates the structure and compliance of the human arm and hand using a combination of 3D-printed lattices, cast silicone, and integrated vein structures. It includes a pressurized fluid system to provide visual flashback upon successful cannulation and physically connects with MoHSES™ compatible full-body simulation platforms. This integration allows the trainer to function not only as a standalone procedural tool but also as part of immersive, scenario-based medical simulations.

Designed with modularity in mind, the trainer is divided into multiple segments – core soft tissue, replaceable veins, and silicone sleeve - to accommodate fabrication constraints and facilitate maintenance. Each component was developed to support repeated use while maintaining fidelity and function. The result is a durable, reusable training device that supports skill acquisition, procedural confidence, and clinical readiness for learners across a range of experience levels.

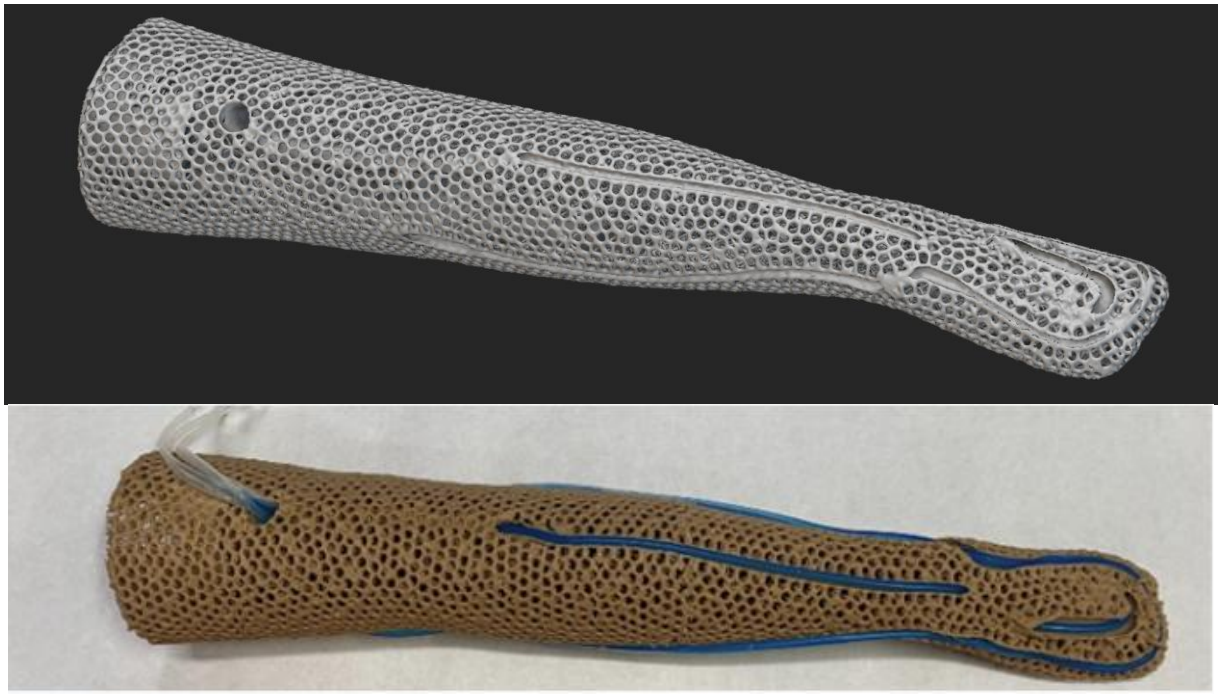

Fig. 34. Top view of final core model: (a) digital lattice design and (b) physical prototype.

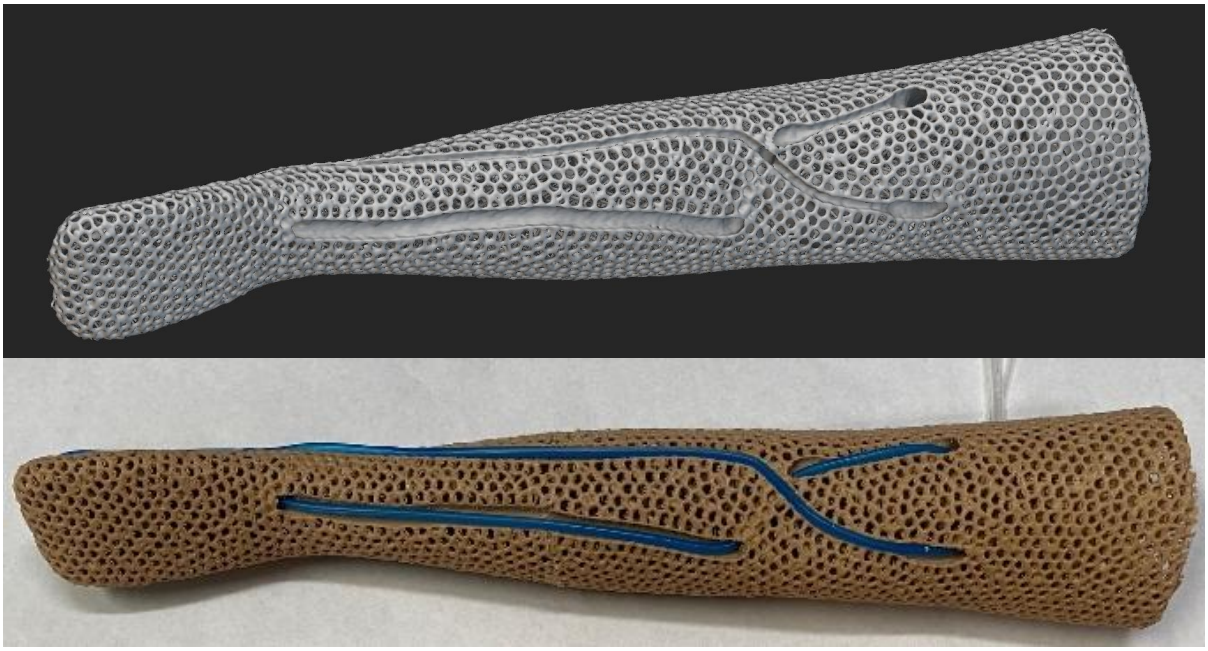

Fig. 35. Bottom view of final core model: (a) digital lattice design and (b) physical prototype.

Fig. 36. Rolling vein feature

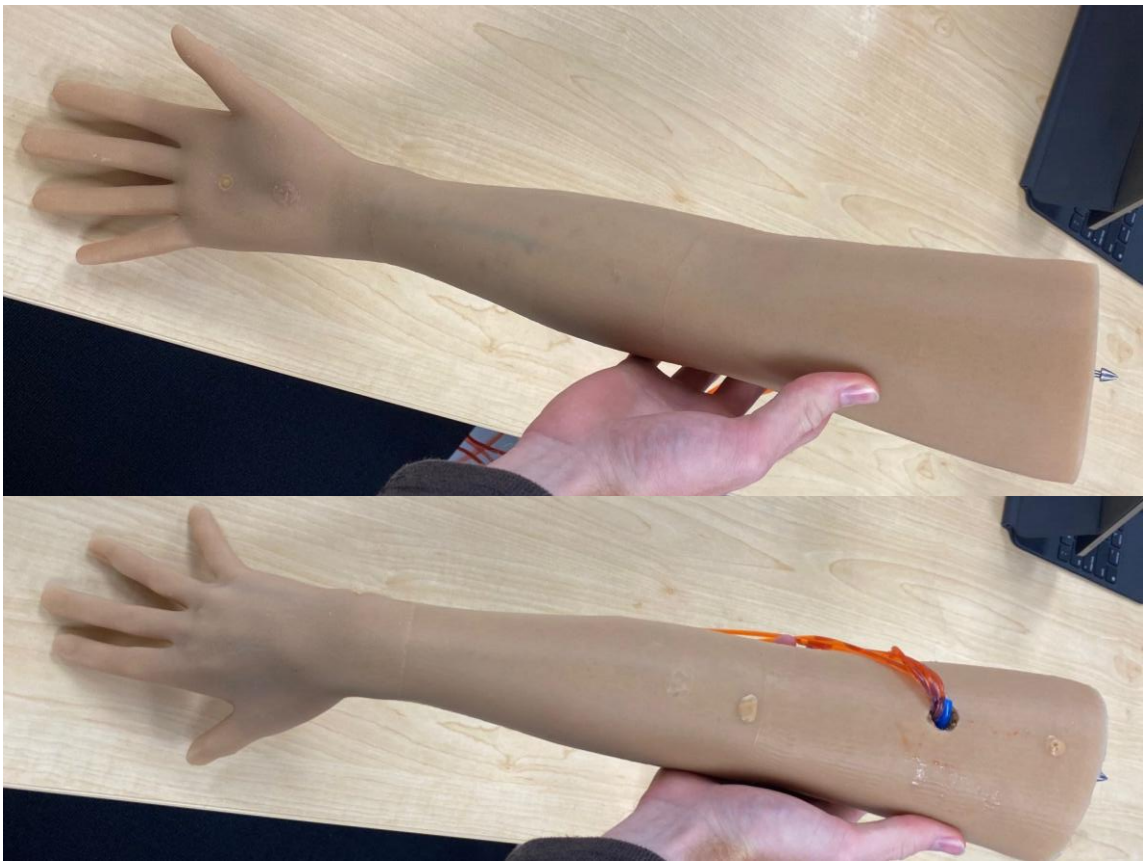

Fig. 37. Final prototype arm (a) inner forearm view (b) top of arm

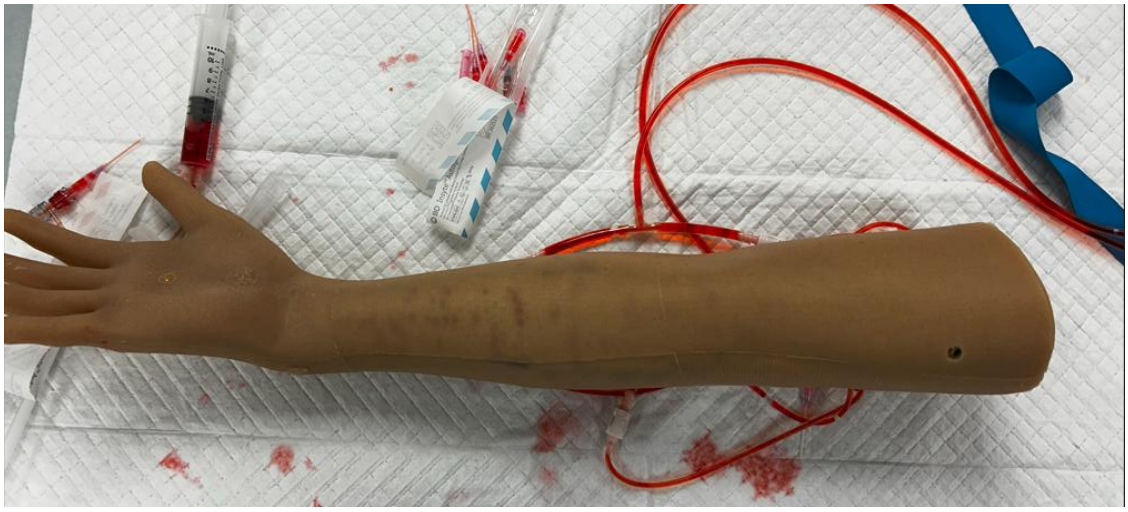

Fig. 38. PractIV final arm after usability study

Fig. 39. Usability study setup with full arm and fluid system configuration

b. Usability Study Findings & Feedback

Participants

The participant group consisted of five nurses (5F), one surgeon with prior IV experience (1M), and two simulation technicians(1M, 1F).

System Usability Scale

The System Usability Scale (SUS) was used to evaluate the perceived usability of both the Commercial Trainer and the PractIV trainer. The Commercial Trainer received an average SUS score of 49.72 (SD ± 17.74), whereas the PractIV trainer achieved a score of 73.61 (SD ± 14.95). According to established SUS benchmarks, the PractIV trainer falls within the "Acceptable" range, while the Commercial Trainer is categorized as having "Usability Concerns Requiring Revision." This 23.89-point difference reflects a substantial improvement in perceived usability with the PractIV trainer. Given the magnitude of this difference, and because SUS scores are already designed as aggregated usability measures, further statistical analysis was not conducted.

Educational Utility

To assess educational utility, participants rated statements on a slider scale where 0 indicated "Very Unlikely", to 100 indicating "Very Likely". Ratings were collected from a total of six participants (five nurses, one surgeon with prior IV experience), each of whom evaluated both devices. The raw data is provided in Appendix III.

For the statement “In your view, does this trainer have the potential to train in IV access to a level consistent with professional competence?”. The Wilcoxon signed-rank test indicated a statistically significant difference in ratings between the Commercial Trainer (Mdn = 44, IQR = 35.75) and the PractIV trainer (Mdn = 67.5, IQR = 13.5), W = 0, p = .043 (two-tailed). These findings suggest that participants consistently rated the PractIV trainer higher in educational utility than the Commercial Trainer.

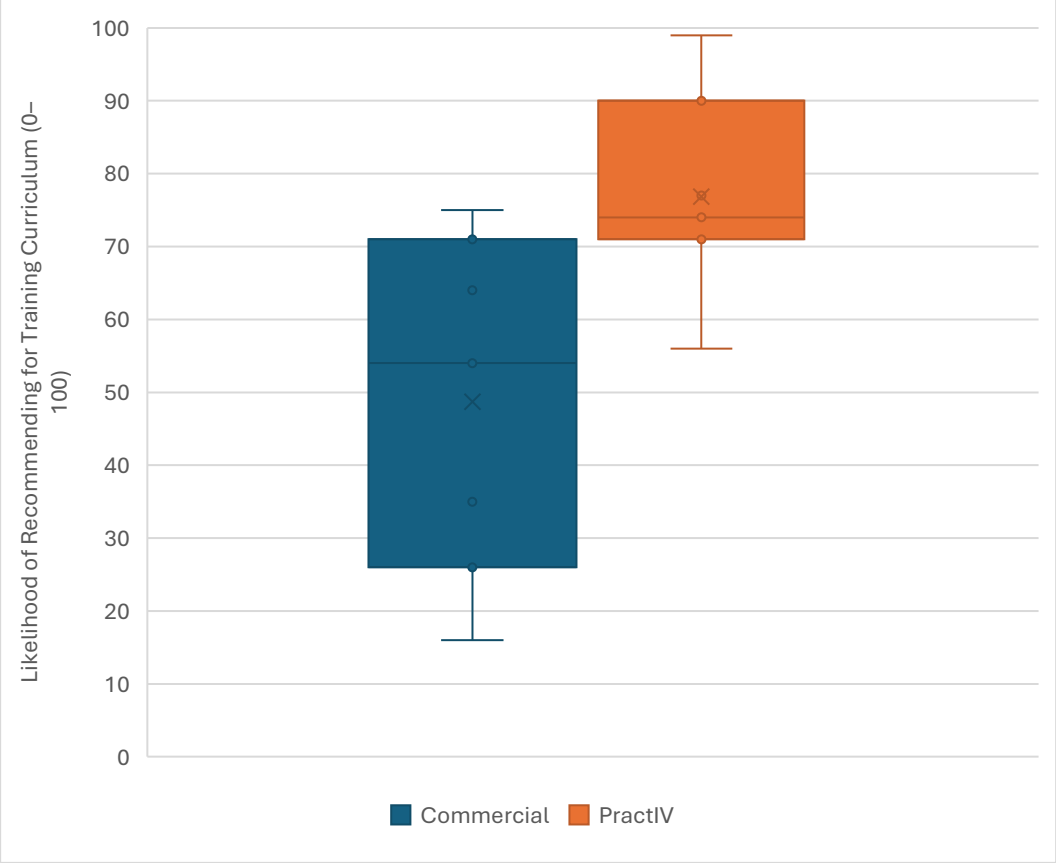

Fig. 40. Subject matter experts’ perceptions of the trainer’s potential to train in IV access to a level consistent with professional competence. (n=6)

For the question “How likely are you to recommend this IV Arm Trainer for incorporation into a formal nursing or medical training curriculum?” The Wilcoxon signed-rank test indicated a statistically significant difference in ratings between the Commercial Trainer (Mdn = 54, IQR = 37) and the PractIV trainer (Mdn = 74, IQR = 12.5), W = 1, p = .031 (two-tailed). These results suggest that participants were substantially more likely to recommend the PractIV trainer than the Commercial Trainer.

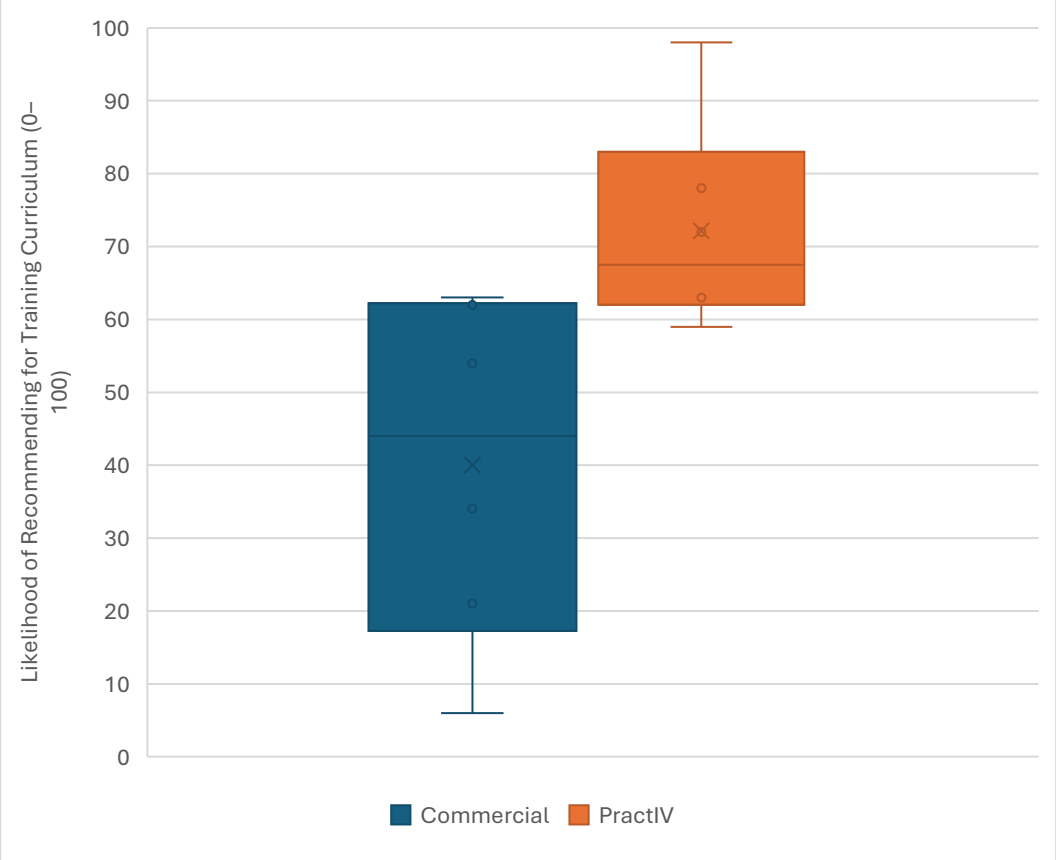

Fig. 41. Subject matter experts’ likelihood of recommending IV arm trainers for training curriculum. (n=7)

TABLE III

PRACTIV VS. COMMERCIAL IV ARM TRAINERS—EDUCATIONAL UTILITY RATINGS (0–100) AND WILCOXON TEST RESULTS

Trainer		In your view, does this trainer have the potential to train in IV access to a level consistent with professional competence?	How likely are you to recommend this IV Arm Trainer for incorporation into a formal nursing or medical training curriculum?
	n	6	7
PractIV	Median	67.5	74
	Mean	72.17	76.86
	SD	14.44	13.99
Commercial	Median	44	54
	Mean	40	48.71
	SD	23.5	23.18
Wilcoxon	W	0 *	1
	p (two–tailed)	0.043	0.031

* 0 indicates that all the differences between paired observations have the same sign.

Anatomical fidelity

To assess anatomical fidelity, participants rated statements on a slider scale where 0 indicated “not realistic at all” and 100 indicated “extremely realistic” as compared to how things "look" or “feel” relative to real life.

For the question “Consider the veins of the IV Arm Trainer. How closely does their coloring resemble real human veins?”, the PractIV trainer received consistently higher realism ratings (M = 82.71, SD ± 15.62) compared to the commercial model (M = 24.14, SD ± 23.52). A paired samples t-test revealed that this difference was statistically significant, $t(6) = 4.41$, $p = 0.0045$ (two-tailed). This suggests that participants perceived the vein coloration in the PractIV trainer to be far closer to that of actual human veins, with less variability in ratings compared to the commercial model.

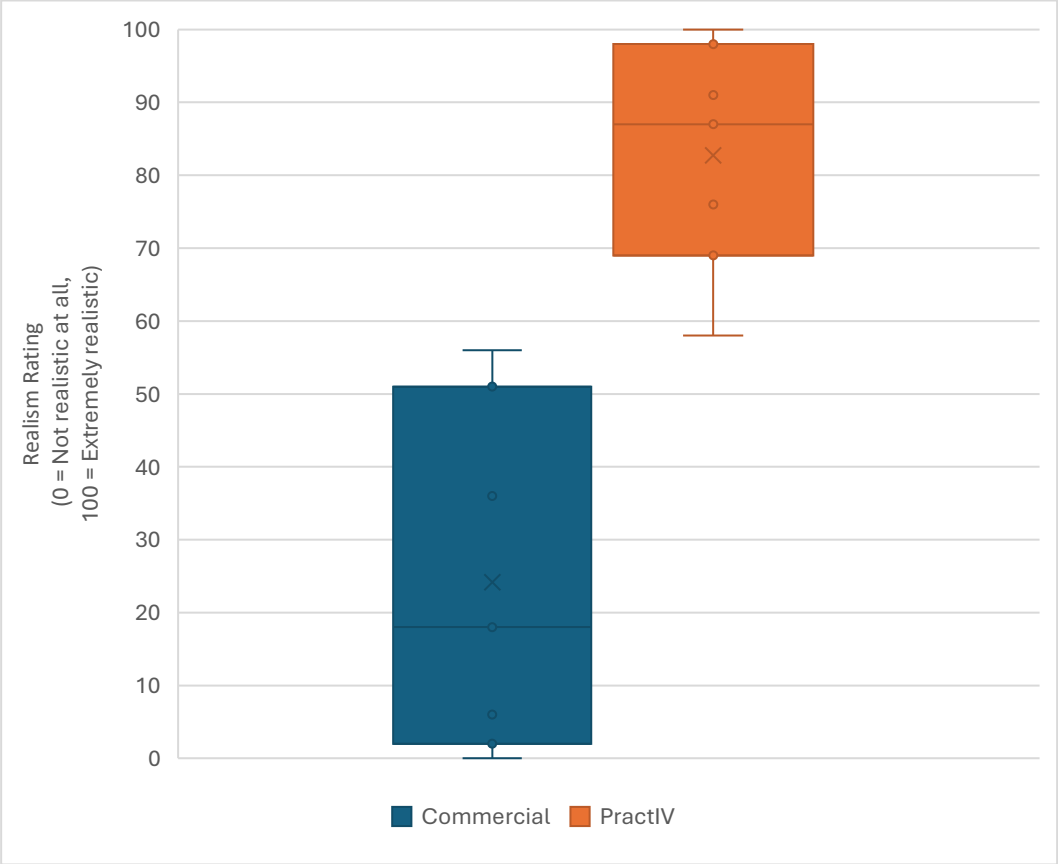

Fig. 42. Subject matter experts’ realism ratings of vein coloring in commercial and PractIV IV arm trainers. (n = 7)

For the question “Consider the veins of the IV Arm Trainer. How closely does their arrangement (branching, location relative to landmarks) resemble real human veins?” The PractIV trainer (Mdn = 72, IQR = 18) and the commercial model (Mdn = 70, IQR = 19.5) received similar ratings. A Wilcoxon signed-rank test showed no statistically significant difference between the two models, W = 12.0, p = 0.8125. These results suggest that participants perceived the vein arrangement of the two trainers to be equally representative of real human veins.

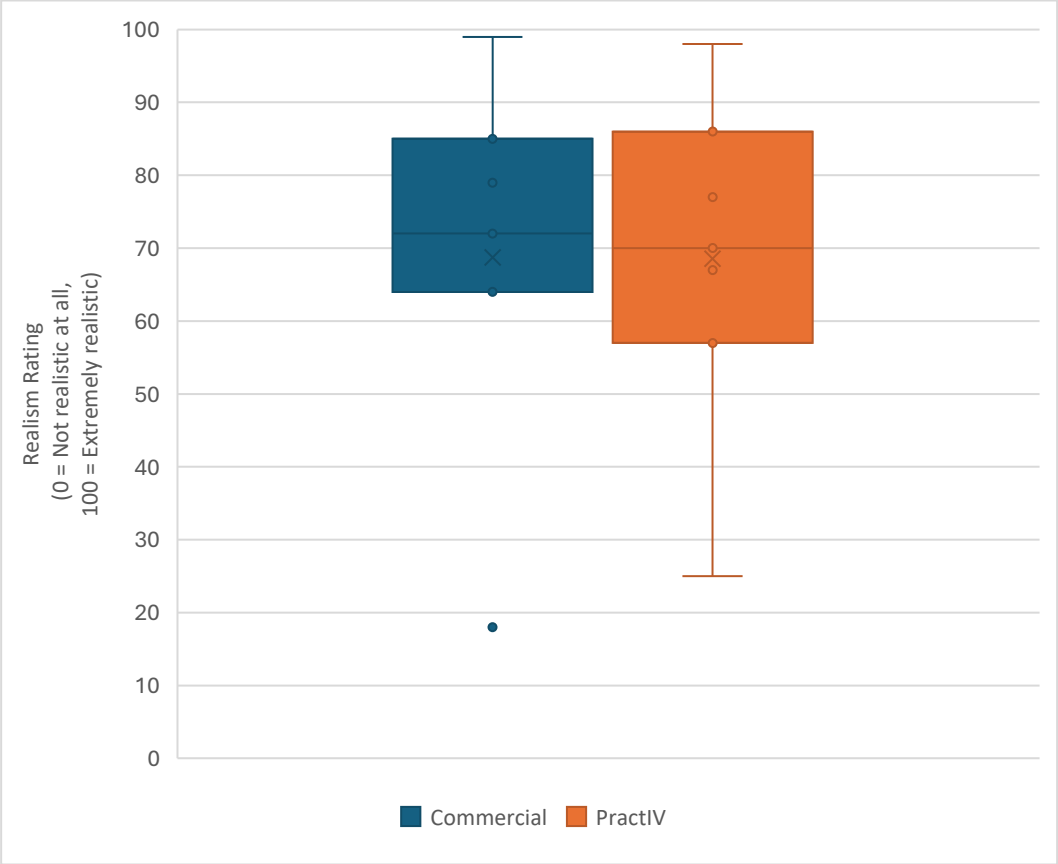

Fig. 43. Subject matter experts’ realism ratings of vein arrangement in commercial and PractIV IV arm trainers. (n = 7)

For the question “Consider the skin of the IV Arm Trainer. How closely does its color (or "skin tone") resemble real human skin?” The PractIV trainer received consistently higher realism ratings (M = 71.86, SD ±13.83) compared to the commercial model (M = 33.71 SD ± 28.70). A paired samples t-test revealed that this difference was statistically significant, $t(6) = 3.01$, $p = 0.024$ (two-tailed).

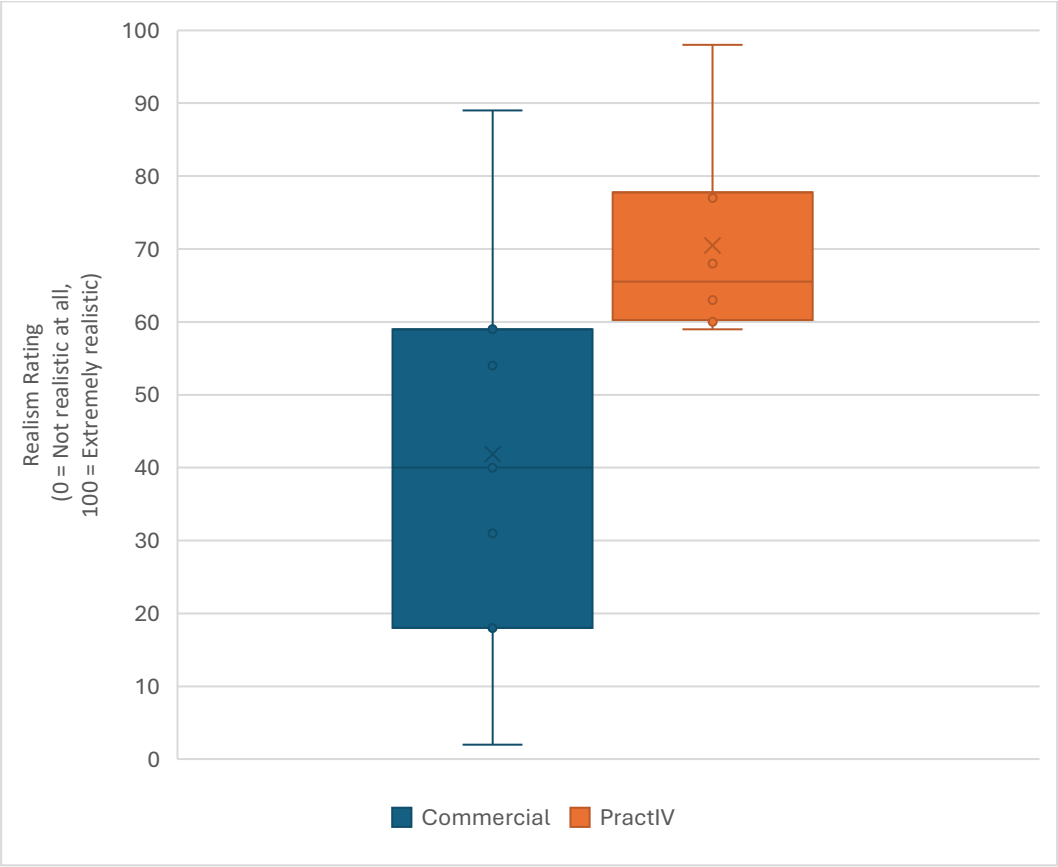

Fig. 44. Subject matter experts’ realism ratings of skin tone in commercial and PractIV IV arm trainers. (n = 7)

For the question “How would you rate the fidelity of the vein(s) during palpation?” The PractIV trainer received consistently higher realism ratings (Mdn = 64, IQR = 9.5) compared to the commercial model (Mdn = 36, IQR = 13.50). A Wilcoxon signed-rank test showed that this difference was statistically significant, W = 1.0, p = 0.0312 (two-tailed).

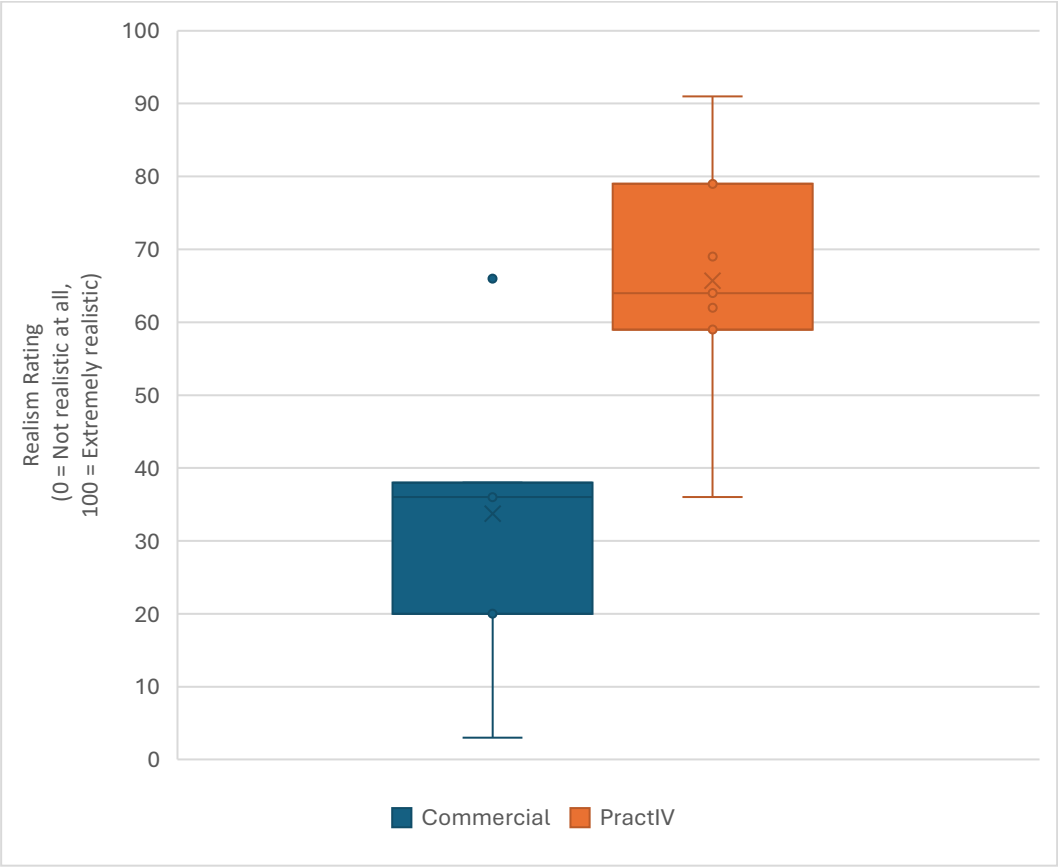

Fig. 45. Subject matter experts’ realism ratings of vein palpation in commercial and PractIV IV arm trainers. (n = 7)

For the question, “How would you rate the fidelity of the needle insertion into the vein?” The PractIV trainer received higher ratings (Mdn = 60, IQR = 29) than the commercial model (Mdn = 29, IQR = 29). A Wilcoxon signed-rank test showed that this difference was statistically significant, W = 0, p = 0.016 (two-tailed).

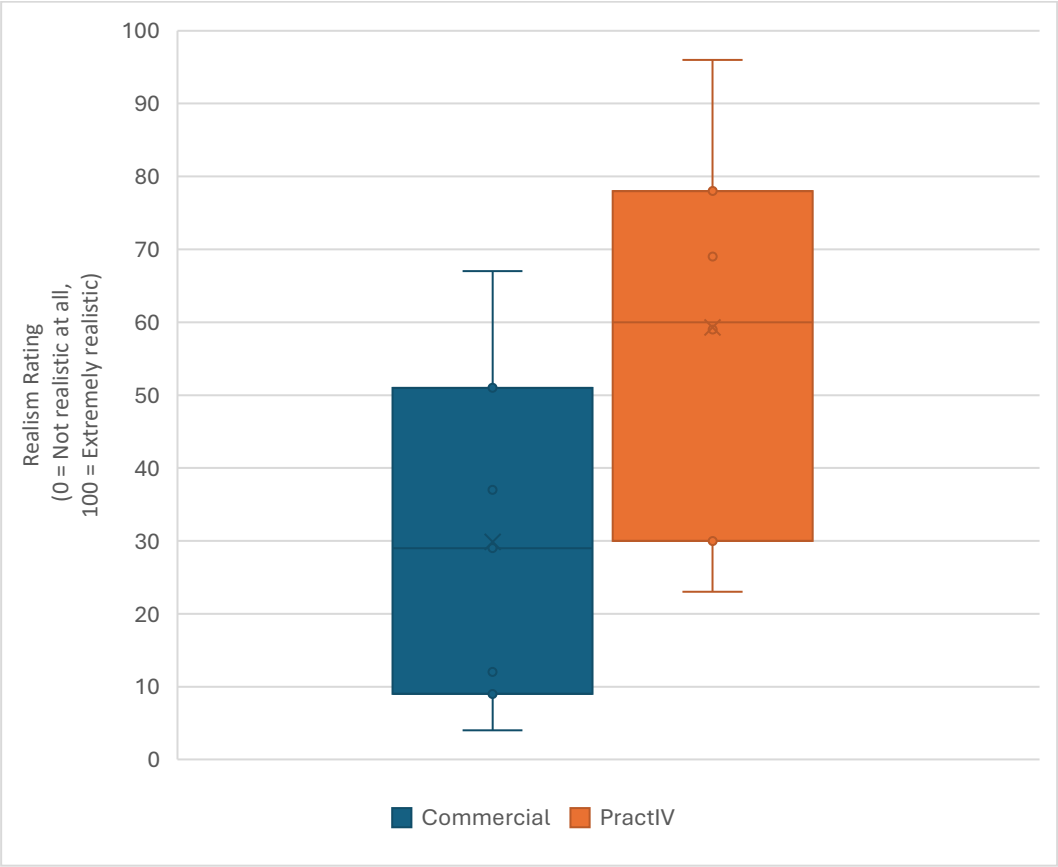

Fig. 46. Subject matter experts’ realism ratings of needle insertion for commercial and PractIV IV arm trainers. (n = 7)

For the question “How would you rate the fidelity of the soft tissue of the forearm?” The PractIV trainer received substantially higher ratings (M = 55.57, SD ± 19.44) than the commercial model (M = 17.86, SD ± 13.17). A paired samples t-test showed this difference was statistically significant, t(6) = 7.40, p = 0.00031 (two-tailed). All participants rated PractIV higher than the commercial trainer.

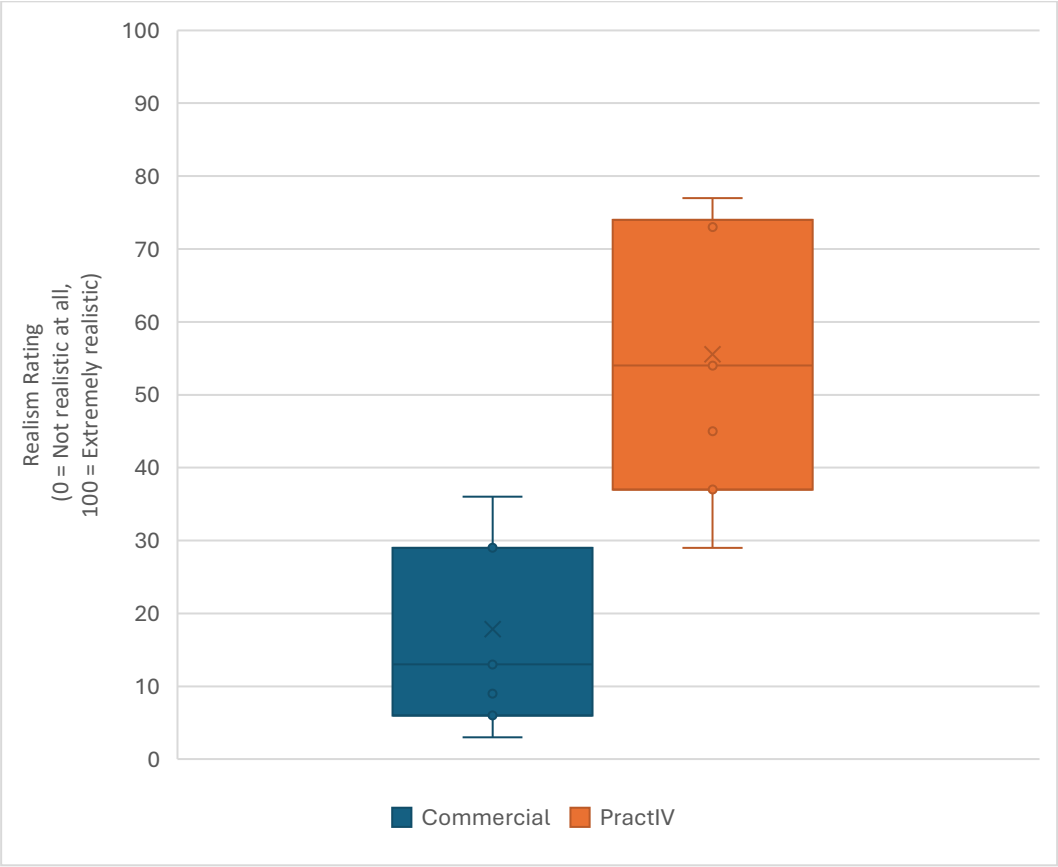

Fig. 47. Subject matter experts’ realism ratings of soft tissue in commercial and PractIV IV arm trainers. (n = 7)

For the question “How would you rate the fidelity of the IV Arm Trainer's wrist mobility?” The PractIV trainer received higher ratings (Mdn = 29, IQR = 32.75) than the commercial model (Mdn = 1, IQR = 8.75). A Wilcoxon signed-rank test indicated this difference was statistically significant, W = 0, p = .031 (two-tailed).

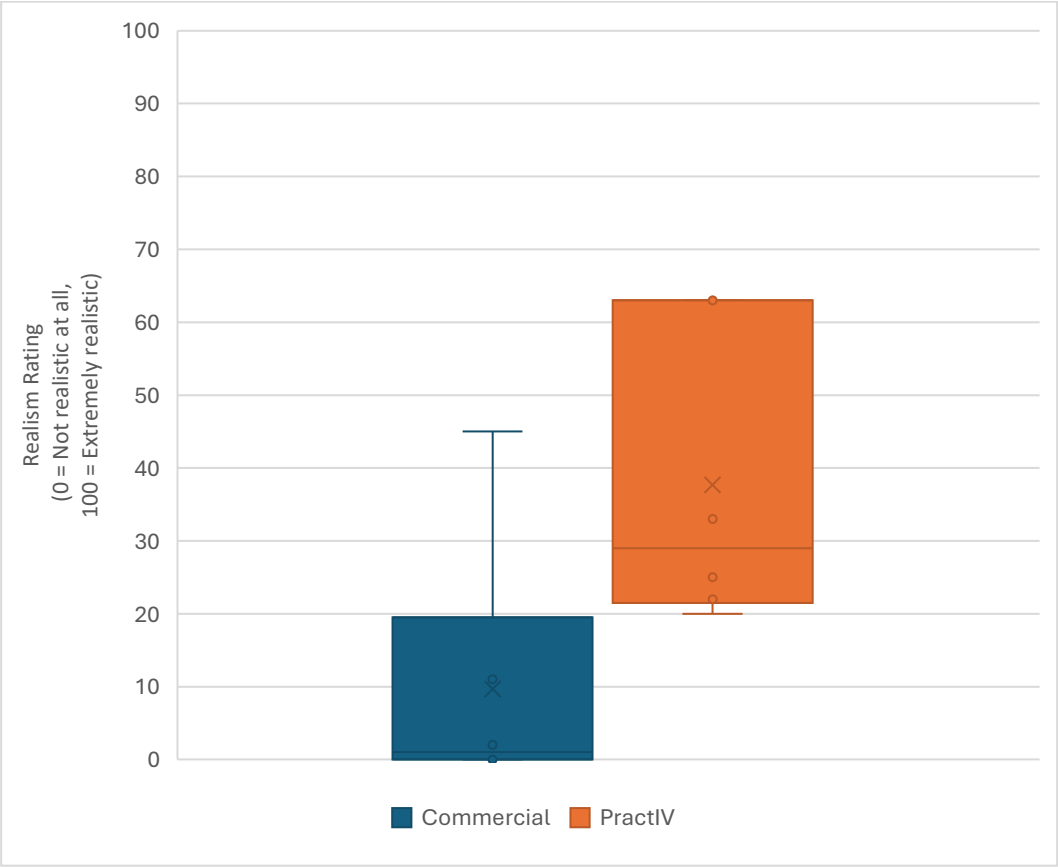

Fig. 48. Subject matter experts’ realism ratings of wrist mobility in commercial and PractIV IV arm trainers. (n = 6)

For the question “How would you rate the fidelity of the IV Arm Trainer's elbow mobility?” The PractIV trainer received substantially higher ratings (Mdn = 27, IQR = 20) than the commercial model (Mdn = 4, IQR = 10.5) A Wilcoxon signed-rank test indicated this difference was statistically significant W = 0.0, p = 0.0156.

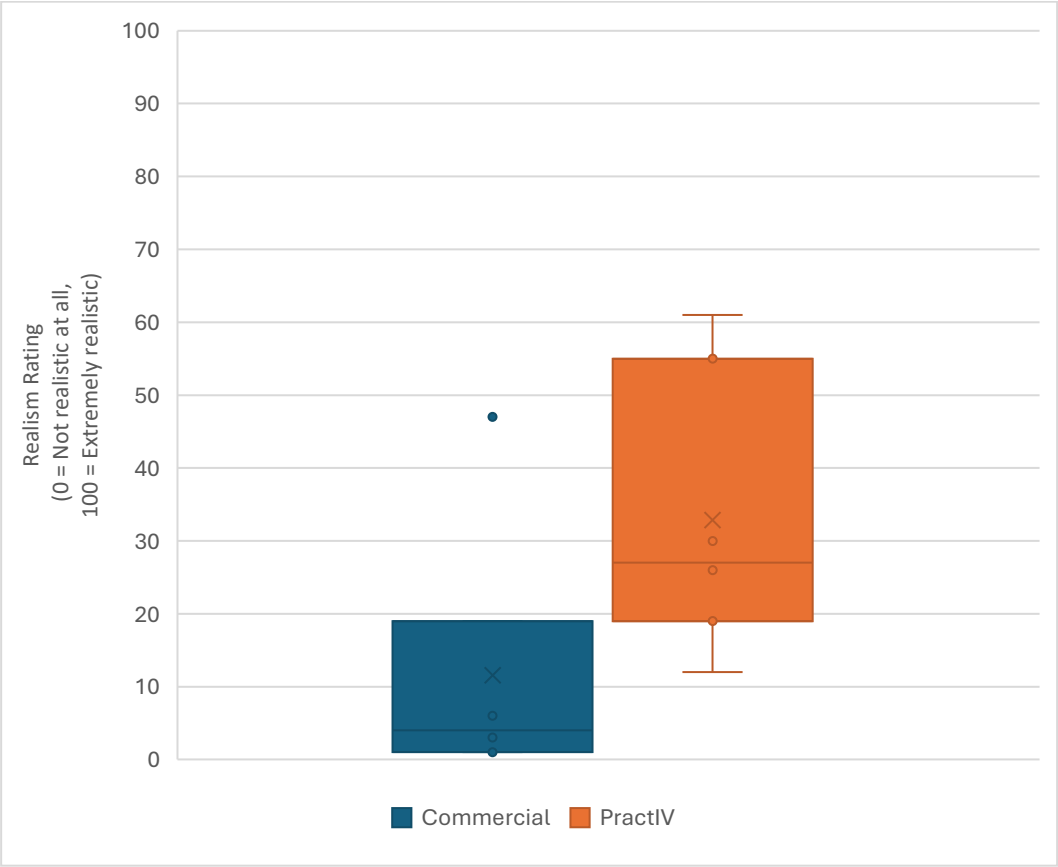

Fig. 49. Subject matter experts’ realism ratings of elbow mobility in commercial and PractIV IV arm trainers. (n=7)

TABLE IV

SUBJECT MATTER EXPERTS' PERCEPTIONS OF ANATOMICAL FIDELITY OF COMMERCIAL AND PRACTIV IV ARM TRAINERS

Trainer		Consider the veins of the IV Arm Trainer. How closely does their coloring resemble real human veins?	Consider the veins of the IV Arm Trainer. How closely does their arrangement (branching, location relative to landmarks) resemble real human veins?	Consider the skin of the IV Arm Trainer. How closely does its color (or "skin tone") resemble real human skin?	How would you rate the fidelity of the vein(s) during palpation?
	n	7	7	7	7
PractIV	Median	87	70	68	64
	Mean	82.71	68.57	71.86	65.71
	SD	15.62	24.60	13.83	17.18
Commercial	Median	18	72	40	36
	Mean	24.14	68.71	41.86	33.71
	SD	23.52	25.69	28.70	19.21
Wilcoxon	W		12.0		1.0
	p (two–tailed)		0.8125		0.0312
t-test	T Stat	4.41	-0.011	3.01	3.15
	P(T<=t) two-tailed	0.0045	0.0992	.024	.019

TABLE V

SUBJECT MATTER EXPERTS' PERCEPTIONS OF ANATOMICAL FIDELITY OF COMMERCIAL AND PRACTIV IV ARM TRAINERS - CONTINUED

Trainer		How would you rate the fidelity of the needle insertion into the vein?	How would you rate the fidelity of the soft tissue of the forearm?	How would you rate the fidelity of the IV Arm Trainer's wrist mobility?	How would you rate the fidelity of the IV Arm Trainer's elbow mobility?
	n	7	7	6	7
PractIV	Median	60	54	29	27
	Mean	59.29	55.57	37.7	32.86
	SD	25.71	19.44	20.12	18.25
Commercial	Median	29	13	1	4
	Mean	29.86	17.86	9.7	11.57
	SD	23.46	13.17	17.83	16.81
Wilcoxon	W	0.0		0.0	0.0
	p (two–tailed)	0.016		0.31	0.0156
t-test	t Stat		7.40		
	P (two-tailed)		0.0003		

6. Discussion

This research focuses on addressing limitations in IV placement training by developing and validating a modular, anatomically accurate IV arm trainer. Through the integration of the user-centered design process[11], CREST's expertise in medical simulator development, and additive manufacturing methods to produce compliant lattice structures, the PractIV model was created to provide a more realistic and clinically valuable training tool. Compared to the commercial trainer, PractIV achieved significantly higher ratings in several domains of realism, including vein coloring ($p = 0.0045$), skin tone ($p = 0.024$), vein palpation fidelity ($p = 0.019$), soft tissue fidelity ($p = 0.0003$), and needle insertion fidelity ($p = 0.016$). Experts also rated

PractIV higher in its educational utility, with higher scores for potential to train in IV access to a level consistent with professional competence ($p = 0.043$) and likelihood of curriculum adoption ($p = 0.031$). Lastly, the System Usability Score of the commercial trainer received an average SUS score of 49.72 (SD ± 17.74), Scoring a "Usability Concerns Requiring Revision", whereas the PractIV trainer achieved a score of 73.61 (SD ± 14.95). This is characterized as "Acceptable" as a performance rating for the SUS (See Table III for reference). These findings suggest that the approach outlined in this thesis can be utilized to produce more clinically relevant training tools that better prepare clinicians for real-world challenges.

The results of this study should be interpreted in the context of a limited body of published usability research on IV arm placement trainers. While direct comparisons are scarce, findings can be considered alongside broader work in medical simulation, where numerous studies have demonstrated that simulation improves clinical skills, enhances patient safety, and leads to better clinical outcomes compared to traditional training methods[17]. It is important to note, however, that the value of high-fidelity simulation may vary depending on learner experience; for example, novice trainees may benefit more from simplified models when first acquiring basic skills, as experience with high fidelity simulation (HFS) can lead to inflated self-confidence which is an undesirable effect in educational programs, due to a positive link between overconfidence and risk-taking behavior[16]. whereas advanced learners – such as experienced clinicians looking to build upon their skills, are more likely to benefit from exposure to higher fidelity models, within more complex scenarios[18]. This highlights the need for thoughtful design of IV training models that balance fidelity with learner readiness, ensuring both effective skill development and safe translation into clinical practice.

While PractIV outperformed the commercial trainer in most areas, vein arrangement realism (branching and relative position to landmarks) did not differ significantly between models ($p = 0.8125$). This result highlights an opportunity for further refinement in anatomical fidelity, possibly through the implementation of more vein channels. From the posted advertisements on the Commercial trainer [27] the trainer has 8 tubes used as vein channels, compared to only two in the current PractIV prototype. Expanding the number of venous access sites in future iterations could improve the realism of vascular branching and provide learners with greater opportunities to practice clinical decision-making in more varied scenarios.

Limitations

Several limitations of this study should be acknowledged. First, the sample size of subject matter experts was relatively small ($n = 6–7$), which limits the statistical power of the analyses and the generalizability of the findings. Second, participants were not blinded to the purpose of the study or the models being compared, which may have introduced bias into their evaluations. Additionally, the study was conducted with the researchers present in the room, which could have influenced responses through subtle cues or observer effects.

Another limitation is that the evaluation was based on expert perceptions rather than direct training outcomes. While subject matter experts provided valuable insight into anatomical realism, usability, and educational utility, the study did not measure the effect of PractIV on learner performance. As such, it remains unclear whether the improved ratings observed would translate into measurable differences in student training or clinical skill acquisition.

Finally, the scope of anatomical variations tested was limited. Although the modular design was intended to allow for interchangeable components and greater diversity in patient

scenarios, only a single configuration was evaluated in this study. Further testing with expanded anatomical variations, repeated use durability studies, and assessments across different learner populations will be needed to more fully establish the trainer's effectiveness and long-term utility.

Future Directions

One important direction for future work is a training effectiveness study to determine whether the improvements in anatomical realism and usability observed with PractIV translate into measurable differences in learner performance. Such studies could compare student outcomes—such as IV placement success rates, number of attempts, and confidence—between cohorts trained on PractIV and those trained on existing commercial models.

In addition, there is an opportunity to expand the model's scope through integration with full-body simulators. Embedding the trainer into complex, team-based simulation scenarios would allow evaluation of its performance when IV placement occurs alongside other patient care tasks. This approach would more closely replicate the multitasking and dynamic environments encountered in clinical practice, allowing students to integrate technical and non – technical skills such as communication and teamwork, better preparing students for real-world situations[17].

This work demonstrates the development of compliant lattice structures, guided by user-centered design and additive manufacturing, to produce a modular IV arm trainer that is both realistic and clinically valuable. PractIV outperformed a commercial model in key domains of realism, usability, and educational value, addressing gaps in current training tools and aligning with broader efforts in medical simulation to improve patient outcomes through enhanced

fidelity. By highlighting both the strengths and areas for improvement, this thesis provides a foundation for future research and positions PractIV as a promising next-generation solution for IV placement training.

This thesis presented the development and evaluation of PractIV, a next-generation intravenous (IV) training model designed to address the limitations of existing simulators. By integrating modular layers - a 3D-printed thermoplastic polyurethane (TPU) lattice, and silicone sleeve - the trainer successfully replicated key aspects of human tissue compliance and venous anatomy. A pressurized fluid system provided realistic flashback and haptic feedback during cannulation, while compatibility with the MoHSES™ full-body simulator enabled seamless use in immersive training scenarios. Together, these features positioned PractIV as an accessible, durable, and adaptable platform for IV placement training.

The comparative evaluation in the study performed demonstrated that subject matter experts rated PractIV higher than a commercial model in terms of anatomical realism, usability, and perceived educational value. These findings highlight the potential of additive manufacturing and user-centered design approaches to advance medical simulation tools and improve clinical training outcomes.

While the study was limited by its small sample size, reliance on expert perception rather than learner outcomes, and testing of only a single anatomical configuration, the results provide a strong foundation for continued research. Future work should focus on evaluating the trainer's impact on the training effectiveness of the model, expanding the range of anatomical variations, and integrating the device into team-based, full-body simulation environments.

In summary, PractIV was built by translating foundational concepts into a high-fidelity, modular, and clinically relevant trainer. Through its technical advancements and design philosophy emphasizing clinician needs, adaptability, PractIV represents a significant step toward improving the fidelity and effectiveness of IV placement training, ultimately supporting safer and more effective patient care.

7. Conclusions

a. Summary of Contributions

The development of *PractIV* was a collaborative effort made possible through the support and expertise of numerous individuals at the University of Washington. Significant contributions were made by Courtney Cho, B.S. in Human Centered Design & Engineering, who co-led the design, development, and validation process as part of her senior capstone project, as well as continuing work after graduation. Her work in user-centered research, design iteration, and early testing was integral throughout the entire process.

Key guidance was provided by Shawn Swanson, Per Reinhall, Eric Seibel, and Michael Malone through the Engineering Innovation in Health (EIH) program. Their combined expertise in medical device development, clinical simulation, product commercialization, and prototyping played a critical role in shaping the direction and execution of the project.

Expert technical guidance and laboratory support were provided by DJ Traina and Jason Speich from the Center for Research in Education and Simulation Technologies (CREST). Their extensive experience in clinical simulation technologies and anatomical modeling directly informed key aspects of the project, including the mechanical design, material selection, and integration of the trainer with existing simulation systems.

Victoria Roach, also from CREST, brought deep expertise in study design and clinical education research. Her guidance was instrumental in running the usability study, outlining the methods, data collection, and securing IRB approval. Victoria's motivating enthusiasm helped drive the evaluation process forward, fostering a productive environment for collecting user feedback and translating it into rapid design improvements with our pilot usability study.

Lastly, the nurses and clinicians at the University of Washington Medical Center (UWMC). Their willingness to share clinical experiences, demonstrate IV placement techniques, and provide candid feedback on prototype evaluations directly shaped the design of the PractIV trainer. By grounding the development process in their practical knowledge, this project was able to identify critical shortcomings of existing IV simulators and prioritize features—such as realistic vein palpation, variable insertion sites, and modularity—that matter most in clinical training.

b. Clinical and Educational Implications

Intravenous (IV) catheter placement remains one of the most common yet challenging clinical procedures, requiring precise technical skill, anatomical knowledge, and sound decision-making. Through our interviews, experts found that the traditional IV arm trainers, while widely used, often fall short in replicating the anatomical variability, tactile feedback, and patient diversity encountered in real clinical settings. As a result, learners may become proficient in simulated environments yet remain underprepared for the complexities of practice. These limitations underscore the need for more realistic, adaptable, and inclusive training solutions. The PractIV project was developed in direct response to this gap, with the goal of creating a modular, high-fidelity IV training model that integrates seamlessly with existing simulation systems, enhances educational realism, and ultimately supports safer, more effective patient care.

The PractIV model developed in this work offers full venous access from the hand through the forearm and above the elbow, enabling multiple insertion sites and more realistic clinical scenarios. A closed-loop, pressurized fluid system provides visual flashback, enhancing user feedback and supporting proper cannulation technique. The combination of silicone sleeves with a 3D-printed TPU lattice structure replicates tissue compliance, improving realism during palpation and needle insertion. Additionally, integration with a MoHSES™-compatible manikin ensures that the trainer can be used in immersive, scenario-based simulations, which traditional IV arm trainers do not support. Its modular design further supports part replacement, maintenance, and iterative upgrades, making the system adaptable and sustainable for long-term educational use.

While many existing IV trainers are limited to basic venipuncture practice, the high-fidelity design of PractIV supports more complex and clinically relevant training scenarios. Full venous access from the hand through the forearm and above the elbow enables learners to practice site selection, escalation strategies, and troubleshooting when faced with difficult or failed cannulation skills that are rarely addressed with traditional trainers. By incorporating anatomically realistic tissue compliance and vein behavior, the model challenges learners to rely on palpation, visualization, and clinical judgment rather than predictable landmarks.

Integration with the MoHSES™ full-body simulation system further extends the scope of training by embedding IV placement into immersive, team-based clinical environments. This can provide students with experience with the pressures of time-sensitive decision-making, communication, and patient safety considerations—factors that are difficult to replicate with stand-alone IV arms.

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9. Appendices

I. IRB

UNIVERSITY of WASHINGTON
HUMAN SUBJECTS DIVISION

DETERMINATION OF EXEMPT STATUS

June 23, 2025

Dear Victoria Roach:

On 6/23/2025, the University of Washington Human Subjects Division (HSD) reviewed the following application:

Type of Review:	Modification; Update
Title of Study:	Assessing usability of an IV Arm trainer for applications in medical education: Perspectives from instructors, technicians and students
Investigator:	Victoria Roach
IRB ID:	MOD00022934
Funding:	None

Exempt Status

HSD determined that your proposed activity is human subjects research that qualifies for exempt status (Category 1 and 101). This determination may or may not be based on the Limited IRB Review process.

- This determination is valid for the duration of your research.
- This means that your research is exempt from the federal human subjects regulations, including the requirement for IRB approval and continuing review.
- **Depending on the nature of your study, you may need to obtain other approvals or permissions to conduct your research. For example, you might need to apply for access to data or specimens (e.g., to obtain UW student data). Or you might need to obtain permission from facilities managers to approach possible subjects or conduct research procedures in the facilities (e.g., Seattle School District; the Harborview Emergency Department).**
- HSD does not make determinations on behalf of other institutions. If other institutions are involved in the research, they may need to make their own determination or they may decide to be guided by our determination.
- If you obtain federal funding or other support for this research, inform HSD immediately.

Only certain types of changes to exempt research require that you submit a modification in Zipline. For information about what changes require a Modification, refer to the guidance on Exempt Research. If you are unsure if your proposed changes require a modification, contact your HSD team before preparing the modification.

4333 Brooklyn Ave. NE, Box 359470 Seattle, WA 98195-9470
main 206.543.0098 fax 206.543.9218 hsdinfo@uw.edu www.washington.edu/research/hsd

HSD does not review or approve consent plans and consent materials for exempt research. Researchers are still responsible for providing subjects with information about the research prior to their agreement to participate. Refer to the guidance on Exempt Research for details about what information should be provided. You may wish to use the optional Exempt Consent Template as a guide.

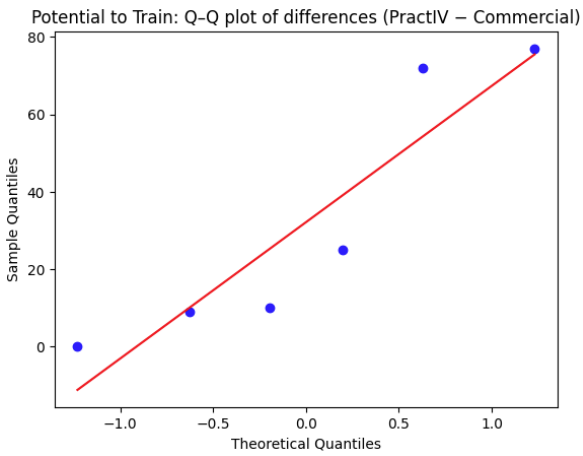
Thank you for your commitment to ethical and responsible research. We wish you great success!

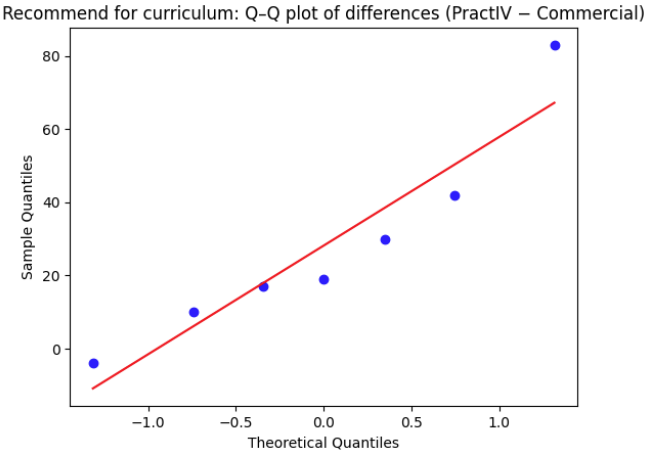
Sincerely,

Marya Kinsler, MS
Administrator
206-543-0471
maryaj@uw.edu

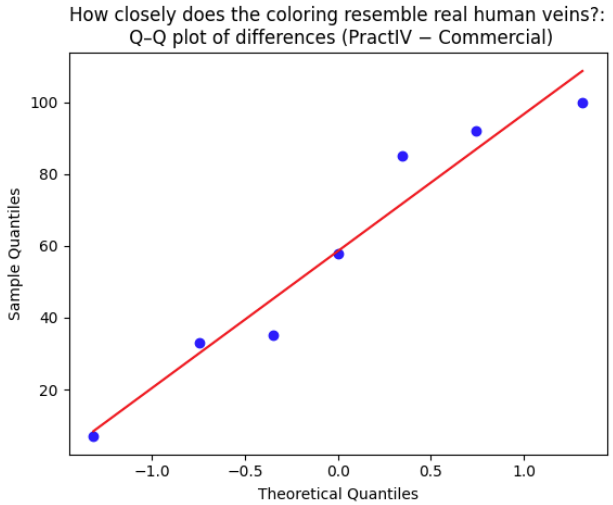
II. QQ Plots

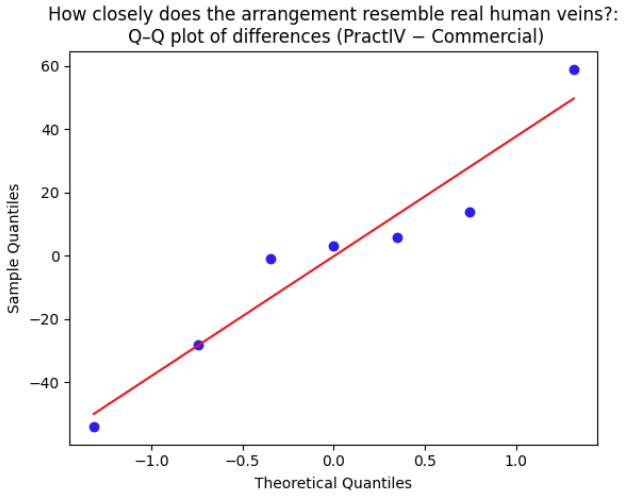
Educational Utility

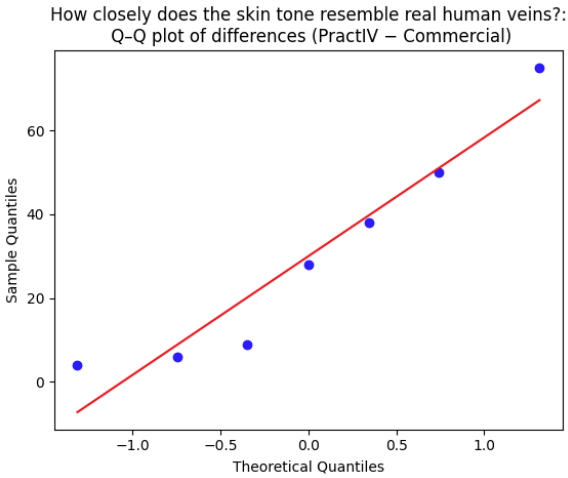


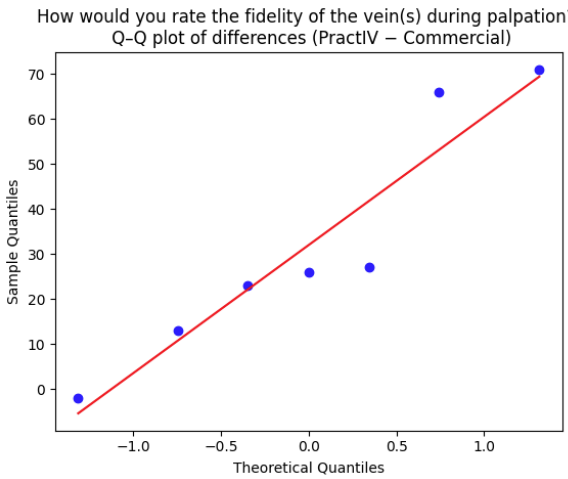


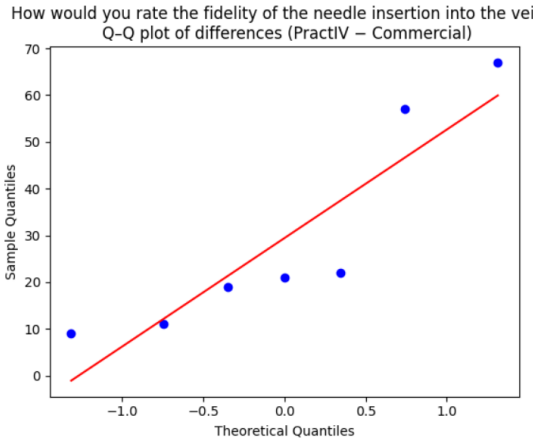
Anatomical Fidelity

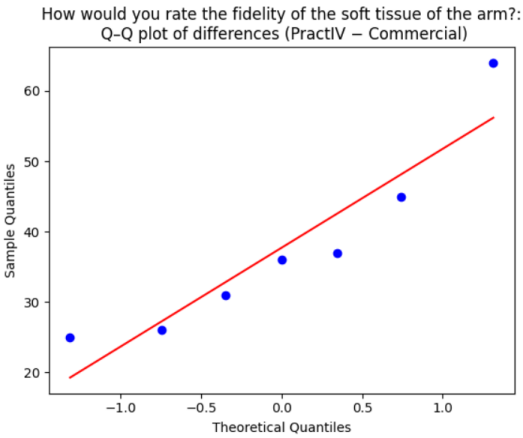


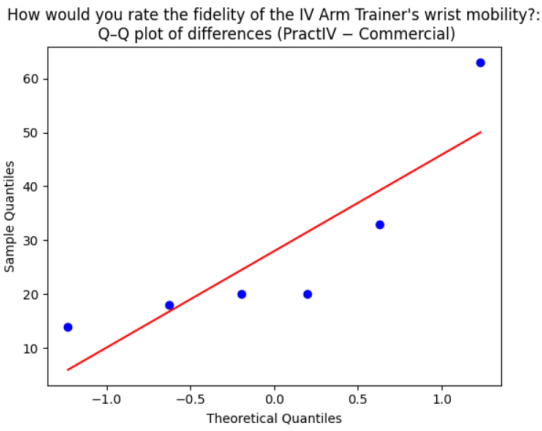


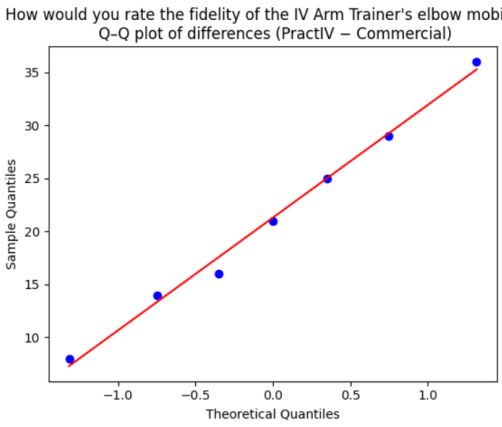

How closely does the skin tone resemble real human veins?:
Q–Q plot of differences (PractIV − Commercial)
Sample Quantiles
Theoretical Quantiles


How would you rate the fidelity of the vein(s) during palpation?:
Q–Q plot of differences (PractIV − Commercial)
Sample Quantiles
Theoretical Quantiles


How would you rate the fidelity of the needle insertion into the vein?:
Q–Q plot of differences (PractIV − Commercial)
Sample Quantiles
Theoretical Quantiles


How would you rate the fidelity of the soft tissue of the arm?:
Q–Q plot of differences (PractIV − Commercial)
Sample Quantiles
Theoretical Quantiles


How would you rate the fidelity of the IV Arm Trainer's wrist mobility?:
Q–Q plot of differences (PractIV − Commercial)
Sample Quantiles
Theoretical Quantiles


How would you rate the fidelity of the IV Arm Trainer's elbow mobility?:
Q–Q plot of differences (PractIV − Commercial)
Sample Quantiles
Theoretical Quantiles

III. Raw Data from Usability Study

Educational Utility

How likely are you to recommend this IV Arm Trainer for incorporation into a formal nursing or medical training curriculum?		In your view, does this trainer have the potential to train skills in IV access to a level consistent with professional competence?	
Commercial	**PractIV**	**Commercial**	**PractIV**
64	74	62	72
75	71	63	63
71	90	54	63
54	71	34	59
26	56	6	78
35	77	21	98
16	99		

Anatomical Accuracy

Consider the veins of the IV Arm Trainer. How closely does their coloring resemble real human veins?		Consider the veins of the IV Arm Trainer. How closely does their arrangement (branching, location relative to landmarks) resemble real human veins?		Consider the skin of the IV Arm Trainer. How closely does its color (or "skin tone") resemble real human skin?		How would you rate the fidelity of the vein(s) during palpation?	
Commercial	**PractIV**	**Commercial**	**PractIV**	**Commercial**	**PractIV**	**Commercial**	**PractIV**
36	69	64	70	54	60	66	79
0	100	79	25	18	68	38	36
56	91	72	86	40	78	37	64
51	58	85	57	59	63	36	59
18	76	64	67	31	59	36	62
2	87	18	77	2	77	3	69
6	98	99	98	89	98	20	91

How would you rate the fidelity of the needle insertion into the vein?		How would you rate the fidelity of the soft tissue of the forearm?		How would you rate the fidelity of the IV Arm Trainer's wrist mobility?		How would you rate the fidelity of the IV Arm Trainer's elbow mobility?	
Commercial	**PractIV**	**Commercial**	**PractIV**	**Commercial**	**PractIV**	**Commercial**	**PractIV**
67	78	29	74	0	63	19	55
9	30	9	45	0	33	1	26
29	96	36	73	45	63	1	30
51	60	29	54	0	20	47	61
37	59	6	37	2	22	4	12
4	23	3	29	11	25	3	19
12	69	13	77			6	27