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Number of words: 3972
Number of figures and tables: 7
Number of equations: 0
Number of supplements: 1
Number of references: 8

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Abstract

Cardiac catheterization is a procedure that involves the insertion and maneuver of a catheter into a vein or artery. During this operation, X-rays are used to visualize the catheter. When undergoing a lateral X-ray, a patient's arms must be positioned overhead to give an unobstructed view of the abdomen. However, the current commercially available arm positioning device only fits adult patients. Therefore, pediatric cardiologists create makeshift solutions by balancing patients' arms using readily available materials. The lack of a reliable pediatric alternative increases the risk of brachial plexus injuries and reduces procedure efficiency. By observing pediatric catheterization, using computer-aided design, and 3D printing, we built a device that accommodates this patient population by extending and retracting to fit patients of ages zero to twenty-one. The base of our pediatric device attaches to the side of the operating table mat. A second piece attaches to the base using an interference fit, sliding in and out from the side of the mat 2.8 cm to 9.7 cm, accommodating patients' shoulder width. A telescoping rod adjusts vertically 8.9 cm to 20.3 cm, adapting to the upper arm length of patients. Finally, the arm resting piece is positioned parallel to the mat and is 33.4 cm long, with strap loops that can secure patients with forearms as short as 2.4 cm. Virtual simulation testing showed that when a load of 50 N is applied to the final iteration of our device, the device displaces vertically less than 1 cm and will not permanently deform. After constructing our device, physical weight testing indicated that our device could support up to 6 lbs., which exceeds the average weight of an adult's forearm and hand. This confirms its suitability for securely supporting the arms of pediatric patients of various ages and sizes during catheterization.

Keywords: Cardiac Catheterization, Pediatrics, Patient Positioning, Medical Device Design

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Introduction

Heart disease is the number one cause of death in the United States, killing one person every 33 seconds (CDC, 2025). Cardiac catheterization is a procedure performed to both diagnose and treat various heart diseases with over a million procedures performed annually in the U.S. (Mozaffarian et al., 2015). The procedure involves the insertion of a thin, flexible tube called a catheter into a blood vessel through the groin or arm of the patient. The catheter is then maneuvered through veins and arteries toward the heart (Mount Sinai, n.d.). During this operation, the physician uses a lateral X-ray to visualize the position of the catheter as it moves through the body. To provide an unobstructed view of the catheter in the abdomen, the patient's arms must be securely positioned overhead.

Problem

Currently, there is only one commercially available device used to position patients' arms overhead, which is the *Overhead Arm Support* manufactured by Adept Medical (Figure 1). This product holds a patient's arms at the proper angle overhead during catheterization, helping avoid procedure inefficiencies. The device is made of durable, lightweight plastics that are radiolucent and easy to transport between operating rooms. However, this device only fits full grown adults.

The device only adjusts vertically and, even when fully retracted, it does not fit pediatric patients. Trying to force a small patient into the device increases their risk of brachial plexus injury, harming the nerves that connect the patient's spine, neck, shoulder, and arm. This product therefore

Fig. #1. Overhead Arm Support Device. The current commercially available device developed and manufactured by Adept Medical for use in catheterization procedures or other procedures in which lateral X-rays are necessary.

excludes pediatric patients and even some small adults. As a result, pediatric healthcare professionals currently use readily available materials, such as rolled up towels, foam blocks, straps, etc. to balance a pediatric patient's arms up and away from their body. However, these jerry-rigged solutions can be unstable, which creates a risk of the patient's arms falling or jerking while under anesthesia. We observed our advisor and pediatric interventional cardiologist, Dr. Michael Shorofsky, use these makeshift solutions during a catheterization procedure on an 8-month-old patient born prematurely. The healthcare professionals needed to readjust the patient three times throughout the procedure, which is inconvenient and increases the chance of patient injury. Therefore, pediatric cardiologists need a safe and reliable method of positioning patients' arms overhead during catheterization.

Project Aims

The goal of this project is to design and build a novel, adjustable arm positioning device for pediatric patients undergoing lateral X-rays during cardiac catheterization. We aim to construct a durable, radiolucent device that adjusts vertically and laterally to accommodate the shoulder widths, upper-arm lengths, and forearm lengths of patients ages zero to twenty-one and does not obstruct anesthesiologists' access to the patient. We also aim to consult with pediatric healthcare providers to verify the functionality and effectiveness of our design through multiple iterations and clinical testing.

Results

Identification of Design Constraints:

To determine the design specifications needed for our pediatric arm positioning device, we met with our advisor, Dr. Michael Shorofsky, to discuss the current standard of care and observe a catheterization procedure on an 8-month-old patient. We identified what characteristics of the current device were favorable and what problems existed through examination and discussion with healthcare professionals. For example, it is important that the device is radiolucent, meaning it is transparent on the X-ray imaging. The device's material should also be easily sterilized and lightweight. Our goal was for the device to be less than 5 lbs. for easy transportation between operating rooms. The device should also easily slide under the operating mat to be positioned properly, which has a thickness of 6.5 cm (Artis Icono, n.d.). It should not protrude from the edge of the mat to prevent impeding the healthcare professionals. It is ideal for the device to be completely open above the patient's head, unlike the current device, to allow anesthesiologists to connect the proper wires/tubing without obstruction.

As for the specific measurement constraints, it is necessary that the device can adjust to accommodate the shoulder width, arm height, and forearm length of various pediatric patients ages zero through twenty-one. Based on pediatric and adult arm measurements obtained through research, we identified our target range of dimensions for our prototype in the most retracted and most extended positions. The device should ideally extend perpendicular to the mat's edge 3.5 cm to 17.9 cm to accommodate patients' shoulder width (Verspyck et al., 1990; Fitness Volt, 2023). We aim to have the device adjust vertically 9.1 cm to 25.8 cm depending on patients' upper arm (above the elbow) length (Edmond et al., 2020). Additionally, our initial target range for the arm resting platform is 8.6 cm to 25.4 cm and we need adjustable straps to secure patients' forearms on this platform (Edmond et al., 2020). The data available for full-grown patients' upper arm and forearm lengths were limited to 17-year-olds, so our target patient population of up to 21-year-olds may be slightly larger than this research. However, the current standard of care would likely be suitable for these larger patients. Finally, our pediatric device needs to support a patient's arm weight. We identified the weight of the forearm and hand of a patient, which will be resting on the device's platform, to be equivalent to 2.52% of a person's body weight (Plagenhoef et al., 1983). Therefore, we aim for our device to withhold 6 lbs., which would be the forearm and hand weight of about a 238 lb. person, which is larger than most pediatric patients.

Design & Prototyping:

During the design process, we developed multiple iterations before reaching our final design.

First Iteration

During our initial brainstorm, we determined that the device would have three extension points to accommodate the shoulder width, arm height, and forearm length of pediatric patients. This consisted of three sections of the device: a base with an extension that moves perpendicular to the mat, a telescoping pole that moves up and down from the mat, and an arm resting platform that moves parallel to the mat.

Base: In the first design, the device had one base that would slide completely underneath the patient and mat. It would then come above the mat on either side of the patient, near their shoulders and head. There would be an interference fit piece that could slide perpendicular to the mat (y-axis) to adjust for a patient's shoulder width, sliding in for smaller patients and out for larger patients. We were unable to print the first iteration of the base since it was too long for the 3D printers available. This motivated us to split the base in half (left and right) for subsequent iterations.

Telescoping Pole: To achieve height adjustability and accommodate the upper arm length of patients, we brainstormed different mechanisms that would allow simple adjustments. We created a telescoping pole using three cylinders with 1 mm gaps in between each, so they could slide within each other, allowing the device to extend to three times its smallest height (Figure 2). The bottom telescoping cylinder was 3D printed directly on the base's sliding piece. Lining the inner diameter of each cylinder are ribbed levels in which the device can be further adjusted, allowing more than just three height positions. Each cylinder has a knob on its outer diameter that lies in the ribs of the larger cylinder it is positioned in. The poles need to be twisted to the open rail section to adjust up/down and twisted back to the ribbed section to lock the height in place.

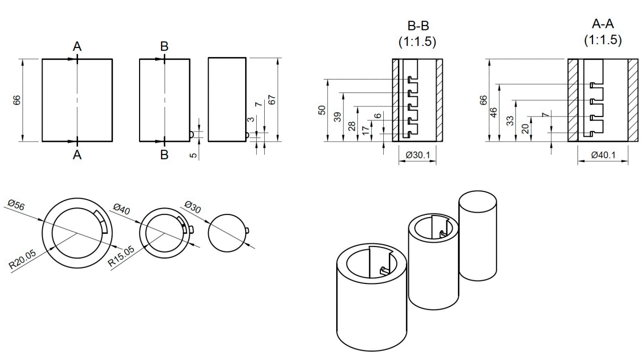

Fig. #2. Drawing of Telescoping Poles. The cross-sectional view of the telescoping poles highlights the locking mechanism allowing height adjustability.

Arm Resting Platform: The arm resting platform originally extended parallel to the mat (x-axis) by sliding with an interference fit. This was designed to accommodate the forearm lengths of various patients and had loops on either side to attach adjustable straps to secure the patient's arms in place. The platform was designed wide enough to fit all forearm diameters. The bottom part had a hollow rail, and the top part had a small knob that slid within the rail. We had to design the attachment loose enough so that we could 3D print the two parts separately and attach them afterwards. However, when the piece was extended, the top part would fall off the bottom part's rail and was not stable in place, even with the rail and knob mechanism.

A full visualization of our first iteration with the axes referred to is seen in Figure 3A.

Second Iteration

Based on our initial 3D printing observations, we improved the design of our device, as shown in Figure 3B.

Base: After review, we chose to split the base into a left and right piece. This made 3D printing the device possible and would make sliding the device under the mat and patient easier for healthcare professionals. We decided to focus on iterating the right side of the device throughout our project to limit wasting materials. We then split the right side of the device into two pieces (top and bottom) to speed up the printing process and minimize the amount of supports needed. We also made the y-axis interference sliding piece less bulky because it was larger than necessary, however it ended up being too tight and difficult to slide.

Telescoping Pole: In the second iteration of the device, the telescoping pole did not undergo any major changes. The gap between the outer diameter of each cylinder and its corresponding larger cylinder was still 1 mm. This, however, proved to be too large of a gap between each cylinder and caused the device to lean extensively when in its fully extended position. Additionally, the ribs within the cylinders and the knobs that held the cylinders in place had 90º edges, causing some difficulty when making height adjustments.

Arm Resting Platform: We lengthened the bottom piece of the platform beyond its hollow rail to hopefully support the top piece when it is extended. We also made the knob on the top piece wider and taller so that it would fill more of the hollow rail for stabilization. However, even with these adjustments, the top piece continued to tilt downwards and fall off the bottom piece when it was extended.

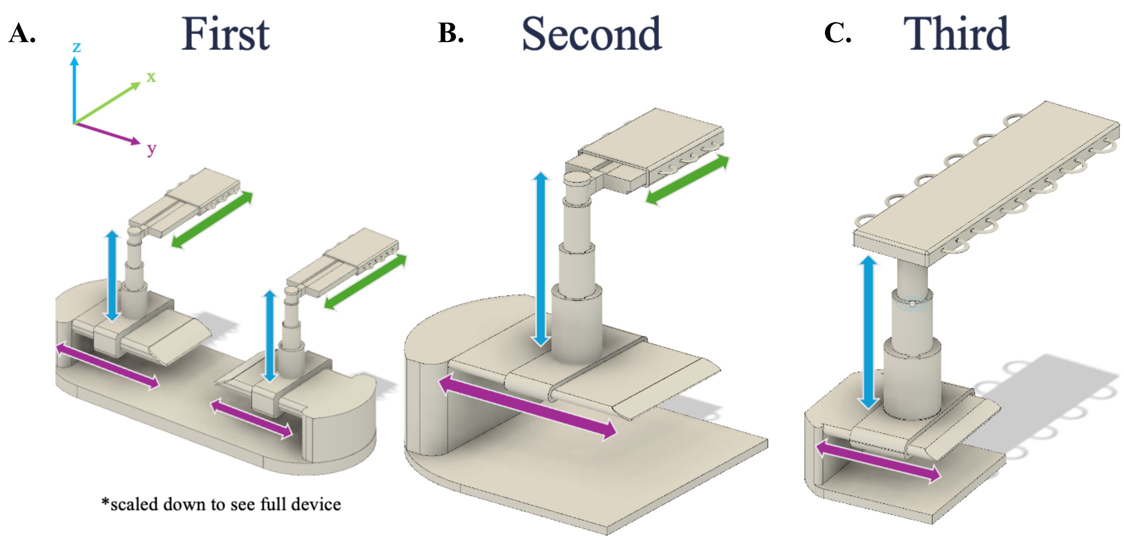

Fig. #3. Three Separate Iterations of Our Device. A. Our first design of the device, B. Our second iteration and design of the device after alterations, and C. Our third and final iteration of the device.

<u>Third Iteration</u>

After 3D printing the second iteration of our device and bringing it to the catheterization lab to see how it functions on the operating mat, we made additional adjustments for our final iteration (Figure 3C).

Base: We realized the dimensions of our base were larger than necessary. Therefore, we halved the length, width, and height of the base so that it is less bulky and will fit properly around the edge of the operating mat. A visualization of the differences between our second and third iterations on the catheterization lab mat are shown in Figure S1. Due to the smaller structure, we decided to 3D print it as one, instead of a top and bottom piece. We also loosened the fit of the y-axis sliding piece so that it could be adjusted easier by healthcare professionals. The final measurements it could be adjusted to are 2.8 - 9.7 cm from the mat's edge. Additionally, the gap between the bottom and the top of the base is 5.25 cm, which successfully attaches to the side of the mat.

Telescoping Pole: The gap between the outer diameter of each cylinder and its corresponding larger cylinder was reduced to 0.1 mm. This contributed to a greater level of stability while the device was in the fully extended position, preventing the lean that was present in the second iteration. In addition, the edges of the inner ribs and knobs were made rounder, allowing the device to glide between positions with greater ease and improve the overall vertical adjustment of the device. The final measurements it could be adjusted to are 8.9 - 20.3 cm vertically from the mat, with nine intermittent adjustments.

Arm Resting Platform: To improve stabilization, we decided that if the device accommodates patients with longer forearms, this piece does not need to be retracted for smaller patients. Instead, healthcare professionals can move the adjustable straps to the loops that best accommodate the forearm length of their patient. Therefore, we decided to remove the interference fit sliding rail and make the piece a constant length. The final length is 33.4 cm, with six strap loops going down to 2.35 cm.

The final iteration resulted in a stable, user-friendly device that is radiolucent and transitions easily between retracted and extended states (Figure 4). It is 0.8 lbs. and easily portable. Each design iteration contributed to this success by improving usability and structural stability.

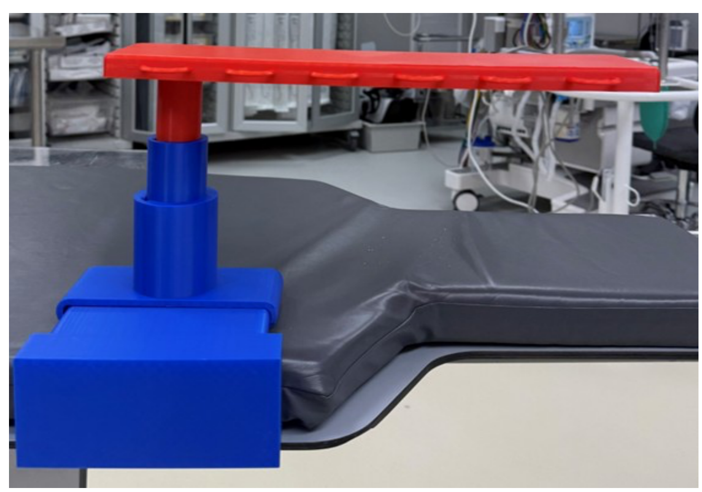

Fig. #4. Third Iteration in Catheterization Lab. The base of the device fits seamlessly on the edge of the mat. The telescoping pole can slide on the base perpendicular to the mat and be adjusted vertically. The arm resting platform is positioned properly for a patient with convenient strap loops.

Testing/Device Evaluation:

Virtual Simulations

To evaluate the success of each iteration before 3D printing, we performed virtual simulations throughout the process. These simulations evaluated stress, strain, displacement, and the safety factor as different levels of force were applied to the third iteration of our device when it was fully extended. Stress and strain analysis showed that our device remains in the elastic region of the stress strain curve, indicating that it can withstand 50 N without permanent deformation. This is shown by the linear slope in Figure 5A. Additionally, force vs. displacement testing indicated that the third iteration of the device would displace less than 1 cm vertically under a 50 N load applied to the center of the arm resting platform, with a maximum displacement of 8.96 mm, as shown in Figure 5B. Lastly, during these simulations the safety factor remained greater than 1, suggesting that the device is structurally sound and is unlikely to fail when used. It is important to note that 50 N is equivalent to over 11 lbs., which is greater than the force applied by most adult forearms and hands.

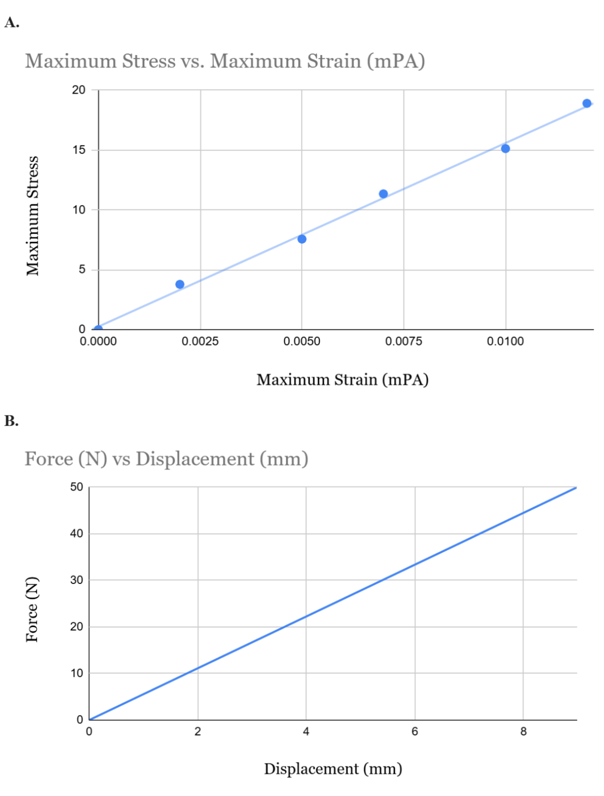

Fig. #5. Virtual Simulation Results. A. Stress Strain Curve when 50N is applied to the fully extended third iteration of our device. B. Force vs Displacement plot that shows the vertical displacement of the fully extended third iteration of our device when increasing load is applied.

Physical Simulations:

We performed physical weight testing on the second and third iterations of our 3D printed device, both when fully retracted and fully extended. We measured the vertical displacement of the arm resting platform as 1 lb., 2 lbs., 4 lbs., and 6 lbs. were applied. As anticipated, both devices displaced more when more weight was applied to them. When greater weights, such as 4 lbs. and 6 lbs., were applied, however, the third iteration consistently displaced less than the second iteration, as shown in Figure 6. Most notably, the second iteration failed when 6 lbs. were applied since the interference sliding piece cracked on the base.

To determine whether the displacement difference between iterations was significant, a two-sample t-test was conducted on the displacement data collected using the average displacement of the four applied weights for each iteration. The mean displacement for the second prototype (2.82 cm) was greater than that of the third (1.38 cm), but these differences were not statistically significant, with a p-value of 0.14. Although the difference in average displacement is not statistically significant between the two iterations, the second iteration was not able to withstand the heaviest weight in the fully extended position without deformation, while the third iteration remained in the elastic region. Therefore, the third iteration, while not significantly more durable with lighter weights (<4 lbs.), showed greater success in its ability to withstand heavier weights, proving greater overall durability. Performing more testing with larger sample sizes and higher weights may prove this difference to be significant, as the second iteration would likely continue to fail. Additionally, the third iteration features a less bulky and more functional design, making it favorable across many aspects.

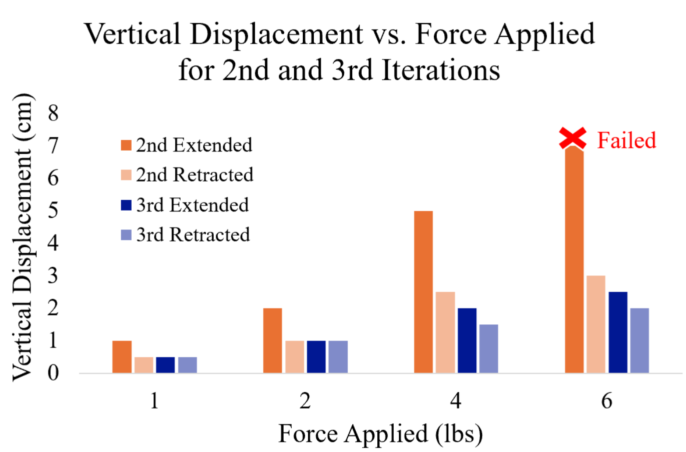

Fig. #6. Physical Weight Testing Results. The vertical displacement measured after 1lb., 2 lbs., 4 lbs., and 6 lbs. were applied to the second and third iterations in their most retracted and most extended states.

<u>Discussion</u>

Significance

Catheterization remains a very popular procedure used to diagnose and treat heart disease. The pediatric population does not have a current device to effectively position a patient's arms to safely perform the procedure. To mitigate this, we successfully developed a device that can accommodate pediatric patients ages zero to twenty-one. Our device is made of PLA, which is radiolucent, sterile, and lightweight. Our goal was for the device to be under 5 lbs., and it is only 0.8 lbs., which is very portable for healthcare professionals. The base of our device has a gap height of 5.25 cm, which is designed to fit snug on the mats used in the catheterization labs at UVA, which are 6.5 cm high and easily compressed (Artis Icono, n.d.). The current device used for adults is positioned at the top of the mat, obstructing the anesthesiologist’s view and hindering procedural efficiency. In contrast, our device is designed to be inserted along the sides of the mat, allowing all healthcare professionals in the catheterization lab to perform their roles without interference. In addition, our device does not protrude from the side of the mats.

As for our device’s specific measurements, it can slide 2.8 - 9.7 cm from the mat’s edge. Although this does not go as far inward as the initial goal of 17.9 cm, it can be positioned toward the head of the mat, which is narrower than the rest of the mat, to accommodate infants. Our device rises vertically 8.9 - 20.3 cm, which accommodates most of our target range. People with longer upper arm lengths would probably fit in the current standard of care adult device. Our device’s arm resting platform is 33.4 cm, with six strap loops going down to 2.35 cm. This range is larger than we initially strived for and accommodates all the anticipated patients. All these measurements can be seen in greater detail in Figure 7. Finally, the weight of a forearm and hand is around 2.52% of total body weight (Plagenhoef et al., 1983). Our final device can successfully hold up to six pounds without failure, as mentioned in the results section. This equates to a person of around 240 lbs., meaning that our device can successfully support pediatric patients and even most adults.

In conclusion, the final iteration of our device design meets almost all the original design constraints. This device would improve the reliability of patient positioning during pediatric catheterization procedures. Further, it would be helpful during additional procedures that require the use of lateral X-rays. Not only does it provide a safer, more convenient method of positioning for pediatric healthcare providers, but it also fits the dimensions of most adult patients.

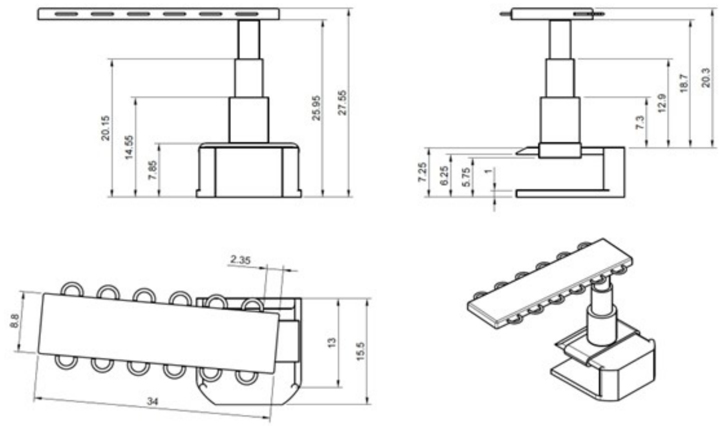

Fig. #7. CAD Drawing of the Third Iteration Fully Extended Design. This shows the specific measurements of our final design when constructed.

Limitations:

The greatest limitations we faced during our prototyping process was the capability of the UVA Scholars’ Lab Makerspace 3D printers and the time constraint of our project. Many of our 3D prints were very lengthy due to their size, some being 16+ hours. Some situations we ran into during this process were the printers being stopped by other students looking to use them, the spools of PLA running out, and the extruder overheating. The speed of our iteration process was dependent on how quickly we could complete each print. This is also why we ultimately decided to only iterate on the right side of the device, focusing on getting the mechanisms correct before printing the second half. Along with this, we were limited in specific materials that we could bring into the catheterization lab, meaning that our physical weight testing had to occur outside of the clinical environment.

Future Work:

Now that we have a stable design that can withstand the max weight of a pediatric forearm and is simple to set up, the next step is to print the left side of the device. Once both sides are built, we would add adjustable, radiolucent straps to the arm resting pieces to secure patients’ forearms in place. We could also add radiolucent padding on the arm resting pieces and on the top of the base where patients’ arms and shoulders may rest. After fully constructing the device, we would write user instructors for the healthcare professionals positioning the device for patients. These instructions would include where to position the base under the patient, how to extend/retract each section of the device, what the ideal positioning is to limit brachial plexus injuries, and where to best place the adjustable straps on the patient’s forearm. At this point, it would be necessary to test the functionality of our device through clinical testing, particularly as it compares to the current standard of care. We would survey healthcare professionals about how easy to use each of the devices are and how confident they feel in them during the procedures. We would also measure the number of device readjustments needed during a catheterization procedure on various patients to quantitatively determine if our device is more reliable for pediatrics. Finally, we would continue to iterate and repeat this process based on the results of our clinical testing. One iteration we have already anticipated is extruding the base further to allow the device to slide further away from the mat's edge, accommodating patients of smaller shoulder widths.

Materials and Methods

Prototype Design & Physical Model

All iterations of the arm positioning device were modelled using computer-aided design (CAD) software, Autodesk Fusion 360. We designed three main sections of our device, the base, the telescoping pole, and the arm resting platform. This began with a dimensioned sketch that was then extruded and filleted to provide the final component. All of the components within the sections were positioned together using assembly tools.

The iterations were 3D printed using polylactic acid (PLA) on an Original Prusa XL 3D Printer in the UVA Scholars' Lab Makerspace. PLA is radiolucent, stable, and easily sterilized. We 3D printed using 15% infill for sufficient strength while also minimizing the duration of our prints. We used organic supports everywhere throughout our device to avoid compression and to hold up parts that would otherwise collapse during printing. Components of the device were printed separately and then attached together through various mechanisms, including interference fits and telescoping poles. Our third iteration consisted of 4 total components (base, sliding piece (with bottom telescoping cylinder), middle telescoping cylinder, and arm resting platform (with top telescoping cylinder). Our second iteration consisted of 6 components as the base and arm resting piece were each split in 2. General observations of each 3D printed component were made and used to inform iteration improvements to our CAD design.

Device Testing

Before 3D printing, the functionality of the device was tested virtually through simulations in Autodesk Fusion 360. These tests evaluated stress, strain, displacement, and safety factors as force was applied. These tests were performed on the third iteration of our device when fully extended with intervals of 10N of force applied starting at 0N and ending at 50N. The force was applied to the middle of the top of the extended arm resting platform. Stress and strain were used to create a stress vs strain graph and determine if the device remained in the elastic region or reached a yield stress point. Force vs displacement was used to determine the overall movement of the top piece and see if the support was strong enough to withstand the weight of an arm. Displacement was measured vertically from the end of the extended arm resting platform. The safety factor was assessed to confirm that the device can endure the anticipated load along with an additional margin for overstress or unexpected conditions.

After 3D printing and assembling the second and third iterations of our device, we brought them into the catheterization laboratory for observation. We also completed physical weight testing where we placed sandbags of 1 lb., 2 lbs., 4 lbs., and 6 lbs., to the middle of the arm resting platform, where a patient's forearm would be placed, and measured the vertical displacement of the outermost corner of the arm resting platform. We completed this procedure for the second and third iterations when they were most retracted, to simulate for the smallest patients, and when they were most extended, to simulate for the largest patients. If the device cracked, we considered that a failure.

End Matter

Author Contributions and Notes

A.G.H, A.J.N, and K.S.R all contributed equally to the background research and original design brainstorm. A.J.N focused on the design of the base of the device. A.G.H focused on the design of the telescoping pole. K.S.R focused on the design of the arm resting platform. A.J.N ran the virtual simulations. A.G.H and K.S.R ran the physical simulations of the device. All authors contributed to the 3D printing of the device and observed the device in the catheterization lab. All authors wrote the paper.

The authors declare no conflict of interest.

Acknowledgments

We would like to give special thanks to our Capstone advisor, Dr. Michael Shorofsky, and to our Capstone instructor, Dr. Timothy Allen, for supporting us throughout the duration of this project.

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Supplemental Material

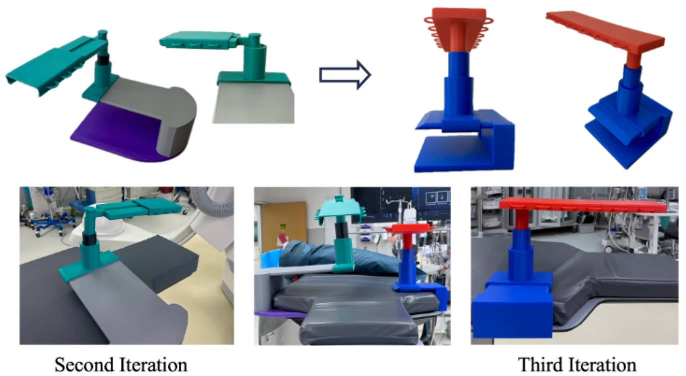

Fig. S1. 3D Printed Prototype of Second & Third Iterations. This shows the improvement of our device throughout the design process. The third iteration fit better on the catheterization lab mat and was more stable.