Development of a Haptic Feedback System with Real-Time Force Monitoring for Enhanced Catheter Placement Training in VR Environments

VR HEAL Hardware Team

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Introduction

Catheter placement is a critical skill in medical practice, particularly in fields such as interventional radiology, where precision and care are paramount to prevent complications such as artery puncture or damage to surrounding tissues. Mastering the tactile feedback involved in catheter insertion and dilation is essential for medical professionals, but current training tools often lack the realism needed to replicate the delicate balance between force and resistance experienced during actual procedures. This project aims to bridge that gap by developing an advanced haptic feedback system for catheter simulation, which will help medical students gain an intuitive understanding of the force dynamics involved in catheter placement, ultimately improving their skills and patient safety.

The core purpose of this project is to design a product in the form of a haptic glove that can track a user's hand movements and the force applied during catheter insertion. The system will not only provide real-time feedback to guide proper catheter placement but also simulate the resistance encountered when inserting wires through catheters. By accurately tracking hand position, pressure, and the interaction between the catheter and simulated anatomy, this device will give users the ability to visualize and understand how much force they are applying, offering precise feedback to avoid overexertion and potential vessel damage.

The project will leverage a combination of hardware and software components to create a highly immersive and realistic virtual reality (VR) environment. The metal guide wire and catheter components will be simulated through a combination of physical materials and sensors, while force feedback mechanisms will mimic the feel of pushing the catheter through blood vessels, giving medical trainees a tactile understanding of how much force is safe. Through the use of piezoelectric sensors and micro-actuators, the system will provide resistance feedback that simulates the natural resistance of human tissues, ensuring that the simulation mirrors the experience of a real-life procedure. Additionally, advanced tracking software will log real-time data on how much pressure is being applied, and a feedback mechanism will alert users when unsafe levels of force are detected, reducing the likelihood of complications such as artery puncture.

Another key feature of the project is the integration of a 3D tracking system, which will monitor the user's hand movements and catheter placement in real-time. This system will ensure that the haptic feedback is accurate and corresponds precisely to the actions being performed by the user. It is quite important to note that guaranteeing no interference between different sensors is crucial for the system to work seamlessly, allowing for a more natural and uninterrupted training experience.

In this simulation, the catheter dilation process is of particular importance. Catheter dilation involves the gradual expansion of the vessel to accommodate the insertion of medical devices. This requires precise control over the force applied, as sudden pressure could result in tears in the vessel, leading to severe complications. The system will track the pressure exerted by the trainee and provide feedback, ensuring that the force applied during dilation is both controlled and gradual.

By combining hardware components such as pressure-sensitive gels, haptic gloves, piezoelectric force sensors, and retractable mechanisms with advanced software for real-time force monitoring, data logging, and force threshold alerts, the system will create a comprehensive and realistic training experience for catheter placement. The ultimate goal is to enable medical students to practice catheter insertion in a safe, controlled environment while receiving real-time feedback on their technique. This not only enhances their learning experience but also ensures that they are prepared for real-world scenarios where precision is critical.

In summary, this project seeks to fill a significant gap in medical training tools by creating a VR/AR-based catheter simulation that accurately tracks force, provides haptic feedback, and simulates the realistic dynamics of catheter placement. The integration of both hardware and software tools will ensure that medical students can practice safely and effectively, ultimately improving patient outcomes by reducing the risk of complications during catheterization procedures.

Background

The hardware requirements for the catheter training device are centered around delivering precise haptic feedback and real-time motion tracking. The system will utilize advanced force sensors and micro-actuators, such as piezoelectric sensors, to simulate the resistance experienced during catheter insertion, mimicking the tactile feedback medical professionals encounter when navigating through blood vessels. A 3D tracking system embedded within the haptic glove will monitor the user's hand movements with high precision, ensuring accurate alignment between physical actions and the virtual environment. In addition to these, cameras may be used to track specific objects or external movements, enhancing the precision of the system by capturing visual data and integrating it with the VR environment for comprehensive monitoring. This requires the camera system to be fully compatible with VR platforms, ensuring seamless integration with both the glove's sensors and the virtual interface. The glove will also feature integrated force sensors to measure the pressure applied during catheter placement, providing real-time data to guide users and prevent overexertion. To ensure effective use in a training environment, the glove must be lightweight, flexible, and durable for extended wear, while maintaining compatibility with VR systems for seamless integration. This hardware setup, combined with the use of cameras for object tracking, is essential for creating an immersive and realistic training experience that mirrors the tactile and spatial dynamics of real-life catheter procedures.

The software requirements for the catheter training device focus on integrating the haptic feedback system with a virtual reality (VR) environment to provide an immersive and interactive training experience. The software must be capable of processing real-time data from the sensors embedded in the haptic glove, such as force, pressure, and hand movement, and translating these inputs into accurate feedback within the VR simulation. Advanced algorithms will be required to model the physical interactions between the catheter, guide wire, and simulated anatomical structures, ensuring that the resistance felt by the user mirrors real-world conditions. Additionally, the software will include a feedback mechanism that alerts the user when unsafe levels of force are detected, reducing the risk of injury in practice. The integration with 3D tracking systems will allow for precise monitoring of hand movements and catheter placement, ensuring that the user's actions are accurately reflected in the VR environment. The camera tracking data will also be processed, enabling the system to track external objects or tools during the simulation, providing additional layers of accuracy and realism. Finally, the software will need to log performance data for review, enabling users and instructors to assess progress and improve technique. This combination of real-time feedback, tracking, and data analysis is critical for creating an effective and realistic training system.

The integration of hardware and software in the catheter training device is essential for creating a cohesive and realistic simulation experience. The hardware components, including force sensors, actuators, cameras, and the 3D tracking system, must seamlessly interface with the software to provide real-time feedback that mirrors the physical sensations of catheter placement. The software will process input from the sensors, translating the physical resistance and hand movements into visual and tactile feedback within the VR environment. This requires precise synchronization between the haptic glove's data, camera input, and the virtual simulation to ensure that the user experiences an accurate representation of catheter insertion, including the feel of resistance and pressure at critical points. The software must also analyze sensor data to provide immediate alerts when unsafe force thresholds are exceeded, while simultaneously recording the user's performance for future evaluation. Ensuring a smooth interaction between the hardware and software components is critical to delivering an intuitive, responsive, and safe training tool for medical professionals.

Existing Solutions and Gaps

Interventional radiology (IR) training remains significantly behind other specialties in adopting innovations. Specifically, the current IR training pathway lacks sufficient simulation-based training methods. Current training practices focus mostly on phantoms and supervised clinical practice. However, high quality phantoms can be very expensive and can be damaged after repeated use. Cheap options exist such as ballistic gels, but these can only sustain a limited amount of uses and fail to accurately simulate the anatomy of a human body. Furthermore, traditional supervised clinical practice or apprenticeship models can greatly compromise patient safety. Medical students learning interventional radiology lack a more realistic simulation to help practice in a lower-stakes environment before moving on to real patients.

VR technology can allow for an immersive and interactive training environment that is both repeatable and eliminates the risks associated with practice on real patients. By utilizing haptic feedback and hardware technologies for catheter navigation and tissue resistance, a training environment can be created that is more realistic than traditional gels and phantoms. In addition, this approach could potentially simulate a wider variety of medical scenarios, giving trainees exposure to different situations or complicated cases.

Simulation-based training has become increasingly recognized as a critical tool for procedural learning in interventional radiology (IR) and other fields requiring advanced catheter skills. The first article reviewed highlights that, unlike traditional hands-on training, simulation-based training allows trainees to develop technical proficiency in IR without the immediate risks posed to patients [1]. For the VR HEAL project, this finding underscores the importance of simulation in safely accelerating skill acquisition for catheter placement, as our device simulates tactile feedback and procedural dynamics in a controlled environment. Similarly, in vascular surgery, simulation training has been mandated for certain skills, providing trainees with extensive hands-on practice before performing high-risk procedures on real patients. These findings align with VR HEAL's objective to reduce the learning curve and enhance confidence among new practitioners.

Moreover, in the field of interventional cardiology, simulation training has been shown to improve procedural outcomes by reducing complication rates and procedural times during cardiac catheterization, pointing to the critical role of simulated practice in patient safety and procedural accuracy [1]. The final study, focusing on neurosurgery, found that simulation-based training significantly enhances trainee competency in diagnostic angiography, a procedure with high patient risk. These findings further validate VR HEAL's approach, emphasizing that training on a simulated platform prepares practitioners better for real-world challenges than traditional methods alone. Collectively, these studies support the adoption of simulation-based training as an effective, safer alternative to traditional training, providing a standardized way to gain essential skills across diverse medical procedures.

Research on Mixed Reality (MR) technology has shown its significant benefits for training medical procedures, with a focus on high accuracy and consistency in skill development. MR technology, which blends real-world and virtual elements, uses devices like head-mounted displays to overlay instructional content in real-time. This allows trainees to interact with both physical and digital aspects of their environment, providing an immersive, step-by-step learning experience.

One study compared MR-based instruction with traditional teaching for bladder catheter placement. Results demonstrated that students using MR scored higher in learning assessments, highlighting MR's potential to enhance procedural confidence and competence [2]. However, the study also identified usability challenges, indicating a need for further refinement in MR technology for seamless application in daily teaching. For the VR HEAL project, these findings reinforce the importance of simulation-based training as a safe, effective, and replicable approach for developing critical medical skills like catheterization [2]. Through an immersive, controlled environment, VR HEAL can address current gaps in medical training by providing consistent, high-quality instruction to trainees, better preparing them for real-life procedures.

Another study examines a hybrid ultrasound training simulator that utilizes mixed reality with a physical phantom. The purpose of the simulator is to improve hand placement and probe manipulation skills for both interventional ultrasound procedures [3]. The hybrid simulator combines a physical phantom, which mimics human tissue, with a 3D environment. The simulator utilizes electromagnetic sensors to track both the probe and internal structures.

In the study, 36 novices were recruited to test the simulator. The novices were divided into two groups so that half trained with the mixed reality simulator and half trained with a traditional phantom. After a short training, the participants were asked to locate a target anatomical structure. The results showed that the participants who used the mixed reality training were more likely to successfully find the target, as 78% in this group were successful compared to just 45% in the traditional phantom group [3]. In addition, four experts were recruited to evaluate the mixed reality simulation, all of whom noted the simulator's usefulness.

Overall, this preliminary study suggests that mixed reality simulation greatly improves training efficiency and skill development for ultrasound training. This strongly suggests that interventional radiology trainees would also greatly benefit from a mixed reality simulation, although the physical aspect requires more nuanced hardware to simulate the upsizing process that leads to catheter placement.

A third study evaluated a virtual reality simulator designed for interventional radiology training, focusing on the Seldinger technique [4]. The simulator utilized a haptic pen device to replicate the feedback essential for performing precise incisions. The haptic pen involved sensors and actuators to provide realistic feedback when interacting with anatomical structures in the virtual environment. This allowed trainees to practice in a controlled environment with realistic physical pressure and resistance within the immersive virtual environment.

Participants were divided into an experimental group, which was trained on the VR simulator, and a control group. The participants who were trained using the VR simulator displayed significantly better performances finding arteries and making incisions. This strongly supports the use of VR simulation integrated with haptic sensors and actuators for training in interventional radiology [4]. However, the study also highlighted the need for future iterations to improve the accuracy of the simulation and get trainees closer to the feeling of real patient care.

Justification for Hardware

The hardware components selected for this device were chosen based on their compatibility with MetaQuest (the VR headset that the software team plans to use) and their functionality. After evaluating several options, a Raspberry Pi was chosen as the primary computing platform. The Raspberry Pi is a compact, single-board computer, and provides the needed processing power and memory to execute the tasks needed for this device. In contrast, an Arduino microcontroller, while well-suited for smaller circuitry projects, lacks the needed memory capacity and processing system required for this device. The Raspberry Pi should allow the device to manage real-time processing tasks while also interacting with the MetaQuest headset and the software chosen by the other team.

To achieve the control needed to simulate physical resistance, a motor driver board will be attached to the Raspberry Pi. This setup will control the force with which a linear actuator creates physical resistance to the “catheter insertion”. The Adafruit motor HAT is the current choice for the motor driver board because of its compatibility with the Raspberry Pi. The linear actuator is currently going to be the Firgelli L16-S mini linear actuator, due to its popularity and reliability for similar applications.

For real-time feedback, a force-sensitive resistor (FSR) will measure the pressure users apply to the catheter device. This data feeds directly into the Raspberry Pi, which adjusts the linear actuator’s resistance to match the user’s force. This instant feedback loop lets users refine their technique on the spot, making the training more effective and lifelike. This feedback loop will help bridge the gap in training between practicing on a phantom and a person, as the phantom does not provide real-time pressure feedback the same way the human body would.

Tracking the user’s hand movements is also essential for accurately rendering the virtual environment. The MetaQuest 3 controllers will be used to track the user’s hands, which will provide coordinate information to render the 3D environment. This part was chosen due to its compatibility with the MetaQuest headset, which the Software Team will be using to help the user visualize the environment. If this method works, then the hand-tracking mechanism is guaranteed to be compatible with the Software Team’s product. However, if this does not work out, then the user will wear fingertip gloves that contain trackers. The fingertip gloves were chosen over a full-sized glove to minimize their potential interference in the user’s navigation of the procedure. These trackers and the information they output are likely to be compatible with the Software Team's choice.

The location of the user's hands is important to help render the 3D environment, which can be accomplished using a camera like the Flex-13 from OptiTrac. This camera will record the user's hand positions and the data will be sent to some hub. From here, the Software Team will be able to extract the location data and create a fully immersive VR environment. Combining these tracking and feedback mechanisms will result in a VR setup that feels natural and responsive, enhancing the user's experience and ensuring it is more lifelike than a phantom model.

Hardware Development Plan

The hardware development plan aims to facilitate a realistic simulation of catheter insertion through a combination of tactile and force feedback mechanisms. The development plan encompasses the integration of sensory and actuation components designed to emulate the forces and resistances encountered in actual catheterization procedures.

Sensor Integration for Force and Motion Detection

To simulate the tactile feedback associated with catheter insertion, Adafruit Force Sensitive Resistors will be employed to measure applied force at the catheter interface. These sensors quantify the real-time force exerted by the user, ensuring that the simulation reflects changes in force.

Hand movements and device manipulation will be captured using reflective markers to allow for accurate tracking of spatial orientation and manual gestures. An optical system (Flex 13 or Vive) will be used to capture precise positional data of the hands, needle, guidewire, dilator, and catheter. This motion capture setup provides the simulation with kinematic information to synchronize virtual actions with real-world input.

Haptic Feedback Through Actuators

To replicate the varying resistance encountered during catheter insertion, Firgelli L16-S Mini Linear Actuators will dynamically adjust to simulate different tissue resistances, providing users with realistic haptic feedback. The actuators' control is managed by an Adafruit Motor HAT, which processes force feedback data and modulates the actuator's response to maintain a consistent simulation of force. This real-time adaptation replicates the tactile feedback associated with the catheter placement procedure.

The integration of these sensors and actuators into a cohesive system creates an immersive hardware interface that closely mimics the physical dynamics of catheter insertion.

Software Integration Plan

The software integration plan is designed to bridge the hardware with a virtual simulation environment, enabling the transfer of sensory data into VR. This section outlines the interfacing protocols, feedback mechanisms, and real-time data transmission needed to deliver a high-fidelity training experience.

Data Transmission and Processing

The Raspberry Pi serves as the central processing hub, responsible for aggregating sensory data from the force-sensitive resistors and actuator controllers, and relaying this data to the simulation environment. Measured force data, alongside positional information from the actuators, is transmitted via WebSocket protocol, facilitating real-time, bidirectional communication between the hardware and the simulation computer. This WebSocket-enabled communication ensures low-latency data transfer, which is crucial for delivering a responsive VR/AR experience.

Haptic Feedback Loop and Real-Time VR Interaction

Within VR, a force feedback loop is established where the Raspberry Pi dynamically adjusts the actuator response based on the real-time interaction metrics from the simulation. The force feedback system operates continuously, ensuring that haptic feedback corresponds precisely to the user's actions in VR. This closed-loop system provides realistic resistance feedback, allowing users to experience the physical constraints of catheter insertion in real-time.

Additionally, a 3D object rendering engine on the simulation computer processes spatial data to visually represent catheter positioning and movement within a 3D virtual space. This alignment of visual cues with physical feedback enhances the immersive quality of the training environment.

Integration of Biometric and Positional Data

To further augment the realism of the simulation, biometric sensors, such as the Empatica and Polar H10, capture physiological data, including skin conductivity (GSR) and heart rate variability (HRV). These metrics, processed through the Empatica app and Polar API, are stored in a dedicated database, providing valuable insights into user stress and engagement levels during the simulation. By dynamically adjusting the simulation parameters in response to biometric feedback, the system can simulate more challenging scenarios based on user physiological responses.

Positional tracking of the hands is achieved through a spatial tracking hub (OptiHub 2), which collects 3D coordinate data for precise tracking of the user's hand and tool location within the virtual environment. This tracking ensures that physical movements correspond accurately to their virtual counterparts, supporting an intuitive interaction between the user and the simulation.

The tracking system also contributes to location-based haptic feedback, enhancing the fidelity of the tactile response in line with hand positioning.

The current plan to begin developing the hardware component of the device is to begin early prototyping following Thanksgiving Break, or whenever the necessary parts are delivered. This phase of prototyping will likely include low-fidelity prototyping as well as assembling the initial components and beginning basic functional tests. From there, the Hardware Team hopes to have a prototype that can be tested by early January. Once the prototype has undergone some initial testing and multiple iterations, integration with the Software Team's VR software will begin, likely in February of 2025. This integration process will focus on synchronizing hardware functionality with the virtual environment, including precise calibration of haptic feedback and ensuring seamless communication between the two systems.

Challenges and Discussion

There are a few main challenges with creating the physical device and integrating it with the VR simulation. Firstly, maintaining a constant view of the needle and accurate representation of the needle in the simulation, especially once it enters the devices will be crucial. A real blood vein has an average of 5 mm and a 0.5 mm wall[5], as such the device must be able to track the needle to very tight tolerances and create a visual recreation overlay that also has very little room for error. This information would be essential to give users correct feedback on if they have punctured too deeply, a common mistake that medical students make when first learning to insert catheters.

The Flex 13 that is planned to be used has a stated and verified accuracy to 0.3 mm within its field of focus [6], however, with a the tip of the needle likely getting obstructed once it enters the device meaning that picking a reliable point on the needle to track and verifying that the device has been taking accurate measurements is crucial and is able to transmit and display this information in real-time with as little latency as possible.

Another challenge that will be encountered is the lack of a database for the precise back pressure that the linear actuator will need to produce to simulate the needle puncturing the skin, tissue, and blood vessel. Making sure that this pressure is an accurate representation for how the procedure will feel with an actual patient will be crucial to train the medical students and build the best muscle memory for the procedure, especially as learning the correct amount of pressure to use is largely based on experience.

To help calibrate the device, experienced doctors will be asked to try using the device and adjustments to the amount of pressure used will be made in accordance with their feedback. A number of doctors should be surveyed in this in order to avoid biases and ensure a device that is able to recreate the real procedure as closely as possible.

Overall, visual reality (VR) and augmented reality (AR) simulations of medical procedures have been shown to greatly boost the confidence and ability of medical students in a relatively safe and low-cost way and have been met with largely positive feedback from students [7]. However, a lot of the feedback related to their experiences has been centered on the accuracy of the devices. For instance, in a study related to otolaryngology–head and neck surgery, students who were using the AR device reported that the AR did not accurately line up with a normal person's field of view, limiting what they could see beyond what was expected [7]. Though this did not prevent the device from being successful, it highlights the importance of recreating an accurate environment.

Furthermore, and more concerning for the catheter training device in particular is that AR also had a tendency to be slightly off alignment. The study of otolaryngology–head and neck surgery AR device noted an average error of 2.47 mm [7]. According to that same study, other studies showed an average misalignment of about 3 mm [7]. As blood veins are an average of 5 mm, this error margin, especially when compounded with errors of tracking the needle, could be a critical failure and further emphasizes the importance of accurately being able to track the location and depth of the needle.

A potential way to combat this would be to have a backup way of tracking the location of the needle and providing a second form of visual or physical feedback to indicate if the needle has gone too far. For instance, a mechanical or second electronic sensor for the exact depth the needle has gone that can be overlaid onto the VR once the needle tip has entered the device. A second way this could be combated would be to calibrate the device specifically to overcome that error, assuming it is fairly consistent.

Conclusion and Future Research

Existing IR training devices lack interactive elements that can emulate the tactical feedback of live operations, an aspect critical to medical students for developing proficiency in skills like tunneled and nontunneled catheter placement. A simulation-based training device with hardware and haptic feedback mechanisms that can be integrated into intuitive and practical medical training tools for IR is proposed. The training device includes hardware and software components. The user manually operates the device through haptic glove gloves with reflective markers. Through light information, a medium-volume high-precision motion capture camera captures the location of the glove. Three-dimensional spatial information of the hand coordinates is analyzed in a simulation computer. Through a virtual reality environment, visual data informs visual feedback for the user to develop an understanding of spatial. Force sensor resistor and accelerometer sensors are embedded in the haptic glove to measure the user's input into the training device system. Force and motion data are processed in a microcontroller and inform visual and haptic feedback through the virtual reality interface. Piezoelectric actuators are also embedded in the glove and linear resonant actuators are embedded in the training "phantom" to provide haptic feedback. The software and hardware components work together to help the user understand the interactions between the catheter, guide wire, and simulated anatomical structures. Integrating electrical, biomedical and visual information, the simulation-based catheter placement training device aims to provide a three-dimensional, immersive training experience, augmented by real-time biometric feedback. The training device may provide trainees with necessary IR skills, ensuring they are prepared to deliver high-quality patient care from the outset of their careers.

Future research should focus on refinement to the proposed control architecture, specifically the haptic glove and sensor array. The proposed hardware platform and three-dimensional virtual reality simulation should be evaluated by medical partners. Further research may analyze any effects in radiologists' real-world experiences and patient outcomes with the IR training device.

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