Simulator for Cardiovascular Procedures

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Abstract. This project integrates an interface and a prototype that allows the simulation of vascular procedures, both previously performed at the "Instituto Nacional de Cardiología Ignacio Chávez", with the objective that these can work together and achieve a simulator with greater competitiveness, performance, and functionality. This simulator incorporates a mechanical, hydraulic, digital, and imaging system like the one used in fluoroscopy, as well as interchangeable and personalized anatomical models. The user can operate it manually by using analog controls or more precise instructions through the interface control panel. By using this simulator, medical specialists, and residents will be able to practice the placement of various cardiovascular devices and have an approach to specific clinical cases.

Keywords: simulator · anatomic models · cardiovascular devices

1 Introduction

Cardiovascular procedures pose a significant challenge in the medical field, particularly within the educational context. This is due to the inherent limitations of the traditional training approach, which relies on expert-guided supervision. The constraints of this approach become apparent when considering factors such as the student-to-teacher ratio, available working hours, the risk stemming from technical complexity, and the legal and ethical implications [1].

In response to these limitations, alternatives to the traditional teaching approach have emerged. These options involve the utilization of animals and cadavers as instructional resources. However, both approaches come with considerable disadvantages. In the case of using animals for experimental procedures, ethical dilemmas and discrepancies arise, as the animals used are often healthy specimens, leading to substantial differences in physiological responses, pharmacological interactions, and disease manifestations compared to patients and their cardiac conditions. On the other hand, the use of cadavers raises legal implications, and specifically, in the manipulation of a guide through the radial artery, it becomes hindered by blood coagulation [2].

Another emerging training method is the use of virtual reality or augmented reality, which is conceptually appealing but doesn't provide a reliable physical feedback medium, potentially lacking realism due to current technological limitations [3].

Currently, various research fields have been working with a range of physically accurate anatomical models, which are based on image capture (Magnetic Resonance Imaging, Computed Tomography, and Ultrasound) and employ 3D printing technology with a variety of materials, each with distinct properties and finishes [4, 5]. By applying these methodologies, the capability to generate models in both common and catastrophic clinical scenarios is attainable. When needed, it is possible to make suitable modifications to replicate situations like serious medical complexities, like arterial blockage or a congenital anomaly.

The focus of this study was directed towards the development of a simulator for transcatheter cardiovascular procedures, which include guided placement of stents. This simulator was constructed within a controlled environment, resembling real procedure situations, utilizing 3D printing technology. Furthermore, it was meticulously designed to comprehensively incorporate critical tools for the procedure, including radial puncture and motion control for fluoroscopy image acquisition, all without exposure to ionizing radiation.

2 Materials and Methods

2.1 Segmentation

Segmentation was executed using the Mimics software (Materialise. https://www.materi alise.com/en/healthcare/mimics-innovation-suite/mimics) and with the support of additive manufacturing, the generation of multiple resin-printed models was achieved (Clear Resin by Formlabs). The segmented files are processed into the area of interest and adapted to the inputs and outputs of the hydraulic system (Fig. 1). The integration of these models with a hydraulic system is essential and will be discussed further, as such incorporation enables the reproduction of both radial and coronary flows. These models are interchangeable, allowing for the selection of the most appropriate one according to the specific scenario of interest.

2.2 Hydraulic System

The hydraulic system is based on circulating water through the segmented model to simulate flow conditions. To achieve this, two tools were employed: a peristaltic pump and a set of hoses with outer and inner diameters like physiological values (Average reported diameter 2.68 ± 0.15 mm [6]). This approach aims to achieve a more realistic pulsation.

Peristaltic Pump. The choice was made to use a 12V peristaltic pump with a 2-roller design. The operating voltage was determined within a range of 4 to 7 V, allowing the generation of simulated pulsations at a frequency comparable to the 60–100 bpm range. This setting can be modulated to meet specific requirements according to the scenario's needs (Fig. 2).

Fig. 1. Aortic artery adapted for integration into the hydraulic system.

Radial Puncture. The puncture process is performed through a simulated artery surrounded by a portion of radial bone, where the hose is routed. This point has been designated specifically for palpation and insertion of the introducer sheath, followed by guide wire insertion and device navigation (Fig. 3).

2.3   Motion Axes

The operation of a fluoroscope involves a C-arm that performs movements known as cephalocaudal and oblique motions. Additionally, there is a linear motion on the bed. The spectrum of movements covers a range of 90° in the cranial direction, 90° in the caudal direction (Fig. 4), 90° in the left oblique direction, and 90° in the right oblique direction (Fig. 5). For this device, a linear bed displacement of 30 cm is controlled. This measurement is determined as the optimal range to allow comprehensive visualization of the printed model.

The system features three axes of movement: cephalocaudal, oblique, and linear. The first two axes can be controlled using a joystick, while the third is operated using two buttons. It is important to emphasize that all three systems are in constant feedback, always enabling precise determination of their position.
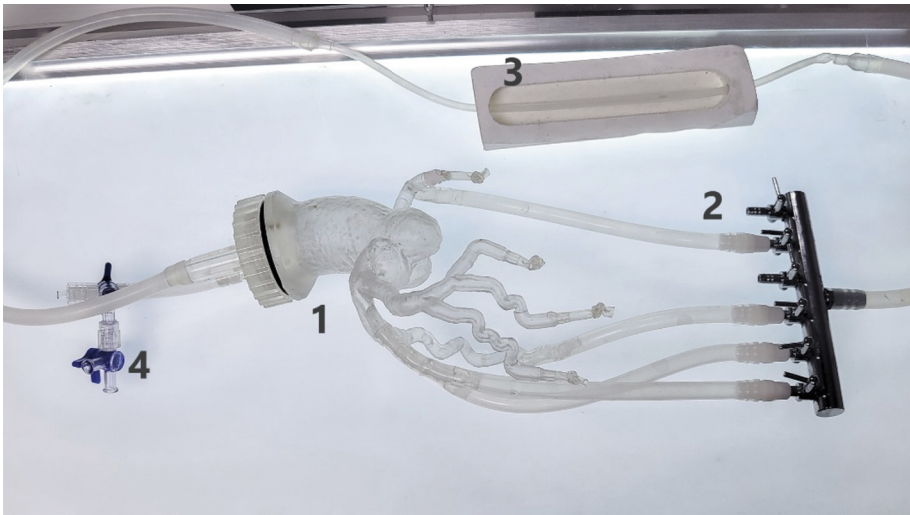
Fig. 2. Detailed representation of the comprehensive hydraulic system. The segmented anatomical model of the aortic artery, accurately segmented beforehand. 4-way return configuration for fluid flow. Internal view of the subsystem dedicated to radial puncture simulation. Includes arterial pulse simulation and a portion of radial bone for reference. 2-way system arrangement, centered on air removal within the model.
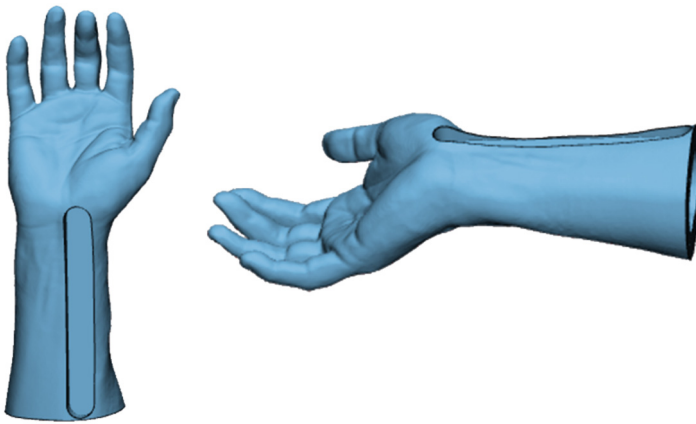

Fig. 3. System for performing radial puncture.

The cephalocaudal movement is based on a mechanical transmission and a Nema 23 motor, adapted to move an arc where the camera is situated in a range of 0° to 90° (Fig. 6). A mechanical transmission was incorporated, which also serves to maintain the position of the arc even when the system is not powered by a power source.
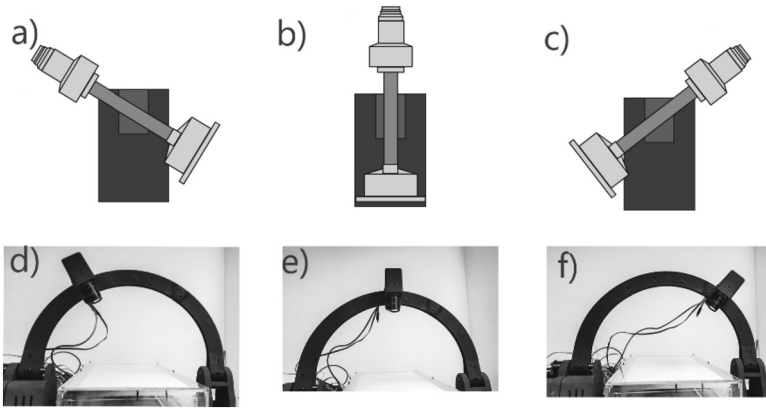
Fig. 4. The top section depicts the oblique axis of the fluoroscope, while the bottom section shows the oblique axis of the simulator. In references a) and d), the positive side is observed; in references b) and e), the neutral position is shown; and finally, in references c) and f), the negative side is observed.
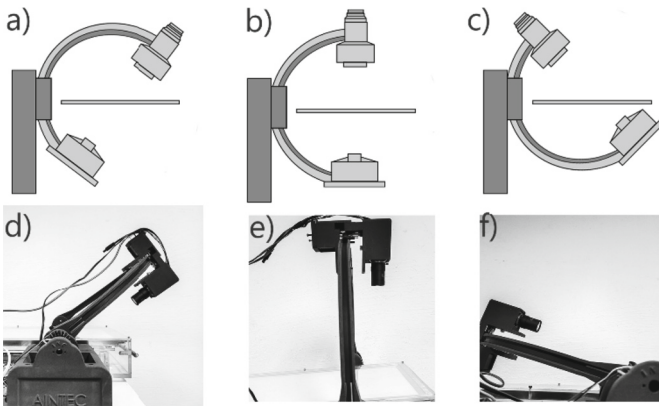

Fig. 5. The top section depicts the cephalocaudal axis of the fluoroscope, while the bottom section shows the cephalocaudal axis of the simulator. In references a) and d), the caudal side is observed; in references b) and e), the neutral position is shown; and finally, in references c) and f), the cranial direction is observed.

The oblique movement comprises a Nema 17 motor and a camera, anchored to a housing. With the assistance of the motor and a toothed belt, it's possible to move the camera along the arc, providing left and right oblique positions (Fig. 7).

The bed's movement is designed using a 12V linear actuator at a speed of 10 mm/s. It's mounted on an acrylic base, and above it, a box holds the lamp and features a rail system to allow smoother movement.
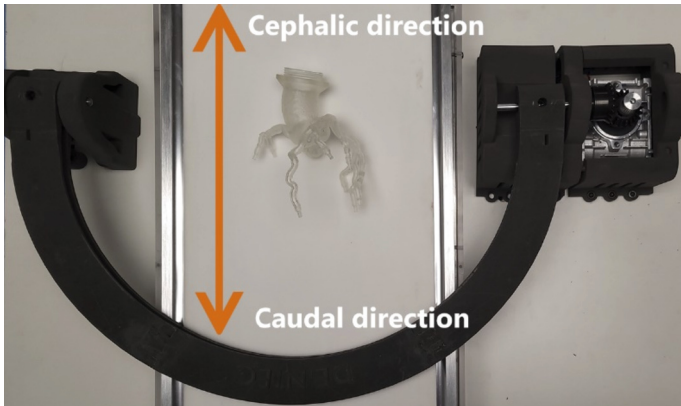
Fig. 6. Cephalocaudal Axis. On the right side, you can observe the transmission mechanism responsible for supplying the required torque for mobility and stabilization of the arc.
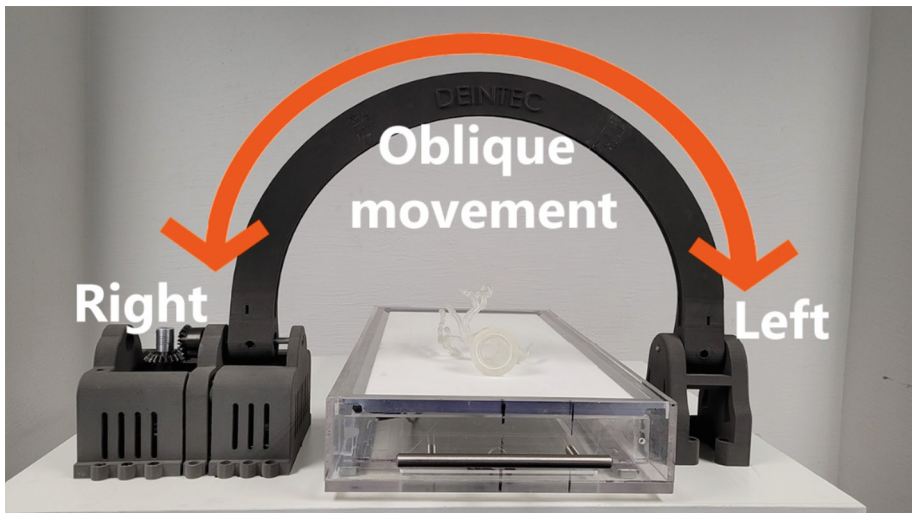

Fig. 7. Oblique Axis. The camera will move along the perimeter of the arc to acquire different viewing angles. The arc's configuration is designed to maintain a constant focal point.

2.4   Mechanical and Digital System

Graphical Interface. The interface was designed using Visual Studio Community (Microsoft Corporation. https://visualstudio.microsoft.com/es/vs/community/) and incorporates image acquisition and motion control features (Fig. 8).

The interface provides predefined positions, including right cranial oblique ($-30°$, $30°$), right caudal oblique ($-30°$, $-30°$), right neutral oblique ($-30°$, $0°$), left cranial oblique ($45°$, $30°$), left caudal oblique ($45°$, $-30°$), left neutral oblique ($45°$, $0°$), among others. However, in case, at some point during the simulation, the specialist or resident
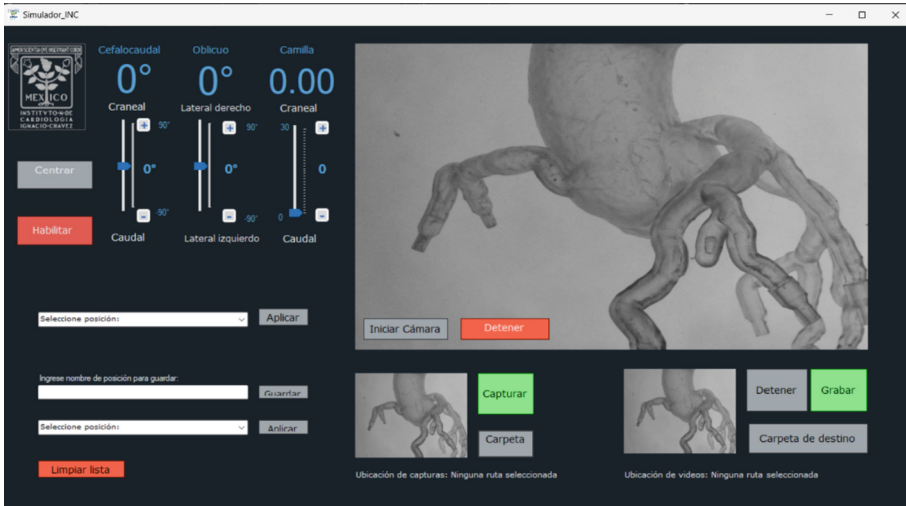
Fig. 8. Perspective of the interface in operation. The three axes of movement are controllable, where the "Center" button resets the three axes to their corresponding neutral coordinates. The "Enable" option authorizes system control directly from the interface. The first line manages predefined positions, while the second line enables the preservation of the current position with its respective identifier. The third line selects a previously established position. On the right-hand side, the camera display is present, with a button to activate and stop the display. Below this section, controls for image and video capture and storage in a predefined folder are situated.

identifies a specific useful position, there is an option to save it for accessing it when needed.

Image Acquisition. With the aim of obtaining images that emulate those acquired through fluoroscopy, the image acquisition technique in grayscale with backlight support, known as "Backlight," was implemented. This strategy involves placing the object of interest between the camera and a light source, allowing the visualization of its silhouette through the generation of contrasts. The resulting signal is presented on the graphical interface in the form of a grayscale image (Fig. 9).

3   Results

The environment has been meticulously designed to replicate the conditions of a trans-catheter procedure. During the simulation, the medical professional can perform a radial puncture guided by the cardiac pulse. They can then insert an introducer, guide a catheter through a real anatomical model assisted by the fluoroscopy-mimicking system, and position the area of interest for the release of trans-catheter medical devices. This process is achieved without exposure to ionizing radiation, is repeatable in a brief period, and is adaptable to any clinical case obtained through imaging techniques such as CT, MRI, or echocardiography.
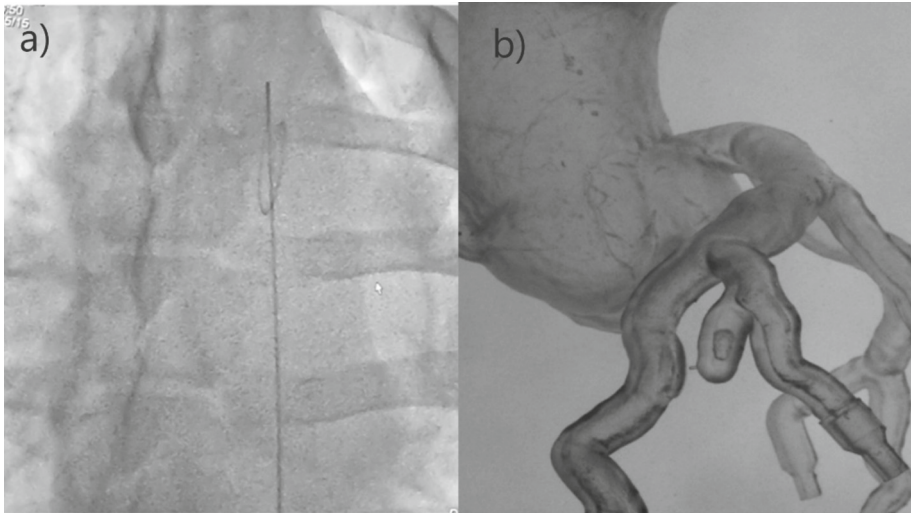
Fig. 9. Comparison between fluoroscopy (a) and its equivalent in the simulator (b). The representation on the left displays the insertion of a guide in a porcine model.

4   Discussion

The cardiovascular procedure simulation system introduces innovative approaches, such as precise segmentation of anatomical models and the implementation of 3D printing techniques. Additionally, it integrates a fluoroscopy system along with radial puncture technique. It is worth noting that being a design developed by the INC, this system stands out for its reduced cost compared to commercially available simulators with similar features. Furthermore, it presents unique attributes, such as the ability to adapt to any clinical case and the potential to adjust based on current needs. These qualities make the simulator a highly suitable tool for training physicians in the field of radial puncture and trans-catheter procedures.

5   Study Limitations

Achieving a complete replication of an environment identical to that of a cardiovascular procedure is a task of great complexity. The proposed system represents an approximation to the procedure's conditions; however, there are opportunities for further improvements. These enhancements could include the use of a blood-analog fluid, precise measurement of pressure and flow velocity, the establishment of a contrast medium injection system, utilization of more transparent and flexible materials for better visualization, among other potential areas of improvement.

6 Conclusions

This work highlights the advantages of incorporating physical simulators for training and educating professionals. The flexibility to encompass a wide variety of clinical cases and the ability to adapt the system to changing needs in the medical field make it a highly valuable tool for training in trans-catheter procedures and radial puncture.

This system marks a step forward in medical education by allowing medical professionals to practice procedures in a controlled and realistic environment. While there is still a path to perfection in cardiovascular simulation, current and future advancements in this field will undoubtedly contribute to the improvement of training and healthcare in the realm of cardiovascular procedures.

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