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OVERVIEW OF MULTIMODALITY MOTION TRACKING FOR TRAINING OF CENTRAL VENOUS CATHETER PLACEMENT

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ABSTRACT

Central Venous Catheter (CVC) placement is a common surgical procedure, with an estimated 400,000 complications every year in the United States (Raad 1998). There are mechanical complications related to arterial puncture and pneumothorax derived from improper technique. The lack of correct and repetitive training on central line placement is considered a key factor in these complications. This paper presents and overviews three state-of-the-art human tracking technologies to determine movements of the physician's head and hands as well as surgical instruments in order to provide a method for performance assessment while performing a CVC placement on a hybrid simulator.

1 INTRODUCTION

Central Venous Catheter (CVC) placement is widely used in care center units in the United States of America. Over 150 million intravascular catheters were purchased in the United States by 1998, including over 5 million central venous and pulmonary-artery catheters (Raad 1998). The main advantage of CVC placement is that it enables administration of medical solutions or run tests without unnecessary injections or transferring the patient to a surgery room. The preferred veins to perform the CVC placement training are the Internal Jugular vein (IJV) and Subclavian vein (SCV) (Farrow et al. 2009), both of which were selected for the current study.

2 CURRENT SURGICAL TRAINING TECHNOLOGY

2.1 Categories

Traditional training of CVC placement is performed on live patients. Simulation-based training has recently shown satisfactory results without patient safety concerns (Barsuk et al. 2009). There are three techniques for learning CVC placement using simulators:

- Part-task trainers (physical manikins)
- Computer-based simulators (virtual reality)
- Hybrid simulators (mixed reality)

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2.2 Part-task Trainers

Physical manikins offer a more cost-effective alternative to human cadavers, providing certain advantages including lengthy life, standardized dimensions and internal structure, and easy accessibility. Artificial skin, bones, organs and muscles are built with synthetic polymers. Depending on the complexity of the manikin, it can contain several different internal realistic structures such as trachea, lungs, diaphragm, kidneys, bladder, liver, pancreas, spleen, heart and skull. Some manikins can be used on training for more than one surgical approach such as CVC placement on the IJV and SCV (SynDaver Labs 2004).

Proper CVC placement training requires manikins to not only have the critical anatomical structures needed for the landmark identifications but also be ultrasound compatible. Utilizing ultrasound visualization makes it easy to recognize the internal jugular vein and carotid artery on a live patient. On the manikin there are no muscles observed and some black spots can be confused with the veins that the physician tries to locate.

Typical CVC Placement training manikin for IJV and SCV cannulation consist of an upper torso with the head tilted to the left side. The internal anatomy of the manikin includes internal jugular and subclavian veins, carotid artery, clavicle, sternum, sternocleidomastoid muscle, and mastoid process. The internal veins and artery are part of an artificial closed loop pipe system to represent the circulatory system where a fluid is filled inside to provide physical feedback for fluid extraction and to determine if the artery was punctured by accident. The fluid is blue for the veins and red for the arteries (Simulab Corporation 2014). Certain models of manikins include a manual pump to simulate blood stream that aides to differentiate artery from vein when using ultrasound guidance (CAE Healthcare 2015).

2.3 Computer-based Simulators

Computer-based medical simulation involves the integration of three main areas: medical expertise, software design expertise, and instructional expertise (Munro and Clark 2013). Typical computer-based simulators recreate interactions with virtual reality representations of real surgical instruments such as syringes, drills, or catheters. Some of the components included in a computer-based medical simulation are haptic devices, tracking systems, tactile screens, real time simulation software, 3D visualization, and computer vision.

In the early 1970s there were limitations on simulating realistic 3D models, particularly the inability to simulate haptic or palpable sensations (Burt 1995). Two decades later, the use of virtual reality in surgical applications started using head mounted displays and cyber gloves. However only 10% of late-1990s virtual reality projects used that technology (McCloy and Stone 2001).

Recent computer-based medical simulators, such as the ImmersiveTouch®, include force feedback, electromagnetic motion tracking, and high resolution 3D displays. Force feedback is provided by haptic devices with servo motors that are activated by the interaction between virtual instruments and 3D anatomical models. The platform that the ImmersiveTouch® provides is adaptable to simulate different procedures such as periodontal training (Luciano et al. 2009) and ventriculostomy catheter placement (Banerjee et al. 2007).

2.4 Hybrid Simulators

Hybrid simulators refer to the combination of computer-based systems and real physical elements (Saouma and Sivaselvan 2008). Hybrid simulators provide tactile and haptic feedback of tissue structure or physical elements with 3D models projected on screen for an immersive experience. The key aspect of hybrid simulators is that the interaction with the physical elements or structures is enriched with real time interaction of virtual objects (Ullrich and Kuhlen 2012). In other words, there is a direct relation between the physical and virtual world while both can be modified by external inputs such as one user as a human-in-the-loop concept.

Timothy Coles and his colleagues designed a femoral needle insertion training simulator using haptic devices for force feedback (Coles et al. 2011). This approach had a container filled with silicone to provide a tactile representation of the pelvis' skin and bone to find the point of insertion. Coles' approach has three major advantages: real tactile skin feedback, low cost repetitions, and reduced computational power required for the interaction of the user's hands. The silicone representing the skin provides a palpable surface where the user can find the target by touching the physical representation of it. There is no need for the user to make any mental transformation of images because the interaction happens with physical materials and the user can see his/her hands represented on the screen. The use of monoscopic display requires less computational power than stereoscopic display. Finally, there is no head tracking processing required because the user is required to have a fixed position over the screen. However, this feature also leads to problems of learning the procedure with wrong eye-hand coordination because variations on the user's head location are not interpreted by the system (Coles et al. 2011).

Another Hybrid simulator for Subclavian Venous Access was developed by Robinson et al. (2014). Their approach uses a physical upper body manikin designed for Subclavian Venous Access to emulate the palpable landmarks of a real patient and a separate monitor for the augmented reality display. The advantages of Robinson's approach include the fact that there is no occlusion of the user's hands at any moment and eye-hand recognition is made intuitively. The monitor where the internal anatomy of the virtual patient is projected functions as one augmented reality visualization because it provides real-time visual feedback to the user about the location of the needle, plus indicating the correct path of access. However, this approach requires that the physician looks away from his hands to see the monitor to understand the changes on both environments (real and virtual). Therefore, the mental location of the needle in both environments is not done intuitively. Furthermore, the part task trainer developed only covers the insertion of the guide needle. Neither the entire Seldinger procedure nor the entire Subclavian approach can be performed to effectively provide a complete training simulation (Robinson et al. 2014).

Robinson's and Cole's hybrid simulators present improvements on training sessions for both target procedures. In order to design one hybrid simulator for CVC placement it is necessary to cover certain human factors such as physician's position, height and instrument handling that are detailed on the next section.

3 HUMAN FACTORS AND ERGONOMICS

Central Venous Catheter (CVC) placement is a process that requires the trainee or medical professional to be standing close to the patient. The physician executing the CVC placement has the freedom to change his posture to improve visualization of the surgical field and handle the instruments with the dominant hand (Farrow et al. 2009). The correct CVC placement performed by a novice physician may take around 20 minutes taking into consideration all the steps required to avoid infection and proper employment of the instruments. However, experienced physicians would probably take less than 5 minutes to perform the entire procedure, independently from the use of ultrasound (US) guidance.

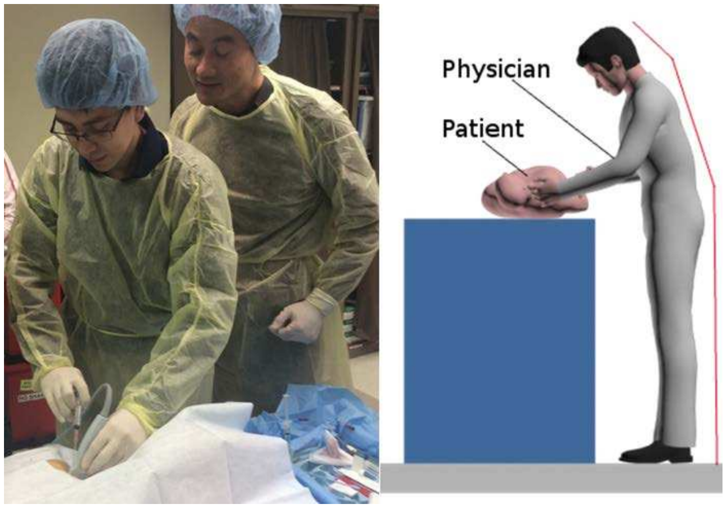


Figure 1: Body posture when performing CVC placement on a real training session (left) and a virtual model representation (right).

3.1 Body Posture

None of the instruments should be manipulated above the height of the chest nor should the physician's face be put close to the insertion area (Farrow et al. 2009). The process in real life may require these rules to be dismissed if complications occur or better positioning is required for the success of the procedure. The physician may also incline the upper body towards the patient to improve his/her field of view. An example of the posture of the physician can be seen in Figure 1 where the red line shows how the upper body is slightly leaned forward towards the patient.

3.2 Instrument Handling

The physician uses both hands throughout the CVC placement. Preceding instrumental preparation for the procedure can be done with both hands (Farrow et al. 2009). Some preparation steps include: prepare the guidewire, catheter and ultrasound probe; position the instruments and tools on the table; clean the area with sterile solution; cover the patient; flush the ports of the catheter; and draw lidocaine into the syringe (Bodenham et al. 2009).

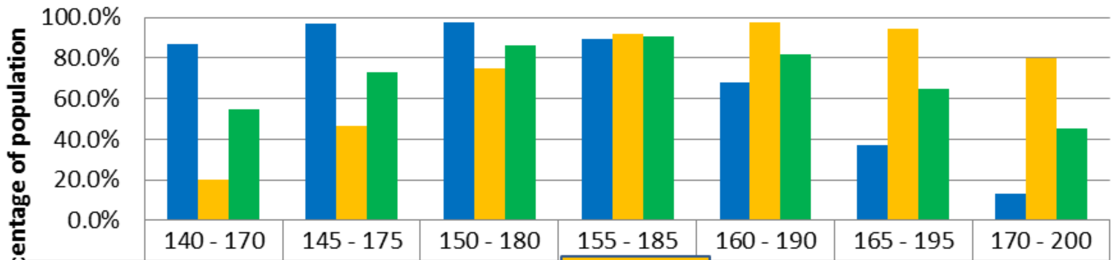
The non-dominant hand is used to manipulate the ultrasound transducer, hold the needle for the guidewire, keep the guidewire in place while advancing the dilator and catheter, and hold the catheter until it is secured with clips. The dominant hand is used to pierce the skin with the needle, advance the guide wire, advance the dilator, place the central line catheter, and sew the secure clips over the insertion site (Bodenham et al. 2009).

3.3 Anthropometric Dimensions Of The Simulator

The location of the workplace plane is determined based on the position where the physician places the hands to perform the Central Line placement, and oriented perpendicular to the line of sight of the user. The height of the workplace plane corresponds to 15 degrees above and below the line of sight that the average American human male has (National Aeronautics and Space Administration 2000). This represents the region where the user needs to perform the entire procedure with his hands over the patient.

The height of the user sets the position for the virtual guidance plane. The virtual guidance plane works as a physical limit for the user to avoid getting closer to the patient as well as keeping all the instrument handling below the chest.

Based on the data from Gordon et al. (1989), a range of 155cms to 185cms covers 89.4% of the female population and 92.0% of males. A virtual guidance plane located within this range of minimum and maximum heights will cover on average 90.6% of the population. The wider the intervals are, the larger proportion of the population is covered. However, if the interval is wider than 30cms, the size of the virtual guidance plane will prevent the tallest users from performing the procedure comfortably. Figure 2 shows the different intervals with their related population covered.



	140 - 170	145 - 175	150 - 180	155 - 185	160 - 190	165 - 195	170 - 200
Female	86.6%	96.9%	97.5%	89.4%	67.8%	37.3%	13.3%
Male	20.2%	46.5%	74.6%	92.0%	97.5%	94.2%	79.8%
Total	54.8%	72.7%	86.5%	90.6%	82.0%	64.6%	45.2%

Figure 2: United States population height covered on different intervals of 30cms.

4 MOTION TRACKING TECHNOLOGY

In order to measure the trainee's performance it is necessary to determine the position and orientation of his/her hands and surgical instruments. The correct alignment and positioning of virtual models with real elements can be determined by tracking the trainee's head. Three technologies are used to track the hands, head and surgical instruments in order to design a hybrid simulator for CVC placement. Each technology's software and hardware included on this study is summarized on Table 1 and is further discussed in the sections below.

Table 1: Software and hardware for each technology.

Technology	Software	Hardware
Head Tracking	Seeing Machines (faceAPI)	Webcam
Hand Tracking	3Gear Systems	Depth Camera
Instrument Tracking	Ascension Technologies	Electromagnetic sensors

4.1 Head Tracking

The user's head location is required to properly collocate virtual models with physical elements. These virtual models could guide the user throughout training sessions with a hybrid simulator, for instance by displaying correct alignment and positioning of the surgical instruments. Therefore, recognizing gestures or user movements is key for such applications. Two examples of systems that accomplish this are the Kinect™ camera (Microsoft Corporation 2015) and the Nintendo 3DS XL (Webster 2015).

The first technology evaluated in this work is the one provided by faceAPI for head tracking using a regular webcam (Seeing Machines Limited 2010). The company that made faceAPI uses this technology to improve safety of drivers (Lebeau 2015).

As part of the evaluation, faceAPI was combined with Coin3D (Kongsberg Oil and Gas Technologies 2014) to display a virtual 3D head model that mimics the position of the user's head in real time. Results of this research are shown in Figure 3.

Figure 3: Virtual model and user head looking to the front (above) and looking up (below).

Table 2 reflects a summary of the time that the computer took to delimit, filter and detect the face of the user at different distances from the camera. It was determined that the algorithm detects the user's face in 3.7 seconds. Once the face is detected, it keeps a constant real-time tracking of the user's head without noticeable delays.

Table 2: Statistics of face detection measurement.

Measurement of statistical dispersion	Distance from the camera			
	45cms [sec]	65cms [sec]	75cms [sec]	Total [sec]
Mean/Average	3.76	3.77	3.56	3.70
Standard deviation	0.90	0.45	0.81	0.74

4.2 Hand Tracking

The landmark technique for CVC placement consists of finding specific anatomical elements by touching them with the hands. Some steps of the CVC placement require the physician to maintain pressure with the hands over the insertion area or holding instruments. Therefore for a hybrid simulator it is relevant to determine the location of the physician's hands over the patient. A depth camera, such as the Microsoft Kinect®, provides a solution for this purpose. It includes a 2D camera and an infrared camera that detects the array of infrared dots projected onto the scene (Microsoft Corporation 2015). 3Gear systems developed a C++ SDK for hand gesture recognition (3Gear Systems Inc. 2014).

Compared to head motion tracking, hand tracking is more computationally demanding as hand orientation and variability of finger positioning make it harder to recognize patterns (Wang and Popovic 2009). The inverse kinematic configuration of the SDK from 3Gear Systems was tested to observe the response to certain hand gestures shown in Figure 4. The software is able to provide acceptable results with multiple gestures, but presents difficulties when a held object partially occludes some fingers.

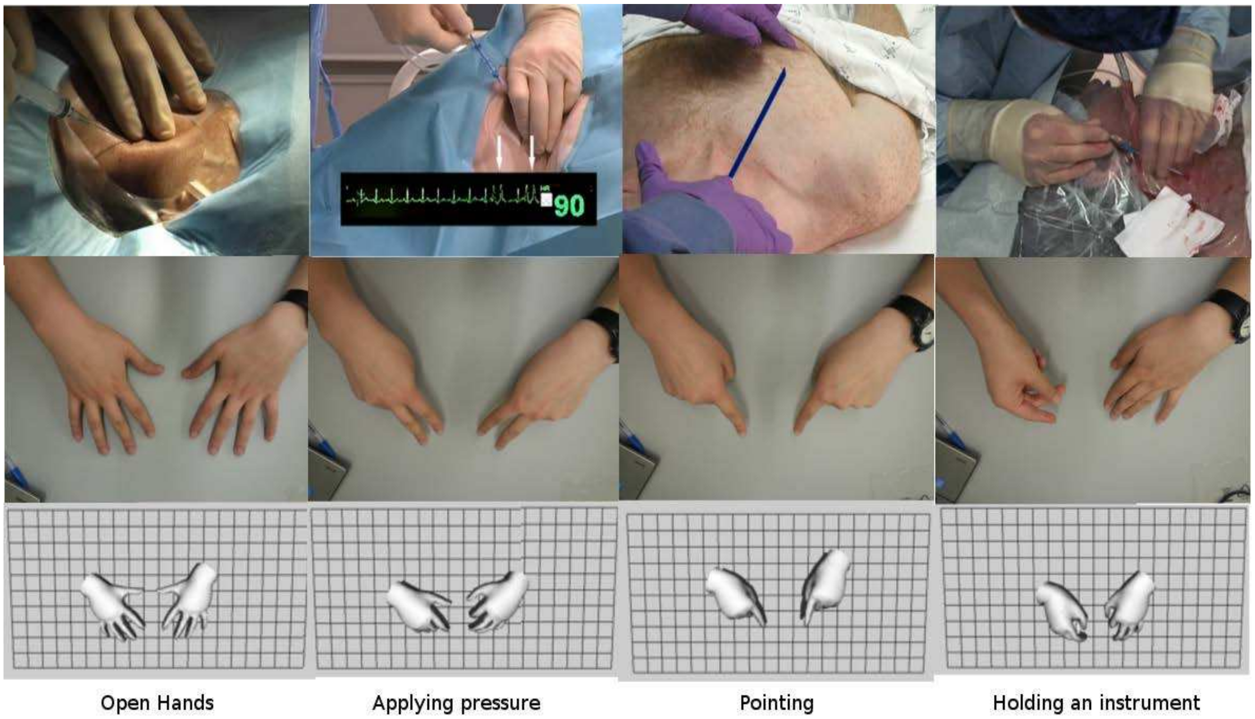


Figure 4: Hand gesture recognition SDK outcomes compared to surgical procedure (top row), laboratory emulation (middle row) and computer-generated 3D hand models (bottom row).

4.3 Surgical Instrument Tracking

In order to measure the performance of a user while handling the surgical instruments in CVC placement, electromagnetic sensors that determine spatial position and orientation were selected. The electromagnetic sensors use orthogonal antennas that detect variance in the electromagnetic field from a transmitter that works as the reference (Egli et al. 1981). NDI is one company that develops electromagnetic sensors which obtain 3D position and orientation (Ascension Technology Corporation 2015).

Figure 5 shows the experiment setup to measure the error of measurement of four electromagnetic sensors connected simultaneously. Figures 6 and 7 show graphically the results obtained compared to the real physical value.

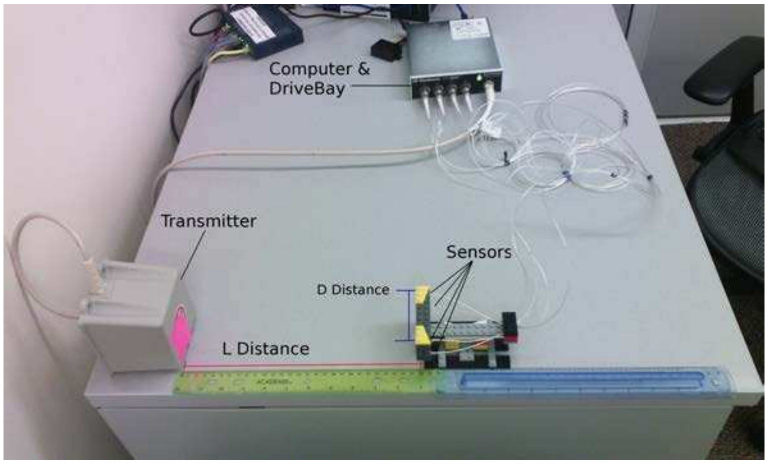


Figure 5: Electromagnetic sensor experimental setup.

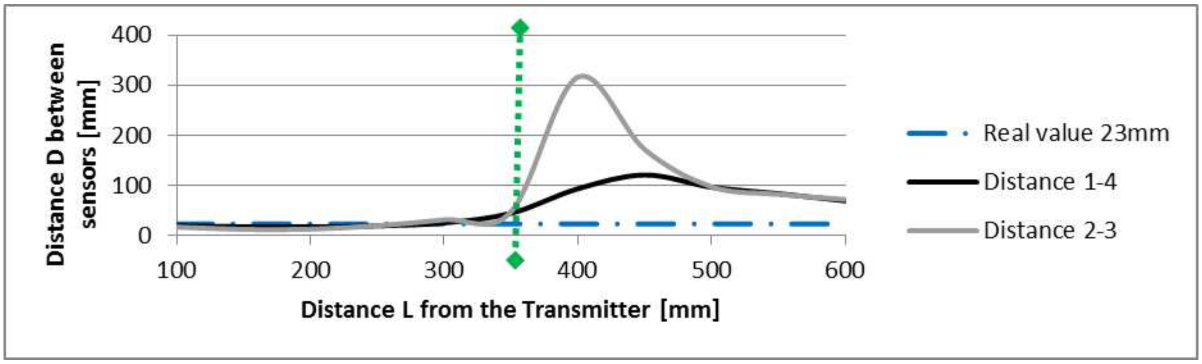


Figure 6: Vertical distance between the sensors couples 1-4 and 2-3.

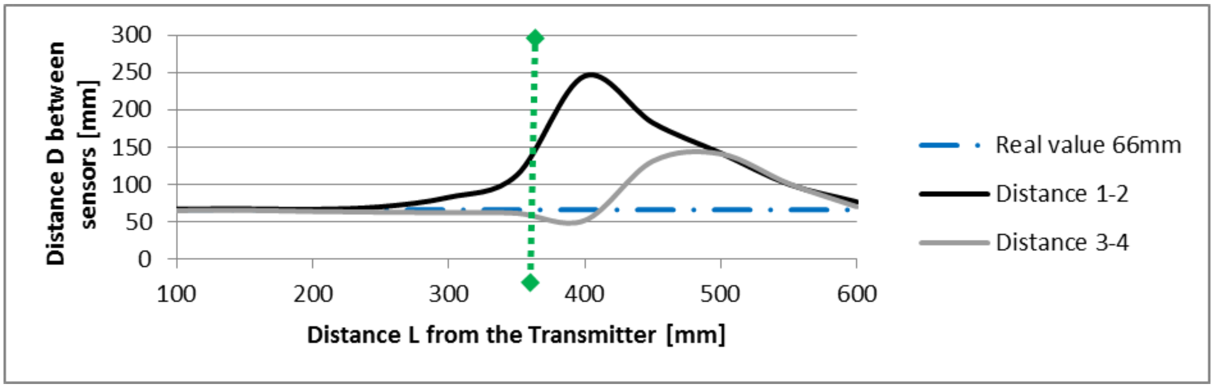


Figure 7: Horizontal distance between the sensors couples 1-2 and 3-4.

Table 3 summarizes the results obtained from the different couples of sensors. The manufacturer provides an estimated “Quality” which represents the accuracy for each measurement. However, high values of this “Quality” do not relate to a low error as shown in Table 3. Finally, it was observed that between 100mm to 300mm from the transmitter, the largest error in distance is 6.3mm. This error is acceptable to detect proper positioning of the instruments handled by the user. Therefore, it was concluded that this technology could be used to measure a physician’s performance while handling surgical instruments for CVC training.

Table 3: Error and quality at different distances L from the transmitter.

Distance L	Error	Quality	Acceptable
100 mm	3.2 mm (0.13 inches)	7	Yes
150 mm	5 mm (0.2 inches)	14	Yes
200 mm	5.6 mm (0.22 inches)	30	Yes
250 mm	4.6 mm (0.18 inches)	44	Yes and optimal
300 mm	6.3 mm (0.25 inches)	57	Yes
350 mm	21.8 mm (0.86 inches)	71	No
400 mm	141 mm (5.55 inches)	83	No
450 mm	115 mm (4.53 inches)	74	No
500 mm	80.9 mm (3.18 inches)	61	No
550 mm	58.8 mm (2.31 inches)	49	No
600 mm	39.8 mm (1.57 inches)	35	No

5 CONCLUSIONS

Central Venous Catheter (CVC) Placement is a widely used procedure. Training on CVC placement is focused on the Internal Jugular and Subclavian vein using ultrasound guidance. There is an extensive checklist of steps to be followed for CVC placement in order to reduce the risk of complications.

Augmented reality and hybrid simulators are a promising technology to improve the quality of CVC placement training. A proctor with such technologies would provide certain benefits, such as: 1) standardized training, avoiding the variance in instruction from other physicians; 2) capability to recognize user’s errors and correct them; and 3) reduced cost, since it does not require the continued presence of a supervising instructor.

The optical head tracking algorithm adapted from Seeing Machines is capable of finding the user’s head in 3.7 seconds and can follow its movements without noticeable delays. The 6DOF coordinates obtained from the head tracking algorithm provide enough data to change the position and orientation of a virtual model with the user’s head in real time. This is a promising milestone for future stereoscopic (3D) visualization where the virtual models adapt their location based on the user’s eyes position.

Optical hand tracking using 3Gear systems algorithm can determine the location and orientation of the hands and certain gestures. The algorithm is not capable of detecting the correct gesture of a hand when it holds a surgical instrument. The software may also fail to recognize the hands when they are in contact with a surface. Regardless of the limitations, this software can be used to provide certain commands to the computer and check for proper landmark technique when not using ultrasound guidance.

The electromagnetic sensors provided enough accuracy to estimate distances with an error of less than one centimeter for distances between 100mm to 300mm from the transmitter. When the transmitter is located at a distance greater than 350mm away from the sensors, the electromagnetic tracking system is unable to provide acceptable levels of accuracy. In order to minimize the error of the electromagnetic tracking system, the transmitter would need to be placed around 250 mm away from the sensors attached to the instruments (i.e., syringes, dilator and catheter of the CVC placement). This layout will be able to determine if the instrument tips are correctly placed inside the targeted vein (IJV or SCV) with an uncertainty of less than 5mm.

In summary, the technology that was evaluated for human motion tracking makes it possible to evaluate a physician's actions during CVC placement. Therefore, a future simulator for CVC placement training is feasible using this technology for tracking the head, hands, and surgical instruments. The technology overviewed in this paper can be applied on other hybrid simulators for other procedures such as blood drawing, laparoscopy, arthroscopy and lung biopsies.

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