Simulation Technology for Central Venous Catheter

Placement Training: Limitations and Opportunities

BY

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THESIS

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Contribution of Authors

Dr. Cristian Javier Luciano: supervised the implementation of software algorithms and logistic of the experiments for the optical tracking and electromagnetic sensors.

Dr. Rachel Yudkowsky: provided general concepts from a medical educator's perspective that are useful for enhancing novice physician training with the long term goal of improving surgical outcomes. As the Director of the Graham Clinical Performance Center at UIC, Dr. Yudkowsky also gave access to the facilities and equipment used for simulation of Central Venous Catheter placement on part-task trainers.

Dr. James Bui: explained to the author and research team the complete process to correctly place a Central Venous Catheter on a patient and on a manikin. The teachings helped us to determine the actions that need to be considered or measured by the computer to detect proper instrument handling.

Joao Vitor da Silva and Julio Villalta: contributed to the development of an optical head tracking system as part of their research experience as undergraduate students. Joao was a participant of the Brazilian scientific mobility program.

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Summary

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 the wrong placement of the catheter at the insertion step, as well as over 80,000 catheter-related bloodstream infections in Intensive care Units every year (World Health Organization, 2015). The Agency for Healthcare Research and Quality (AHRQ) recommends utilizing ultrasound (US) guidance for central line placement to minimize the complications. Nevertheless, taking into consideration all the recommendations and security measures given by the AHRQ, it is considered that the lack of proper training on central line placement is one of the reasons that contributes to complications. This study is the pioneering research towards the design of an "instructor-less" simulator that will self-monitor the performance of the trainee.

This dissertation is organized as follows. Chapter 1 shows a review of Central Venous Catheter (CVC) placement procedure. Chapter 2 gives an introduction to the current methods of training of CVC placement based on part-task trainers, computer-based simulators, and a hybrid combination of both technologies. Chapter 3 covers human factors considered for the posture and instrument handling related to the placement of CVCs. Chapter 4 includes current techniques used on computer-based CVC placement training and technologies such as electromagnetic sensors and computer vision.

CHAPTER 1: INTRODUCTION TO CENTRAL VENOUS CATHETER (CVC) PLACEMENT

A. Description

Intravascular catheters are widely used in surgery intervention for procedures such as bone-marrow, hemodialysis, cardiothoracic and trauma surgery. 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). It can be inferred that the number of Central Venous Catheters has been increased since then.

Central venous catheter (CVC) placement is a surgical procedure where a catheter with two or three lumens is inserted into the patient's body targeting the superior vena cava. The CVC is used to administer medication or other types of solutions, as well as to obtain blood samples for tests and pressure measurements. 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. There are five different approaches for the CVC placement (Farrow, et al., 2009):

- Internal Jugular vein (IJV)
- External Jugular vein (EJV)
- Subclavian vein (SCV)
- Axillary vein
- Femoral vein in the groin

B. Anatomical landmarks involved in CVC placement

It is recommended to use ultrasound (US) guidance for CVC placement to minimize complications, due to the fact that each patient may have small anatomical variations on the location of the veins (Feller-Kopman, 2007), physicians still consider specific anatomical landmarks to determine the right location and orientation of surgical instruments. The landmark technique involves manual guidance based on external parts of the body that help to locate the vein (Table I). This chapter describes the important landmarks for catheter placement on the Internal Jugular vein (IJV) and Subclavian vein (SCV). External Jugular Vein (EJV) and Axillary vein approaches are usually not included in training because there is a wide variability in location and path for both veins. Therefore, they were excluded from this study (Bui, 2014, personal communication). Even though the femoral approach is more comfortable for patients, it is not the preferred method because of the infection rate (Farrow, et al., 2009). Thus, femoral vein approach is also excluded from this research.

Internal Jugular Vein (IJV)

The Seldinger technique (Seldinger, 1953) is preferred since the procedure targets a direct insertion into great veins. The IJV has 15 mm in diameter in an adult (Farrow, et al., 2009). The patient is placed in the Trendelenburg position, rising his/her feet about 10 to 15 degrees above his/her head (Figure 1). For IJV central line placement the patient head is slightly turned towards the left shoulder for easy access of the IJV (Farrow, et al., 2009).

Figure 1 Trendelenburg position (Ebli, 2013)

To determine the IJV location, the thumb of the operator needs to be placed “on the mastoid process and the middle finger on the head of the clavicle. [Then] the index finger [is located around a third of the line between the other two finger tips. The point should be] superior to the apex of the triangle formed by the two heads of the sternocleidomastoid” (Farrow, et al., 2009).

The carotid artery can be palpated by the non-dominant hand, which is also the same hand used to hold the ultrasound probe. The location of the vein should be identified with ultrasound guidance. The needle orientation should be on a 30 degree angle towards the ipsilateral nipple (O'Leary, et al., 2010) .

Subclavian Vein (SCV)

The patient is placed lying down on the Trendelenburg position. One finger is placed on the “subclavian groove and pressed until resistance is felt, [which shows where] the Subclavius [muscle is located]. [Then the guide] needle is inserted below the clavicle, at [the junction of the medial and middle thirds of the clavicle]” (Galloway, et al., 2009). It is important to notice that the subclavian artery or vein cannot be directly visualized or palpated (O'Leary, et al., 2010).

Anatomical Landmarks for Internal Jugular vein (IJV) Catheter Placement	Anatomical Landmarks for Subclavian vein (SCV) Catheter Placement
• Mastoid process (Skull)	• Clavicle
• Clavicle	• Subclavian groove
• Carotid Artery	• Subclavius muscle
• Sternocleidomastoid muscle	• Subclavian vein
• Internal Jugular Vein	• Subclavian artery

Table I Anatomical landmarks involved in IJV and SCV catheter placement

C. CVC Instrumental kit

The surgical instruments used for central venous cannulation are the central line kit and additional items as shown in Table II. There are just minor differences among the kits from different companies.

Central line kit	Additional items	Commercial Central line kit
• Needle or a cannula over needle • Central venous catheter • Guide wire • Dilator • Anchoring clips	• Suture • Scalpel • Appropriate dressing • Syringes • Blue and green needles • Three-way taps, one for each lumen • Drapes • Cleaning fluid • Swabs • Gallipot or similar • Sterile ultrasound probe sheath • 0.9% normal saline	• Needle and syringe • Central venous catheter • Guide wire • Dilator • Anchoring clips • Lidocaine solution • Safety scalpel • Saline solution One-step applicator

Table II CVC placement items included on Central line kit, Additional items needed and Commercial versions of Central Line kit [Adapted from (O'Leary, et al., 2010)]

D. Steps for central venous catheter placement

A standardized list of steps for CVC placement has been defined by (The Joint Commission, 2013). The checklist can be adapted (combining steps or providing extensive details) across different Healthcare institutions as long as no step is omitted. Skipping one step may incur complications such as infections or improper placement of the catheter. Twenty two surgical steps are listed below, adapted from (O'Leary, et al., 2010) and (Barsuk, et al., 2009). Steps that involve explaining the procedure to the patient, letting him/her know about the risks of the surgery, and signing the relevant documents are not included in the list.

1. Place patient in Trendelenburg position. The head should be down to minimize the risk of venous air embolism.
2. Clean skin with chlorhexidine and drape the area. The sterile technique must be maintained until securing the central line.
3. Flush ports on catheter with sterile saline. Three-way taps can be attached to all but the central lumen.
4. Clamp additional ports.
5. Full body drape for patient.
6. Cover the ultrasound (US) probe with sterile sheath. Apply ultrasound transmission gel to provide contact between the sheath and the patient.
7. Locate internal jugular vein (IJV) by anatomical landmarks explained before such as the clavicle, sternocleidomastoid muscle, mastoid process and carotid artery.
8. Apply local anesthetic, 1% lidocaine recommended.
9. Locate vein with the finder needle (optional).

10. Cannulate vein with large needle or catheter-syringe complex while aspirating, or visualize the needle within lumen of vein if using US. The large needle should be introduced at a 30 degree angle on the skin.
11. Remove the syringe from the needle/angiocath and advance the guide wire through the needle into the vein no more than 15 to 20cms.
12. Remove the needle/angiocath and confirm the guide wire placement with ultrasound (if ultrasound is used). It is essential that the non-dominant hand keeps hold of the guide wire until it is removed.
13. Cut down onto wire with scalpel.
14. Advance the dilator over guide wire and dilate the skin and subcutaneous tissues.
15. Place the central line over the guide wire and advance it into the vein.
16. Remove the wire while holding the central line.
17. Use a syringe to ensure that blood can be aspirated from each lumen and that they flush freely.
18. Secure the central line catheter in place with suture and locking clips.
19. Recap each lumen of the central line.
20. Place sterile dressing over the catheter.
21. Clean the area and dispose sharps.
22. Use Chest X-Ray to confirm the correct location of the tip and check for complications.

E. Complications on CVC Placement

There are a number of complications such as pneumothorax and arterial puncture to which the patient can be exposed (Bodenham, et al., 2009). “Inadvertent arterial puncture occurs in approximately 6-8% of CVC placements, with similar rates for different sites [while] the risk of pneumothorax with subclavian CVC insertion is approximately 2%” (Costell, et al., 2013).

Arterial Puncture and bleeding

Inadvertent puncture of an artery can happen during the insertion of any instrument during a Central line placement. Some other complications are associated with arterial puncture such as hematomas and hemothorax (Karapinar, et al., 2007). Ultrasound guidance can reduce the risk of arterial puncture (Bodenham, et al., 2009).

Pneumothorax

Pneumothorax happens if there is air present in the pleural space between the lungs and the chest (Perdue, 2001). Bodenham and Simcock state that "[Pneumothorax] may be caused when a needle, guidewire, dilator or catheter is used to access the subclavian or jugular veins" (Bodenham, et al., 2009). The risk of pneumothorax can be reduced using ultrasound guidance as well (Martin, et al., 2004).

Incorrect catheter position

A central venous catheter is misplaced if the tip is not positioned in the right atrium; the device lies outside the venous system; or the tip is against a vessel or chamber. The use of X-ray is useful to recognize incorrect positioning but it is recommended that in case of doubt, the catheter should be replaced as soon as practically possible (Bodenham, et al., 2009).

Other complications

Additional complications for CVC placement include: irretrievable guide wires or catheters, due to accidental cut of the lines; extravasation injury; pleural infusions of blood, infused fluids and lymph fluid; great veins or arteries perforation. These numerous complications may result in morbidity and occasional mortality. Therefore, it is required that the physician who attempts to make a CVC placement have extensive training for such cases (Bodenham, et al., 2009). Once again, even though ultrasound guidance has reduced the risk of infections and complications, it does not entirely eliminate the risk of any undesirable condition (Martin, et al., 2004).

CHAPTER 2: CURRENT SURGICAL TRAINING: CVC PLACEMENT SIMULATORS

Current CVC placement involves learning on live patients without simulation-based training. This requires a supervising physician explaining the procedure. There are three techniques for learning CVC placement using simulators:

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

Future technology aims to design more realistic and complex approaches on the three different categories of simulators. Special attention is paid for evaluation of the different techniques, validity on context and a strong definition of objectives. (Bewley, et al., 2013).

A. 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, esophagus, kidneys, bladder, liver, pancreas, spleen, heart and skull. Some manikins can be used for training 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. However, the image obtained by the ultrasound on a live patient shows a smooth image of fluid or tissue on that differs from the one obtained by the same ultrasound equipment on a manikin. Figure 2 shows that with ultrasound visualization it is 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.

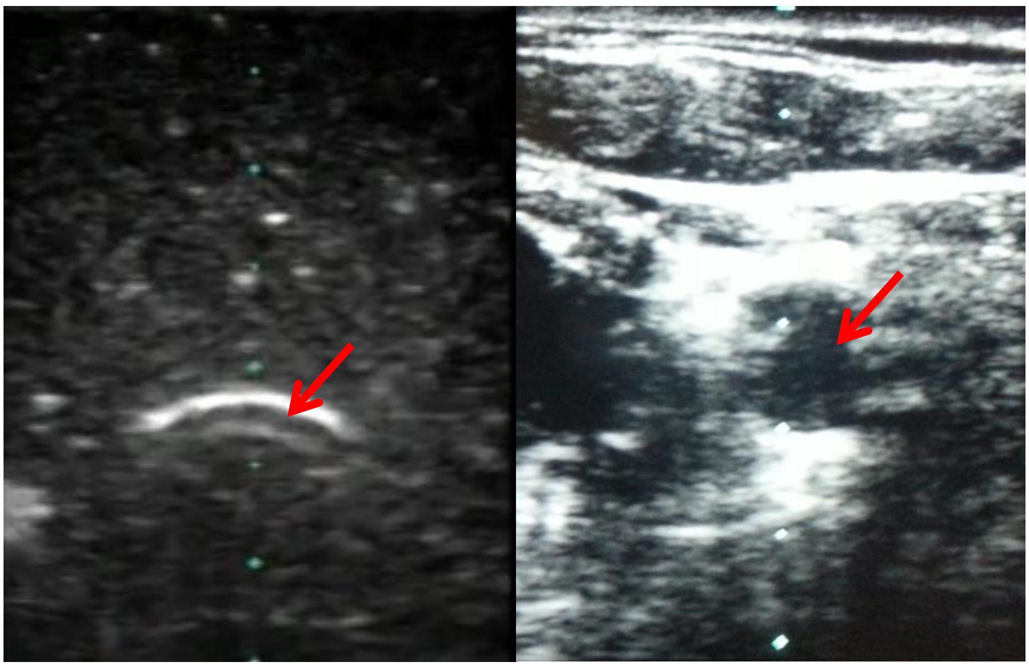


Figure 2 Ultrasound view of the Internal Jugular Vein (IJV) on manikin (left) and on a real patient (right)

Typical CVC Placement training manikin for IJV and SCV cannulation consist of an upper torso with the head tilted to the left side (figure 3). 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).

Figure 3 Blue Phantom Manikin from CAE Healthcare for IJV and SCV Central line placement training. Image adapted from (CAE Healthcare, 2015)

B. Computer-based simulators

Computer-based medical simulation involves the integration of three main areas: medical expertise, software design expertise, and instructional expertise (Munro, et al., 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.

Virtual reality is a concept that started in the 70s as a breakthrough concept. However the technology available at the time was not advanced enough to provide a significant improvement in medical practices. Visualizing realistic 3D anatomical models and obtaining haptic sensations from the insertion of virtual surgical instruments were some of the most important limitations of virtual reality in medical simulation at that time (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 90s virtual reality projects used that technology (McCloy, et al., 2001).

More 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 (Luciano, et al., 2005). 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).

C. Hybrid simulators

Hybrid simulators refer to the combination of computer-based systems and physical manikins. 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. In other words, there is a direct relation between the physical and virtual world while both can be modified by the user as a human-on-the-loop concept.

These types of simulators for surgical procedures are the most recent ones, after the inclusion of more reliable tracking systems and commercially-available haptic devices such as the Geomagic Touch® (Geomagic, 2015)(Sensable, 2015) and the Falcon (Novint Technologies Inc., 2012).

Timothy Coles and his colleagues designed a femoral needle insertion training simulator using haptic devices for force feedback. This approach had a container filled with silicone to provide a tactile representation of the pelvis' skin on the surface and bone to find the point of insertion. The physical syringe emulator was placed on a modified OMNI Haptic device (Sensable, 2015) . The needle position is computed based on the position of the physical syringe emulator. The silicone container is placed over two modified Falcon devices to also provide mobility and force feedback of the femoral area. Finally, there is a monitor that shows the models collocated with a virtual representation of the user's hands (Coles, et al., 2011).

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 cost of the hardware without listing the computer is around $2,500, which represents an acceptable price for simulation. Finally, the use of monoscopic display requires less computational power than stereoscopic display. Moreover, 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 also mentioned that integrating stereoscopic display and ultrasound are features to be investigated in the future (Coles, et al., 2011).

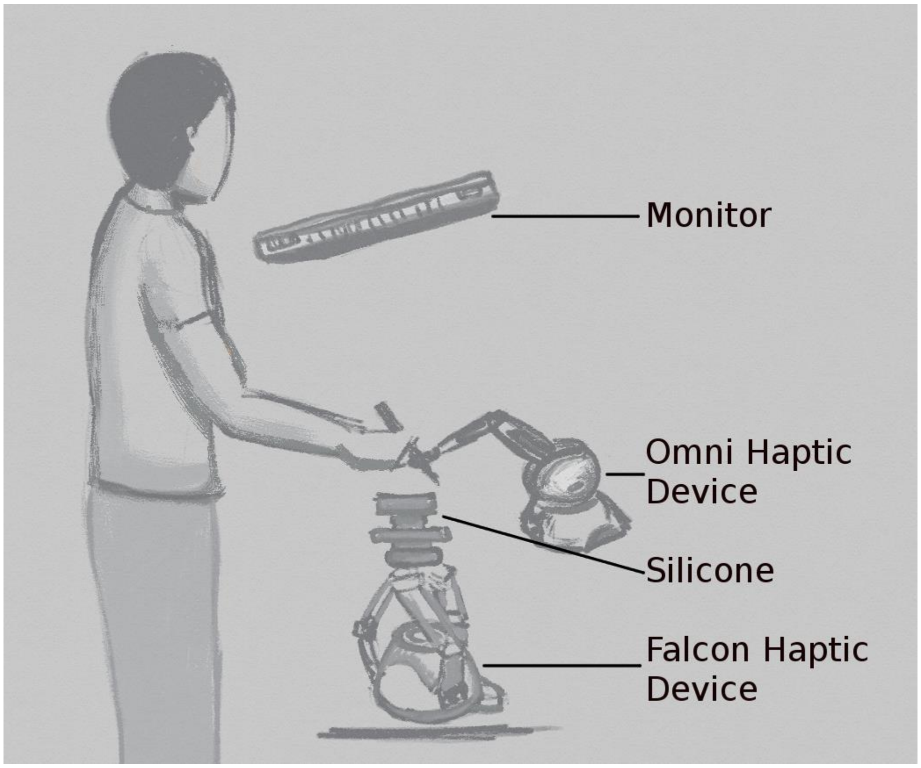


Figure 4 Coles' hybrid simulator [adapted from (Coles, et al., 2011)]

Albert Robinson with his colleagues designed another Hybrid simulator for Subclavian Venous Access. Their approach uses a physical upper body manikin designed for Subclavian Venous Access to emulate the palpable landmarks of a real patient. An electromagnetic sensor attached to a syringe with the needle and finally a monitor where the 3D Models are projected on a monoscopic display (Robinson, et al., 2014).

The advantages on Robinson's approach include 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 right path of access. However, this approach requires that the physician looks away from his hands to see the monitor and vice versa to understand the changes on both environments, physical and virtual. Therefore, the mental location of the needle on both environments is not done intuitively. Furthermore, the part task trainer developed only covers the insertion of the guide needle, not the entire Seldinger procedure nor the entire Subclavian approach to effectively provide a complete training simulation (Robinson, et al., 2014).

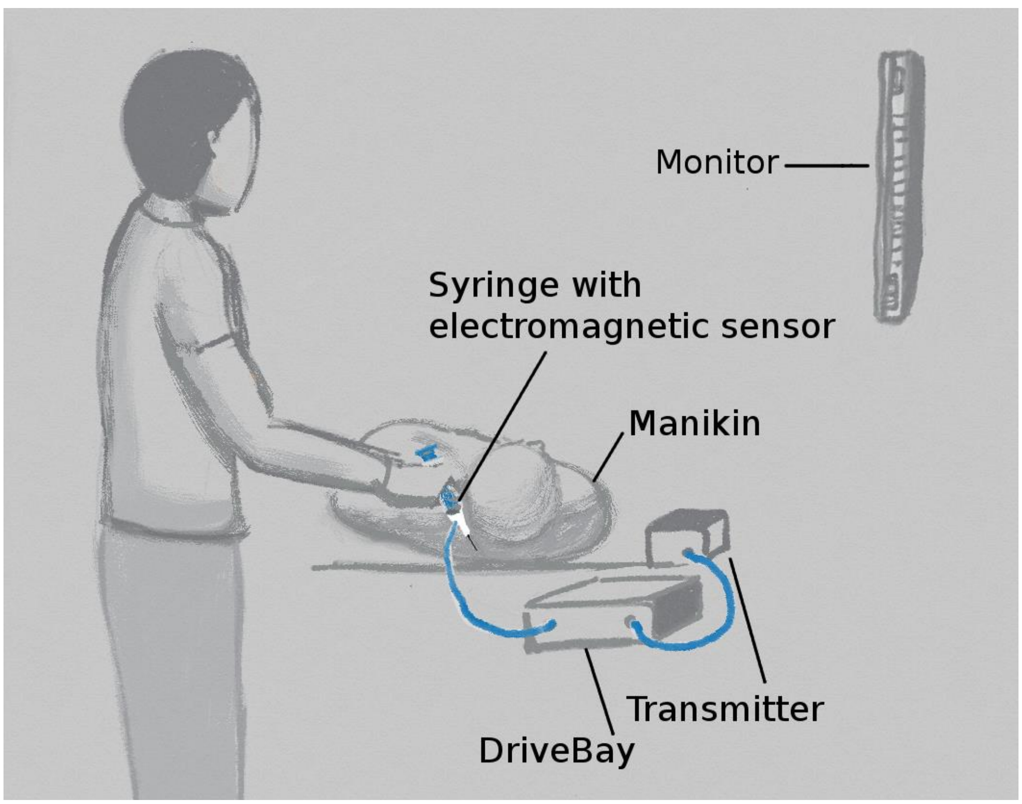


Figure 5 Robinson CVC placement hybrid simulator [adapted from (Robinson, et al., 2014)]

CHAPTER 3: ERGONOMETRIC AND ANTHROPOMETRIC ANALYSES OF CVC PRACTITIONER

Central Venous Catheter (CVC) Placement is a process that requires the trainee or medical professional to be standing close to the patient as shown in Figure 6. The physician executing the CVC placement has the freedom to change his posture to improve visual acuity and reach the instruments needed with the dominant hand. 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 (Bui, 2014, personal communication). Factors such as age, illness, diabetes, size and overweight of the patient may complicate the procedure. Since the trainee or physician are not standing for long periods of time to perform one CVC placement, analysis related to posture fatigue is not required.

Figure 6 Healthcare professional and trainee performing CVC placement

A. Body Posture

As described before, the physician should be standing next to the patient. 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. The process in real life may require this rules to be dismissed if complications occur or better positioning is required for the success of the procedure (Bui, 2014, personal communication). The physician may also incline the upper body towards the patient to improve visual acuity and field of view. An example of the posture of the physician can be seen in Figure 7 where the red line shows how the upper body is tilted to the front instead of keeping a straight posture aligned with the legs.

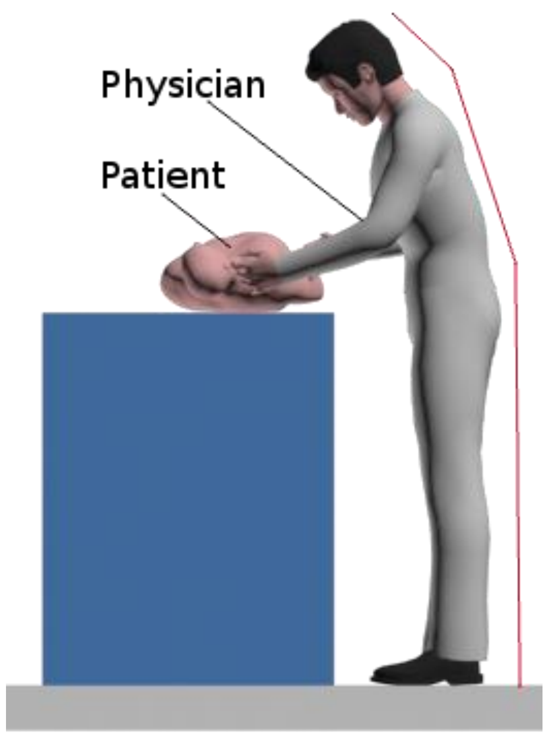


Figure 7 Physician posture on CVC procedure. Upper body inclined towards the patient or manikin

B. Instrument handling

The physician uses both hands throughout the CVC placement. Preceding instrumental preparation for the procedure can be done with both hands. Some preparation steps include: Prior preparation of 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.

The non-dominant hand is used to position the ultrasound, 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, grab the different instruments, advance the guidewire, advance the dilator, place the central line catheter and sew the secure clips over. A summary of the instruments used by each hand is shown below in Table III and IV.

Physician Hand	Instrument or action
Both hands (Preparation)	• Configure ultrasound settings (gain, depth) • Cover the ultrasound probe with sterile sheath • Draw anesthetic into the syringe • Prepare Guide wire • Place the patient in the Trendelenburg position • Take off the Three-way tap attached to the central line • Clean the skin using an antiseptic solution • Cover the patient with drapes
Non-Dominant hand	• Place ultrasound probe • Hold the guide needle • Hold the Guidewire • Hold the catheter

Table III Instruments and actions performed by both hand and the non-dominant hand

Physician Hand	Instrument or action
Dominant hand	• Ultrasound transmission gel • Syringe with lidocaine • Guide needle to pierce the skin • Syringe removal from the guide needle • Insert the guidewire through the needle • Scalpel to cut around the wire • Sew security clips

Table IV Instruments and actions performed by dominant hand

C. Line of sight

The human being can focus comfortably on objects that are around fifteen degrees over or under the line of sight. Any posture where the head is required to move downward more than 30 degrees will avoid the proper support from the lumbar spine (Bridger, 2003). The Central Venous Placement requires the healthcare professional to look down on an angle of approximately 32 degrees. Moreover, the user must be able to look at his hands at all times in an operating position. Figure 8 shows an example of a posture that the healthcare professional will take in order to perform a manual operation (Chang, 2014).

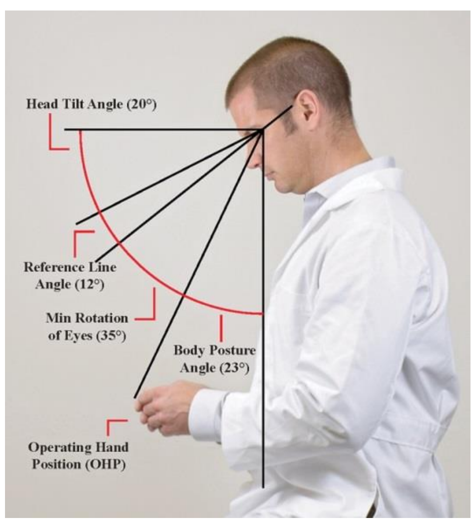


Figure 8 Line of Sight of a Healthcare Professional performing the Central Venous Placement (Chang, 2014)

D. Virtual guidance plane

CVC placement training using physical manikins or part task trainers can be improved with virtual models that guide the practitioner throughout the procedure (see Chapter 2). The projection of the virtual models should take place between the user's eyes and hands to avoid occlusion of the hands or the virtual models. A translucent mirror can be used for the virtual guidance plane so that the user can see his/her own hands while manipulating the manikin and look at the reflected models on the mirror. These reflected virtual models need to coincide with the anatomy of the manikin and they are projected from a screen (monitor plane) placed close to the upper the superior border of the mirror. This setup will allow the user to see his/her hands, the manikin and the virtual models combined in a workplace plane. Figure 9 shows graphically the location of the three planes.

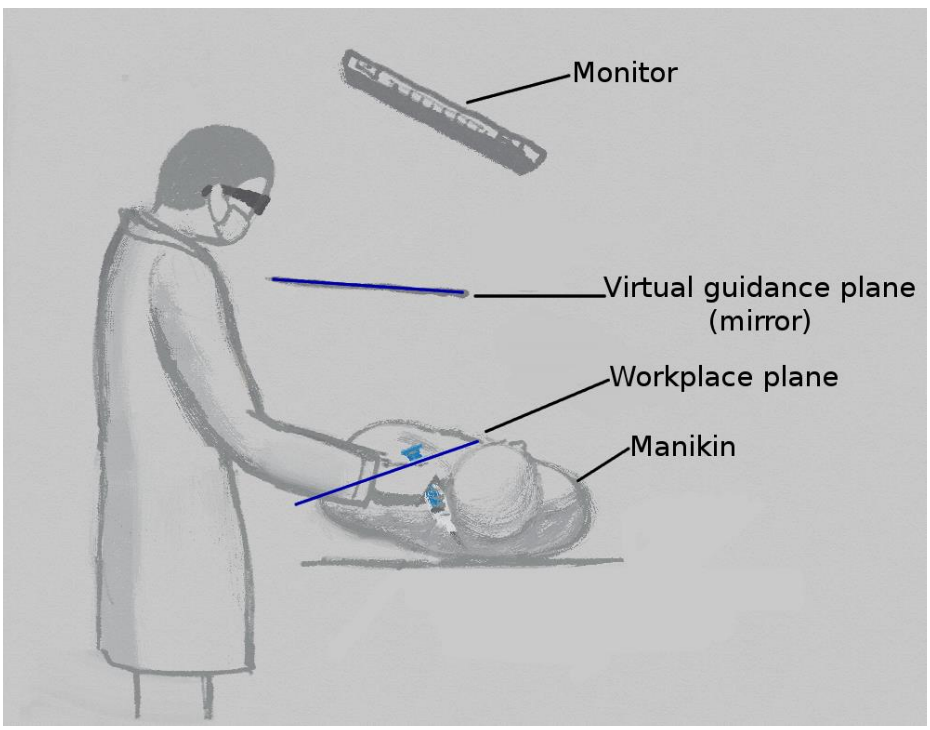


Figure 9 Plane positions

Monitor plane

This plane is related to the location of the monitor screen that the computer will use to project the virtual reality images for the user. The location of the monitor plane is the geometrically opposite to the workplace plane using the mirror or virtual guidance plane as the bisector. Therefore, a change of location of any of the other two planes, affects where the monitor or screen should be placed.

Virtual guidance plane

It refers to the location of the translucent mirror where the images projected by the computer will be reflected towards the user. The translucent mirror will allow the user to see the manikin and his/her hands at all times. The projected images can include the internal anatomy of the manikin/patient or virtual instructional guidance for the right location and orientation of the instruments.

Workplace plane

It is located where the user places his/her hands over the manikin. Here is where the illusion of combining the images reflected on the mirror and the manikin takes place. Therefore the images reflected on the mirror appear to be projected on the real space around the manikin.

Anthropometric dimensions affecting the location of the planes

The Workplace plane's location is determined based on the position where the physician places the hands to perform the Central Line placement. It was determined that the workplace plane needs to be 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 on the patient.

The virtual guidance plane location helps the user to keep his hands under the level of his chest. The user is allowed to incline his/her upper body toward the mirror without occluding the virtual reality images that are projected on the monitor. The physician must not lie closer to the patient throughout the procedure (James Bui, personal source). Therefore the virtual guidance plane or mirror, executes two functions: reflect the virtual models and restrict the position of the physician's head on a safe area.

As described above, the monitor plane is the geometrical opposite plane to the workplace plane using the mirror as the bisector. An important aspect considered for the location of the screen is to avoid the occlusion of the images if the physician inclines over the mirror. Figure 10 shows a tall and a short physician looking the workplace plane over the mirror plane. It can be seen that the screen reflection is not occluded when the user keeps the right position over the mirror.

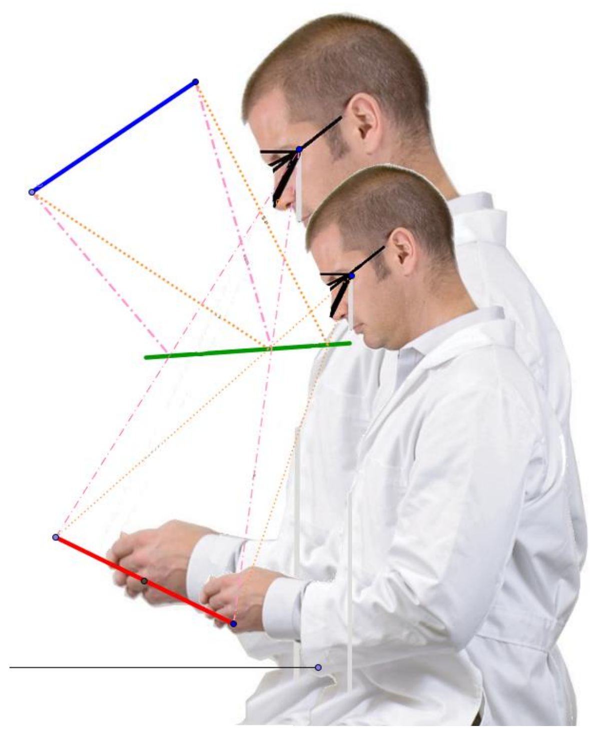


Figure 10 Tall and short users adapted from (Chang, 2014) and using data from (National Aeronautics and Space Administration, 2000)

Figure 11 shows the distribution of female and male heights in the United States, where it can be seen that normally men are taller than women (Gordon, et al., 1989). This data was later used to determine the height of the tallest and shortest physician to maximize the range of population that needs to be covered to use the proposed setup.

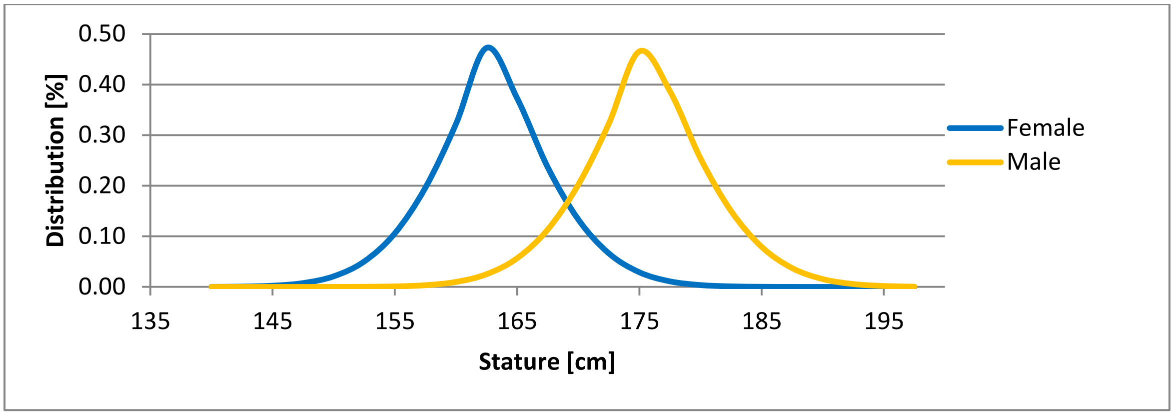


Figure 11 Female and male stature distribution (Gordon, et al., 1989)

In order to restrict the size between the different planes, it was observed the percentage of population covered on intervals of 20cms (7.87 inches) between the tallest and shortest physicians. Data obtained from (Gordon, et al., 1989) and (U. S. Census Bureau, 2012) is summarized in Table V, where it can be seen that the range of 160cms to 180cms is the range that includes the largest proportion of the population (70.4%) on intervals of 20cms.

Range [cms]	Range [ft in]	Female population covered	Male population covered	Total population covered
140 - 160	4' 7'' - 5' 3''	32.2%	1.0%	17.2%
145 - 165	4' 9'' - 5' 5''	62.5%	5.7%	35.2%
150 - 170	4' 11'' - 5' 7''	84.6%	20.2%	53.7%
155 - 175	5' 1'' - 5' 9''	86.5%	46.4%	67.3%
160 - 180	**5' 3'' - 5' 11''**	**67.4%**	**73.6%**	**70.4%**
165 - 185	5' 5'' - 6' 1''	37.3%	86.4%	60.8%
170 - 190	5' 7'' - 6' 3''	13.3%	78.3%	44.5%

Table V Population by gender covered on intervals of 20cms

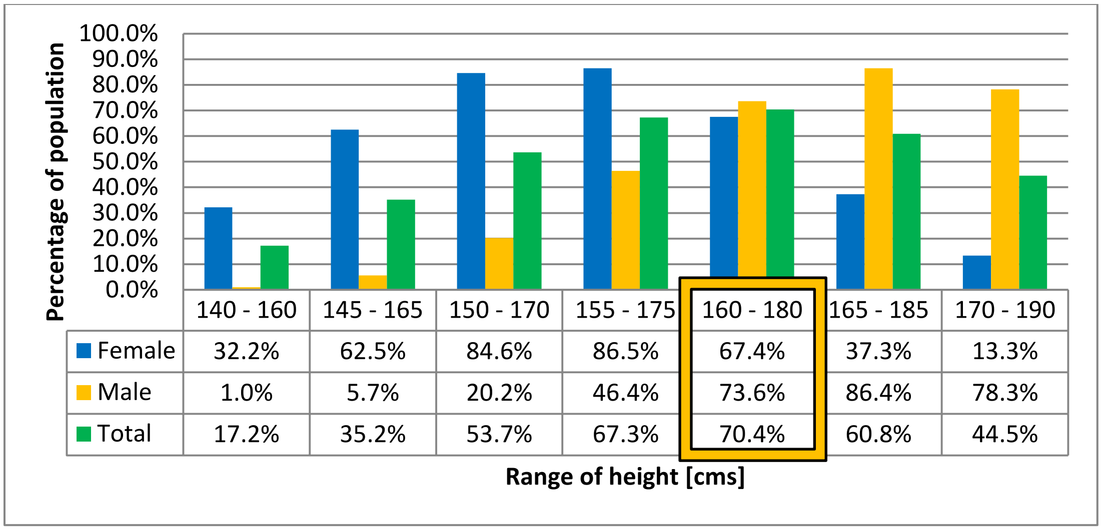
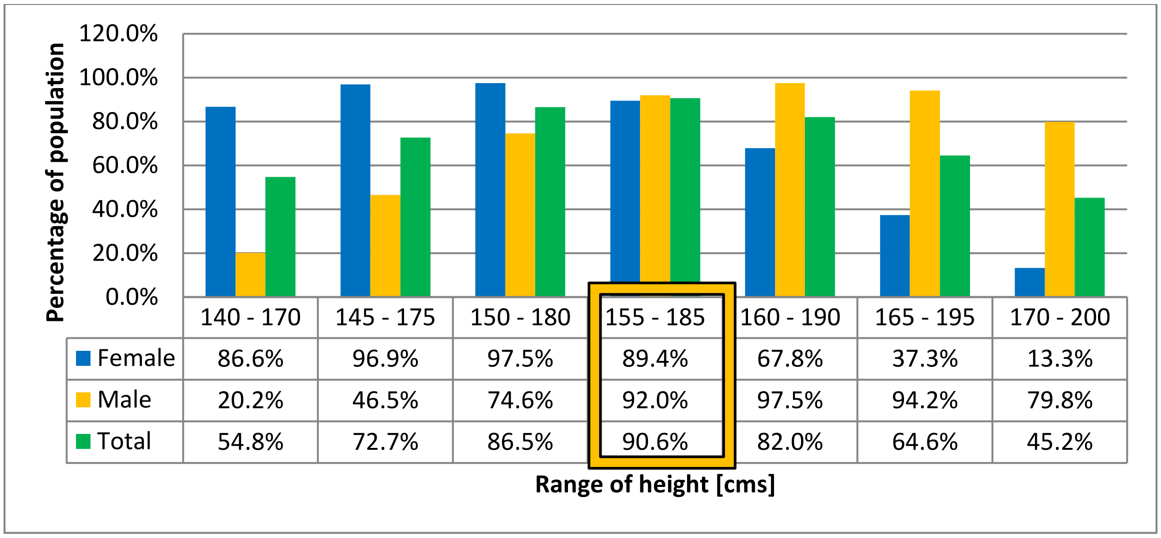


Figure 12 United States population height covered on different intervals of 20cms wide

Running the same study on intervals of 30cms shows that the range that covers a wider population (90.6%) is from 155cms to 185cms (5’1” – 6’1”). The results for the intervals of 30cms are shown in figure 13 and table VI. Almost the total population (99.3%) would be covered if the range of height considered is from 140cms to 190cms. However, the decision of keeping the limits on the interval of 30cms range was made because it reduces the size of the system components (i.e. screen and mirror) and provides a larger and more comfortable workplace for the physician.

Range [cms]	Range [ft in]	Female population covered	Male population covered	Total population covered
140 - 170	4' 7'' - 5' 7''	86.6%	20.2%	54.8%
145 - 175	4' 9'' - 5' 9''	96.9%	46.5%	72.7%
150 - 180	4' 11'' - 5' 11''	97.5%	74.6%	86.5%
155 - 185	**5' 1'' - 6' 1''**	**89.4%**	**92.0%**	**90.6%**
160 - 190	5' 3'' - 6' 3''	67.8%	97.5%	82.0%
165 - 195	5' 5'' - 6' 5''	37.3%	94.2%	64.6%
170 - 200	5' 7'' - 6' 7''	13.3%	79.8%	45.2%

Table VI Population by gender covered on intervals of 30cms



	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 13 United States population height covered on different intervals of 30cms

CHAPTER 4: HUMAN MOTION TRACKING TECHNOLOGY

A surgical training simulator requires to use human-in-the-loop concepts in order de determine with a computer how the user is performing the tasks. Keyboards, buttons and joysticks are input interfaces for the user. However, modern technology has grown to another diversified variety of equipment to track human actions such as electrodes to detect muscle or nerves' activity; or cameras using computer vision software to detect gestures of users such as the Kinect® created by Microsoft (Lowensohn, 2011).

Human motion tracking has also been used in Industrial applications to control robotic arms. Advanced control systems provide commands than combine the reference signal from the user; the environmental disturbances; and the actual response of the actuators. The user would send the commands using a joystick that has force actuators to provide the sense of force instead of numbers displayed on screen. One example of such novel design is from Spar Aerospace Limited by Patrick Fung and his colleagues (Fung, et al., 1992).

Some of the Human motion tracking technologies that can be used for CVC placement training cover three categories: Head Tracking, Hand Tracking and Instrument Tracking. The hardware required for each respective category is a webcam; a depth camera; and electromagnetic sensors with a transmitter. All of these concepts are combined in Figure 14. A more detailed explanation is found on the next sections of the current chapter.

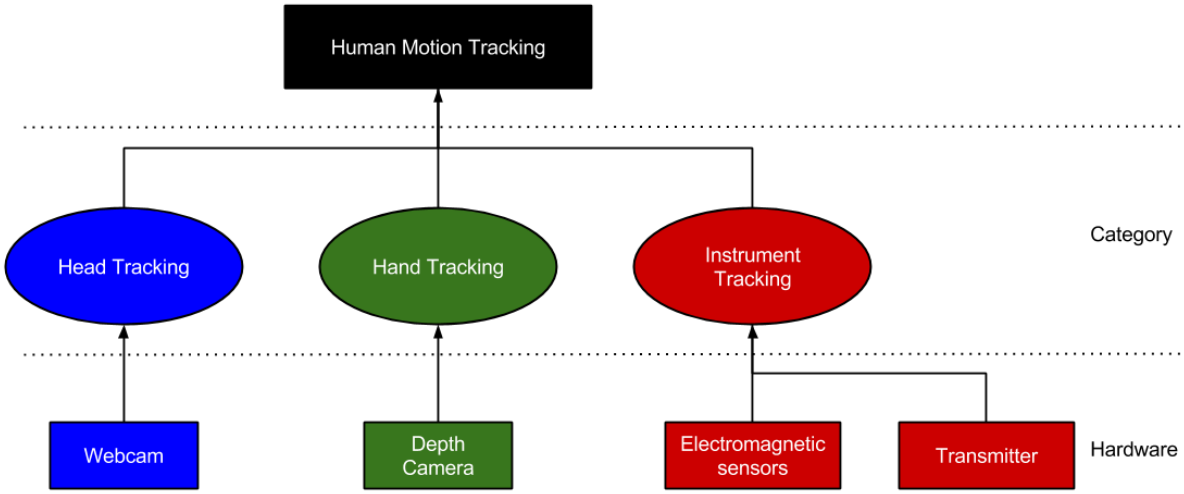


Figure 14 Human motion tracking categories and hardware

A. Head tracking

Current computer vision interfaces such as the Kinect™ camera (Microsoft Corporation, 2015) are capable to recognize gestures or users movement to translate those movements into commands. Other technologies such as the Nintendo 3DS XL console that uses Face tracking recognition allows the user to be immersed in a 3D display without the need of glasses because the console adapts the display according to the position of the head (Webster, 2015). This is not replicable on larger screens because those still need glasses for the three-dimensional effect.

The raspberry PI has also started featuring this workplace with its OEM camera technology. However, the current optical tracking system is not as accurate as other solutions due to its low processing power (Upton, 2013).

Finally, Seeing Machines, an Australian based-company has started to see other uses of head tracking technology to improve safety of drivers (Lebeau, 2015). Seeing Machines has also released a developer kit of the company's faceAPI software that can be used within third party applications (Seeing Machines Limited, 2010).

Factors such as lighting and color contrast of the environment affect the capabilities to detect users in the 2D camera field of view. Therefore, avoiding background lighting and skin colored background would provide a more robust and accurate data acquisition.

The faceAPI algorithm was adapted in a third party application developed for testing purposes on C++. Features of Coin (Kongsberg Oil & Gas Technologies, 2014), an OpenGL based 3D graphics library, were incorporated to make the mesh of a virtual human face. Finally, the algorithm of the software was arranged in such a way that the virtual human face follows the position of the user's head. The user then is required to sit in front of the camera used by faceAPI to start the real time interaction of the virtual model and the position of the user's head. Results of this research are shown in figures 15 to 17.

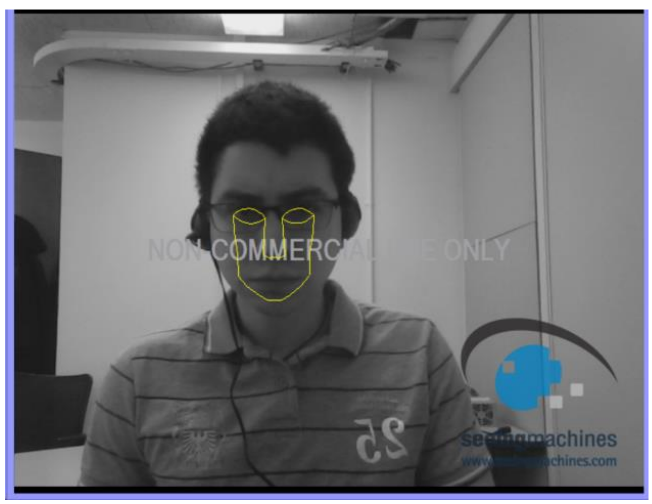


Figure 15 User's face recognition guide adapted from (Seeing Machines Limited, 2010)

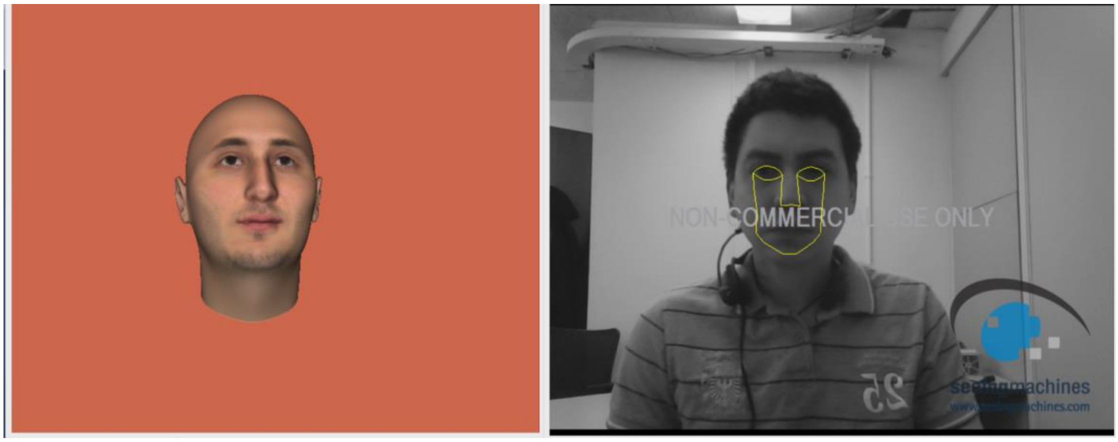


Figure 16 Virtual model and user head looking to the front

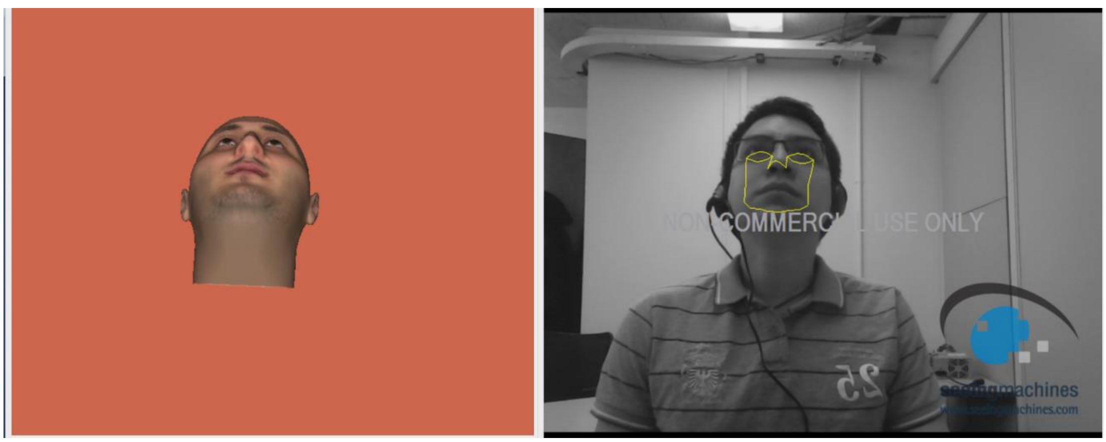


Figure 17 Virtual model and user head looking up

Trial	Distance from the camera		
	45cms [sec]	65cms [sec]	75cms [sec]
1	3.87	3.98	3.29
2	4	3.37	2.88
3	4.57	4.35	4.79
4	4.25	4.09	3.19
5	3.87	3.21	3.05
6	2.54	4.23	4.75
7	3.66	3.73	3.98
8	2.17	4.27	4.27
9	6.29	3.75	3.35
10	2.79	2.74	4.23
11	3.76	3.12	3.73
12	4.03	3.81	4.67
13	2.76	3.8	2.31
14	4.66	3.35	2.94
15	4.37	3.64	4.21
16	3.58	4.43	2.38
17	3.79	4.22	2.86
18	3.06	3.66	3.01
19	3.23	4.1	2.81
20	3.98	3.5	4.51

Table VII Face detection time related to distance from the camera

Table VII shows the time that the face detection algorithm takes to detect the user's face. The average time and deviation is shown in table VIII. Out from these tests, it could be determine that with the proper illumination and low workload on the processor running the algorithm; it takes around 3.7 seconds for the algorithm to detect the user's head. The measurements that correspond to 45cms and 75cms were taken with a chronometer, measuring the time between the camera was uncovered until the face was detected. For 65cms, instead of covering the camera, only the user's head was covered. The measurements on 65cms present smaller deviation in relation to the tests when the camera lens was covered. It is considered that the smaller deviation happens because the camera does not need to adapt the focus or illumination in order to capture a more reliable image. However, the average in all the measurements keeps being around 3.7 seconds with 0.74 seconds of standard deviation.

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

Table VIII Statistics of face detection measurement

B. Hand tracking

The Microsoft Kinect® is a depth camera (able to capture 3D images). It includes a 2D camera and an infrared camera that detects the array of infrared dots projected onto the scene (Microsoft Corporation, 2015). There are other depth cameras available in the market and some of them have their own Software Development Kit (SDK) or are compatible with others. For instance, 3Gear systems developed and SDK built on C++ for hand gesture recognition (3Gear Systems Inc., 2014).

3Gear systems Inc. states that the hand is harder to detect than the face because the orientation of the hand and variability on fingers position makes it harder to recognize patterns. The founder of the company, Robert Wang, started the SDK project using colored gloves and 2D cameras (Wang, et al., 2009) that later were changed for depth cameras.

The inverse kinematic configuration of the SDK from 3Gear Systems was tested to observe how close are certain outcomes for hand positions that are found during the CVC placement. A comparison of these hand gestures is shown in Figure 18.

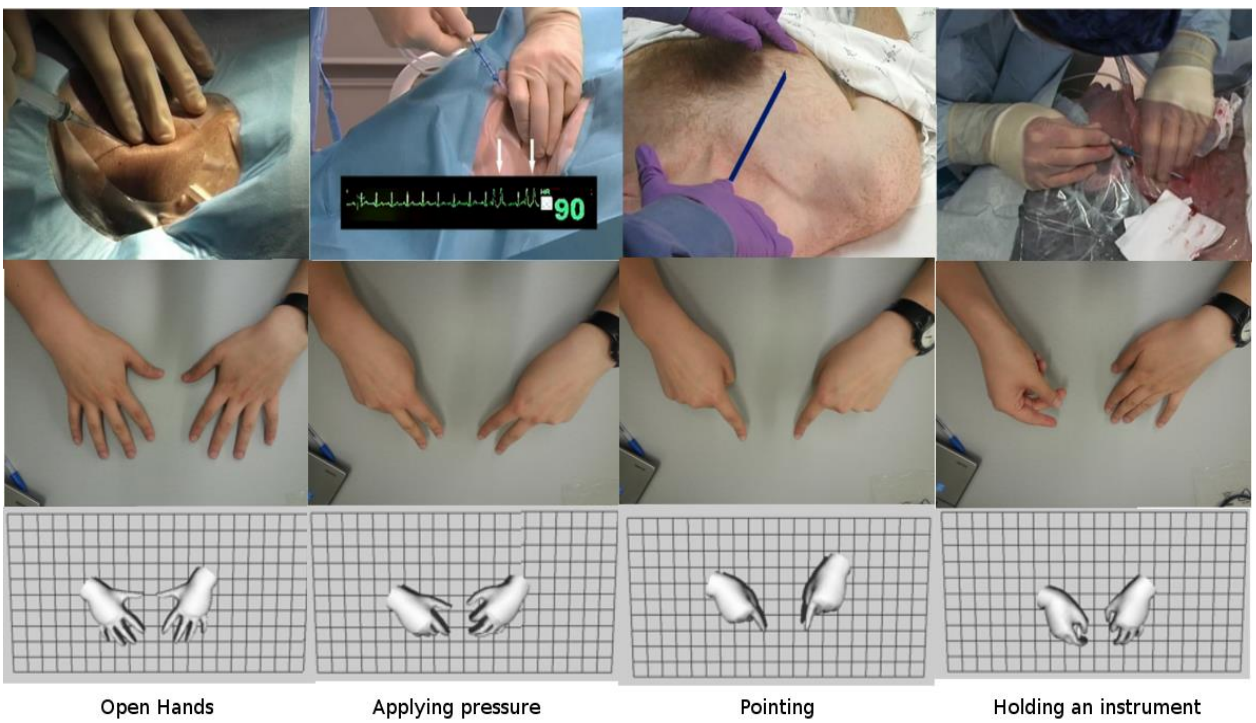


Figure 18 Hand gesture recognition SDK outcomes compared to surgical procedure (top row) [Adapted from (Graham, et al., 2007)], laboratory emulation (middle row) and the software outcome (bottom row)

Figure 18 shows graphically that the hand gesture recognition algorithm is acceptable for the laboratory emulation. However, the software is not capable of detecting the hand when there is an object hold or if the hand is too close to one surface (Robert Wang, 2015 personal communication).

C. Surgical instrument tracking

Electro magnetic sensors are widely used as on/off switches for security systems and as one axis position measurements. These type of sensors work based on a transmitter and a receiver that detects a disturbance in the magnetic field, which is later translated to position. Other high-tech electromagnetic sensors origin around the latest 1970s where an alternating current signal (AC) could generate an AC electromagnetic field that could be detected on the same location by two or three orthogonal antennas. The variance in the electromagnetic field detected by the antennas shall be filtered and amplified to translate the data into location of two or three dimensions (Egli, et al., 1981).

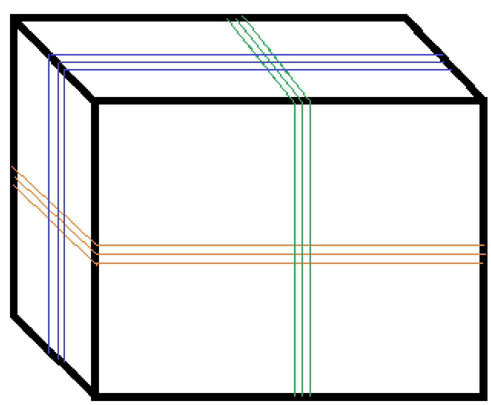


Figure 19 Sensor with three orthogonal antennas adapted from (Blood, 1989)

A Decade later, Ascension Technology Corporation proposed an application for these electromagnetic sensors in such a way that the receptor would be an antenna that using direct current (DC) could be able to determine the three dimensional position of itself. The components used for the technology proposed at that time prevail now: transmitter, receiver, computer, multiplexor, amplifier and converter from Analog to digital signal and vice-versa. These elements are shown in figure 20 (Blood, 1989).

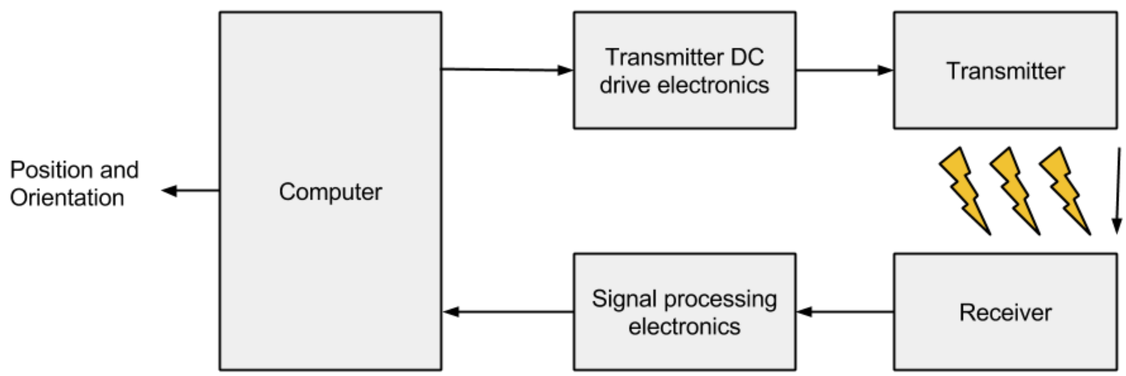


Figure 20 Components for a 3D location system using electromagnetic field [adapted from (Blood, 1989)]

Three years later, Ascension Technology Corporation made some improvements on the system and got reliable measurements of six degrees. Therefore, the sensors could provide the X-Y-Z position and the three different angles or orientation. This time, the earth magnetic field is measured and then each position is determined one at a time, getting twelve data items in the system on a 3 by 4 matrix shown in figure 21 (Blood, 1990).

$$M = \begin{bmatrix} M(1,1) & M(1,2) & M(1,3) & E(1,4) \\ M(2,1) & M(2,2) & M(2,3) & E(2,4) \\ M(3,1) & M(3,2) & M(3,3) & E(3,4) \end{bmatrix}$$

Figure 21 Twelve element matrix for the electromagnetic measurements

The system can be automatically calibrated each time it makes a new measurement. This approach of sensing technique aims to become an alternative for a 3D computer "mouse" without using the scroll function that is usually allocated for depth measurements. This alternative mouse could work as a tridimensional mouse measuring its location and orientation at all times (Blood, 1990).

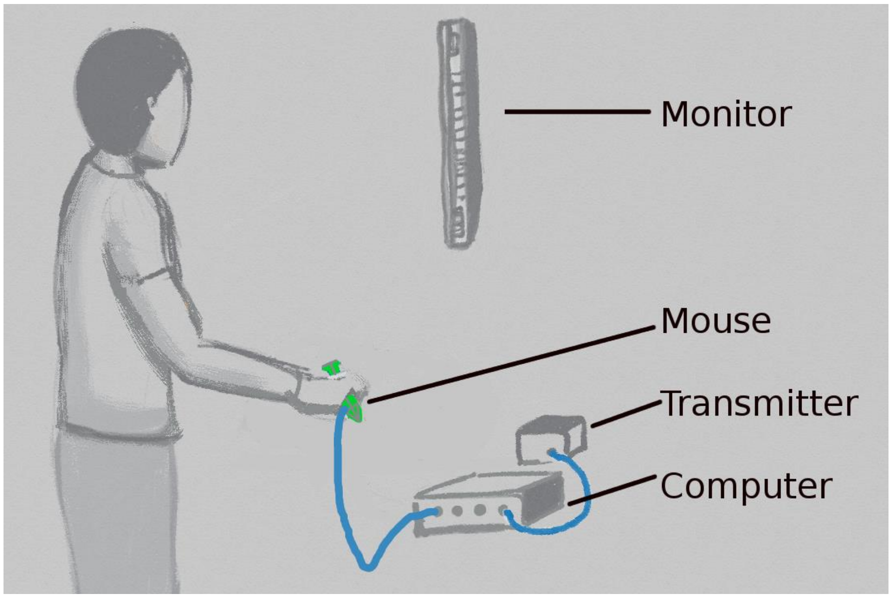


Figure 22 Tridimensional mouse alternative [Adapted from (Blood, 1990)]

For the last decade, Ascension Technology has gotten its leading position in the medical device tracking systems for medical simulators and other state-of-the-art educational systems. Virtamed uses the electromagnetic sensors on its Arthroscopy simulator (VirtaMed AG, 2015). Other applications include a virtual heart simulator that provides a dynamic visualization of the biological pumping process with real time interaction (Ascension Technology Corporation, 2012).

There are also studies related to kinematic data for astronauts' suits to understand and improve the biomechanics capabilities of the suits (Ascension Technology Corporation, 2015). Earlier diagnosis of infantile cerebral Palsy is detected by measuring the mechanic activity on newborns using the same electromagnetic sensors (Ascension Technology Corporation, 2008).

The accuracy of the sensors from Ascension Technology Corporation was tested by comparing the measurements obtained from each sensor at different distances from the transmitter. The layout of the experiment is shown in figure 23. The distance between the sensors (D) obtained at different distances from the transmitter (L) were later compared to the real measurement obtained with a ruler. Table IX shows the obtained distance D (measurement between the sensors) in reference to the distance L (distance between the transmitter and the sensors) along the three orthogonal axes from the sensor. Figure 23 shows the setup using the Z axis for the distance L. Figure 24 shows graphically the difference of measurements from table IX.

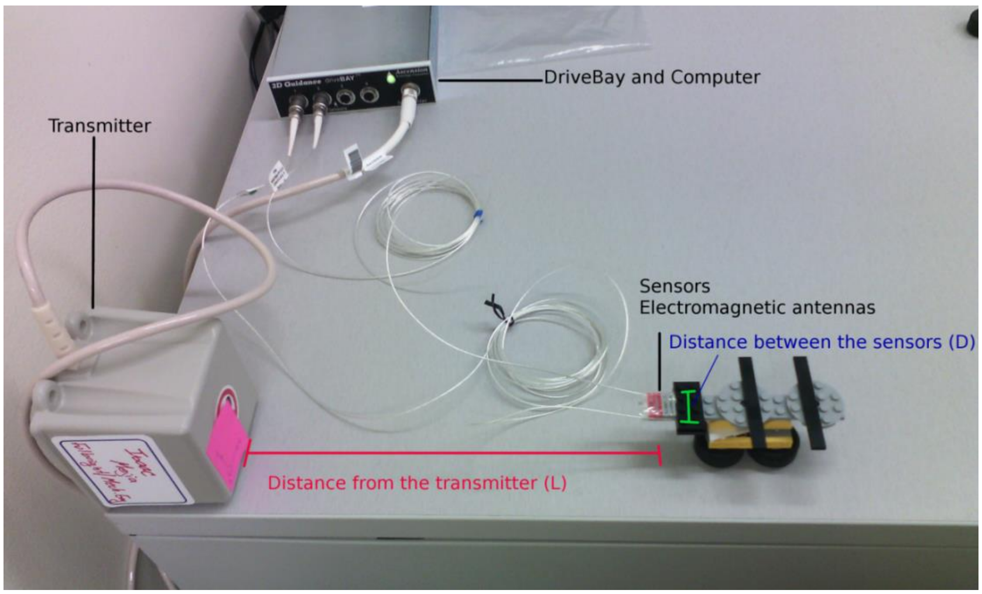


Figure 23 Experiment setup to measure the accuracy of the electromagnetic sensors

Distance L [mm]	X Axis Distance D [mm]	Y Axis Distance D [mm]	Z Axis Distance D [mm]
100	22.0	18.9	18.7
200	18.6	18.4	18.4
300	48.4	36.4	30.5
400	34.7	36.5	36.8
500	20.5	26.6	22.2
600	12.7	14.3	10.6

Table IX Distance D on X, Y and Z axis at different distances L from the transmitter (Reference was 13mm)

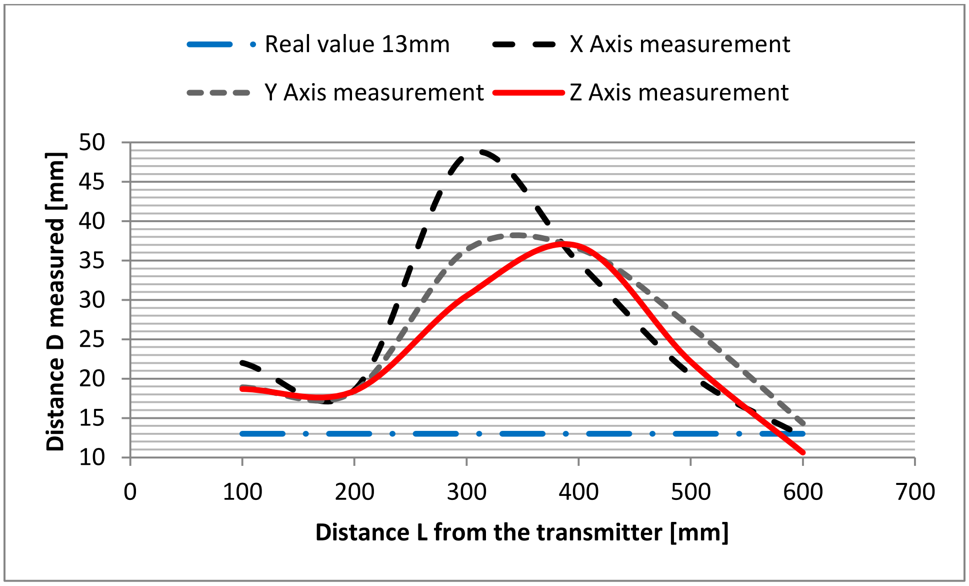


Figure 24 Distance D vs. distance L on the three orthogonal axes (X, Y and Z)

Figure 24 shows that the closest measurements to the reference were obtained on the Z Axis, which is the setup shown in Figure 23. The largest error obtained on Z axis is 35.4mm at a distance L of 300mm from the transmitter (D = 48.4mm and Real = 13mm).

The transmitter will be placed on the same level of the manikin, and oriented in such a way that its Z axis points towards the user. It is therefore needed to measure the accuracy of the electromagnetic tracking system as the sensors attached to the surgical instruments are moved away from the transmitter along the Z axis. A second experimental setup, similar to the one shown in figure 23 was deployed. Figures 25-27 show the second setup were four sensors were used instead of two.

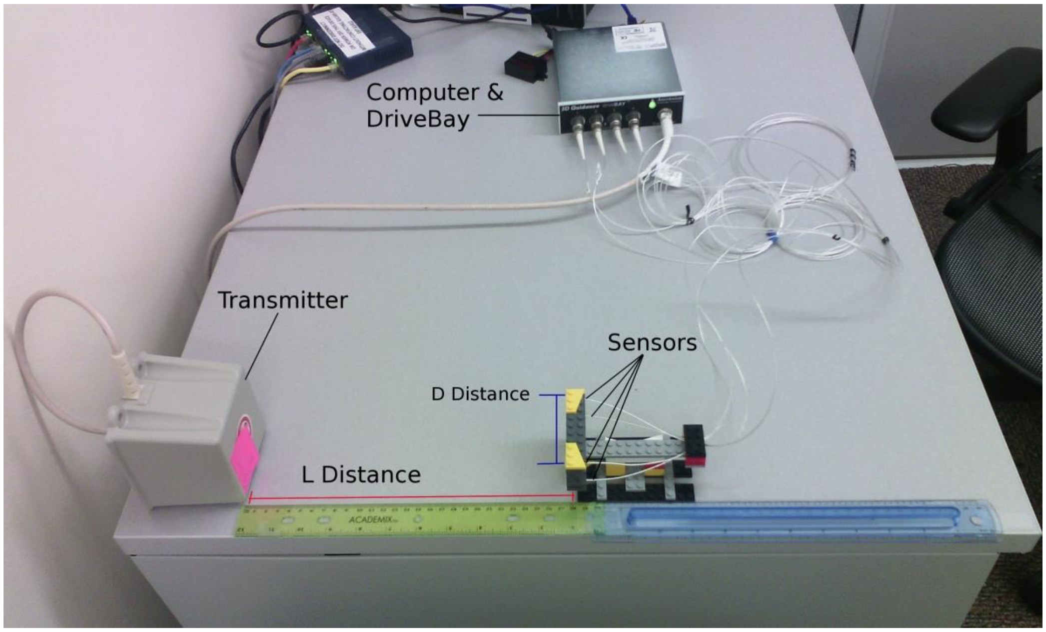


Figure 25 Second experiment setup to measure the accuracy of four electromagnetic sensors

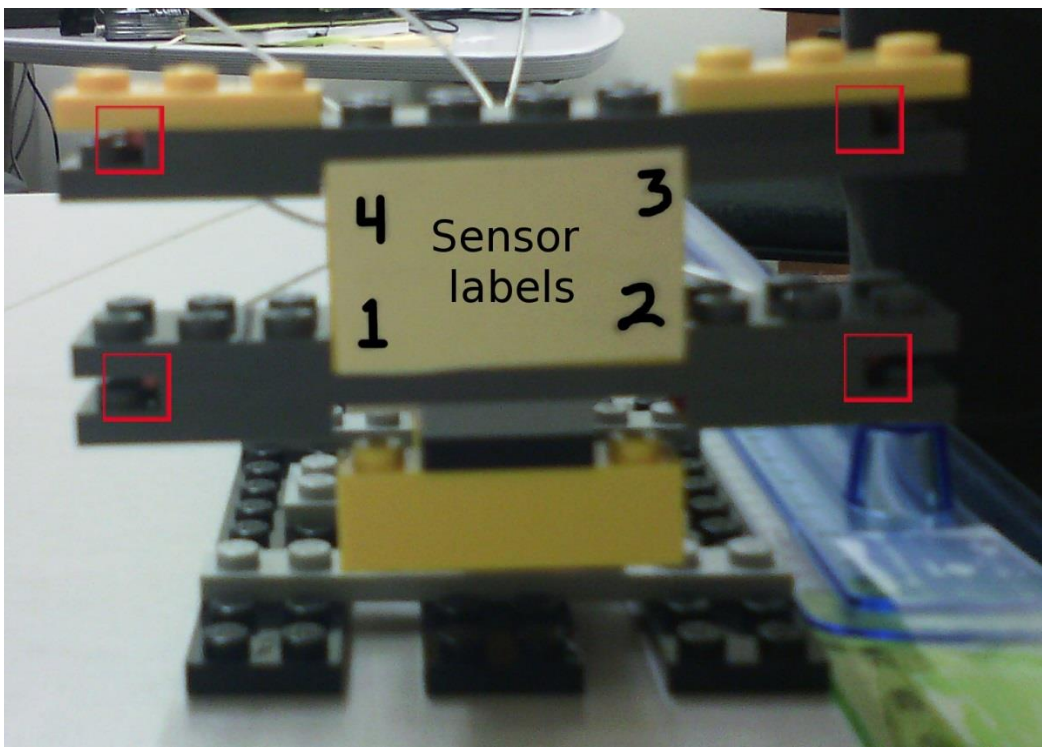


Figure 26 Sensors layout on the second experiment setup

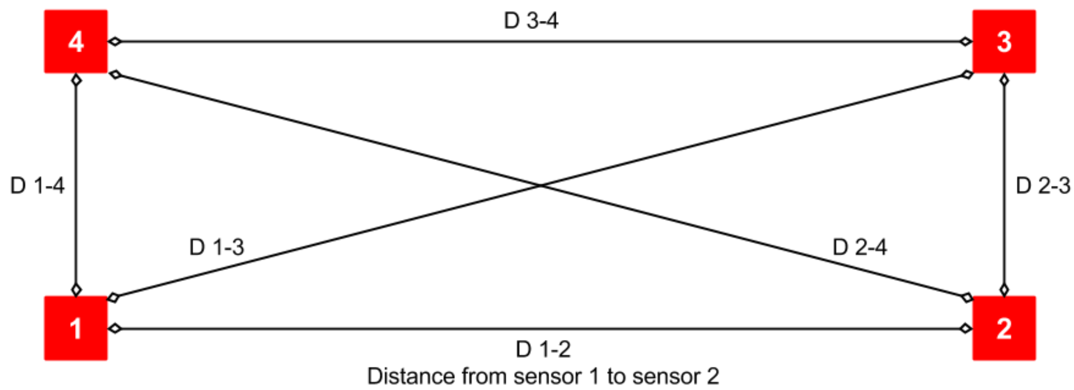


Figure 27 Labels for distances on Experiment setup 2

As presented above, the D measurements are six on the second setup because four sensors are used.

The table IX presents the measurements obtained from the Experiment setup 2.

	Reference 23mm		Reference 66mm		Reference 69.9	
Distance L	**D 1-4**	**D 2-3**	**D 1-2**	**D 3-4**	**D 1-3**	**D 2-4**
100	19.0	16.6	66.9	65.0	71.8	64.6
150	17.2	12.0	67.4	65.4	73.1	62.1
200	17.0	12.5	66.6	63.8	72.9	58.9
250	18.9	19.4	70.0	62.8	73.3	61.0
300	25.1	31.3	82.8	62.2	76.0	70.9
350	44.1	46.9	112.3	61.5	88.3	86.2
400	93.0	316.0	245.4	51.8	98.5	330.9
450	120.6	171.7	182.6	131.2	34.8	296.5
500	96.4	97.1	142.1	141.0	49.0	235.6
550	83.4	82.1	100.2	101.2	18.2	182.0
600	69.1	71.8	76.7	70.1	12.0	141.3

Table X Distances between sensors relative to the distance from the Transmitter (L) on the second experiment

A graphical representation of the results where the deviation can be seen better than the table X is shown in Figures 28-30. The measurements obtained show that above 350mm away from the transmitter, the distances measured vary by over 200mm from the reference value. This concludes that the sensors provide the most reliable measurement when they are placed within 350mm away from the transmitter. Figure 31 shows the D measurements obtained within 100mm to 350mm away from the transmitter.

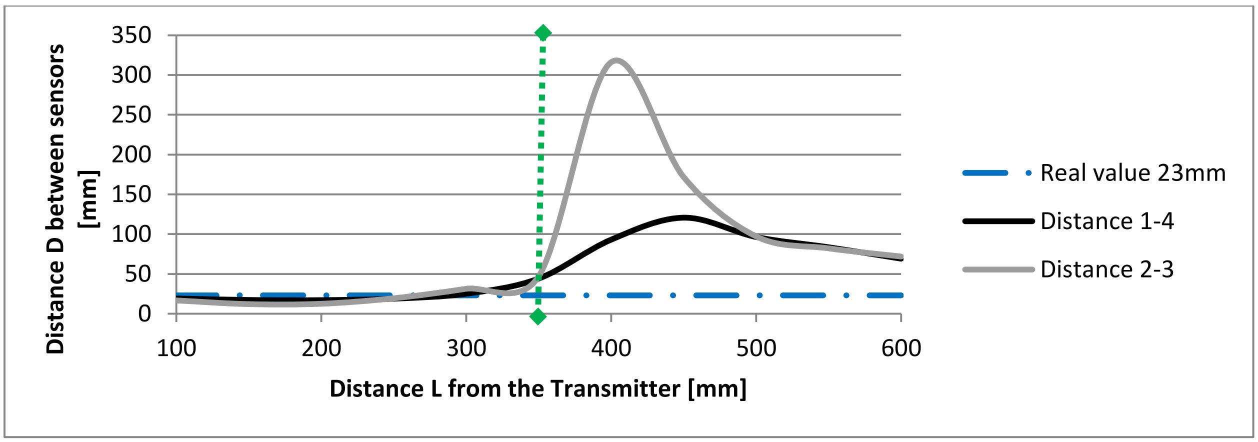


Figure 28 Vertical Distance between the sensors couples: 1-4 and 2-3

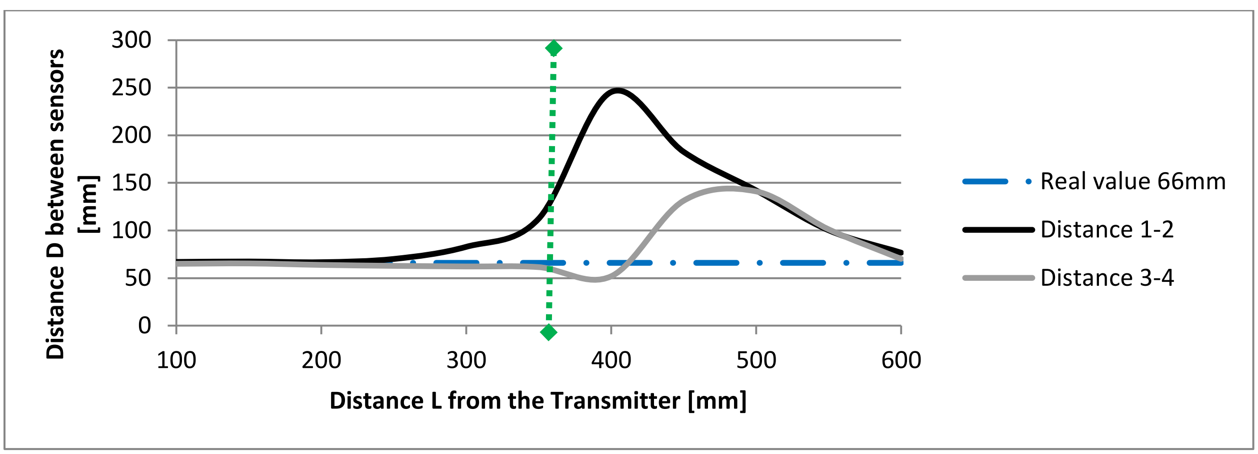


Figure 29 Horizontal Distance between the sensors couples: 1-2 and 3-4

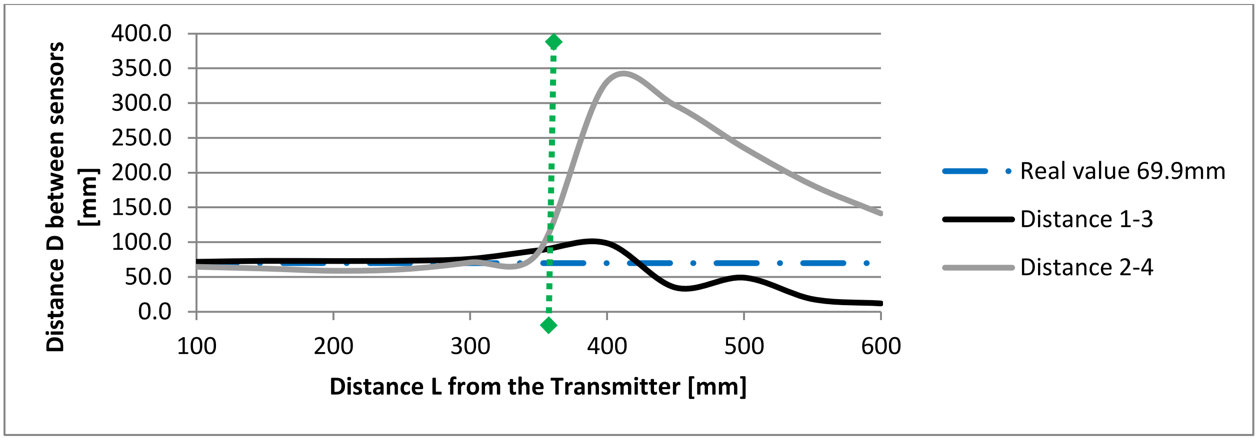


Figure 30 Diagonal Distance between the sensors couples: 1-3 and 2-4

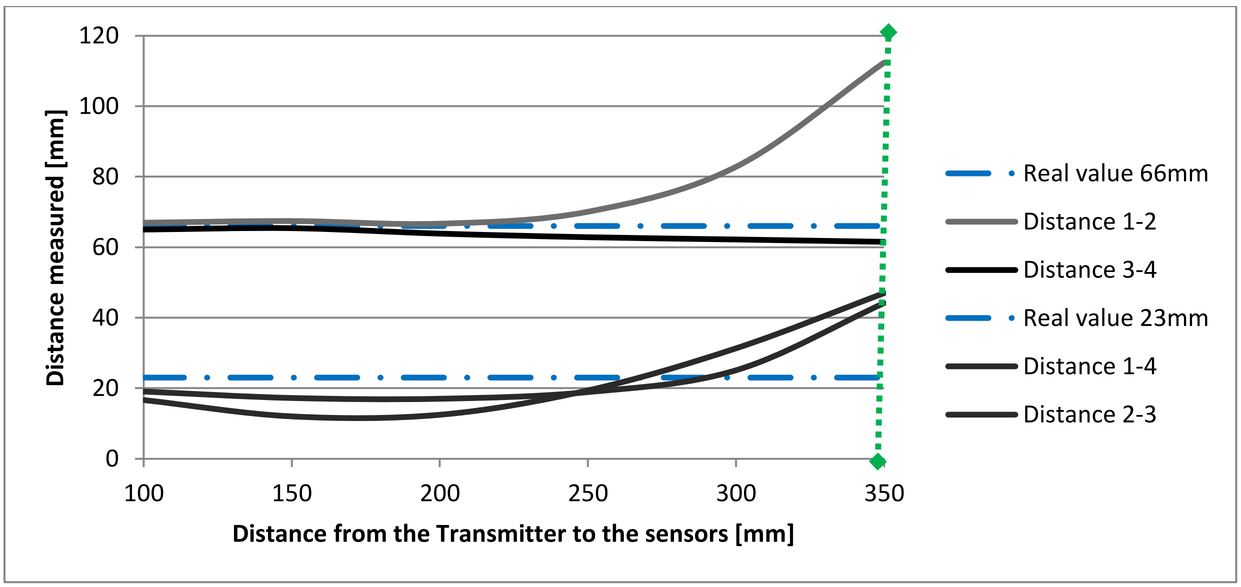


Figure 31 Horizontal and Vertical distances D between sensors on the range of distance L from 100mm to 350mm

It was empirically found that the best measurements belong to the range of distance from the sensor to the transmitter between 100mm and 300mm. Therefore, this is the optimal range to use the electromagnetic sensors. It is important to recall that these measurements gave the distance between two sensors using one as the reference.

The data obtained from the second experiment setup also provided the measurements using the transmitter as a reference. This is to compare the largest error (measurement obtained minus real value) on both scenarios: using a sensor or the transmitter as the reference. The obtained measurements on the optimal range (100mm-300mm) using the transmitter as a reference are shown in figure 32. Only the results in the optimal range are displayed because the difference of the measurements after the 300mm mark are over 50mm and therefore not acceptable.

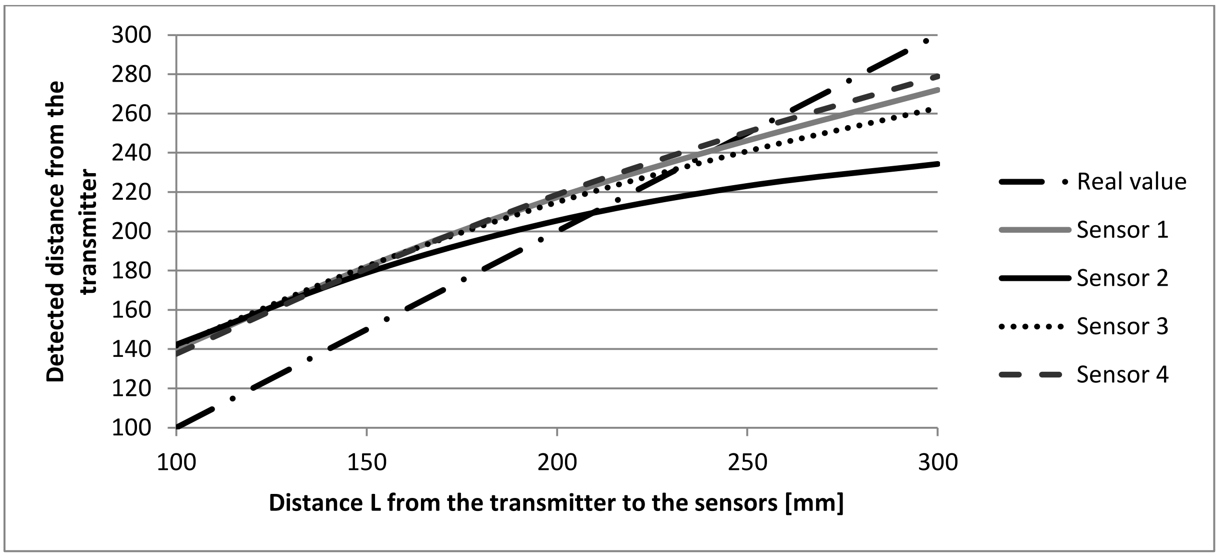


Figure 32 Distance from the transmitter on the Z axis using the reference as the transmitter

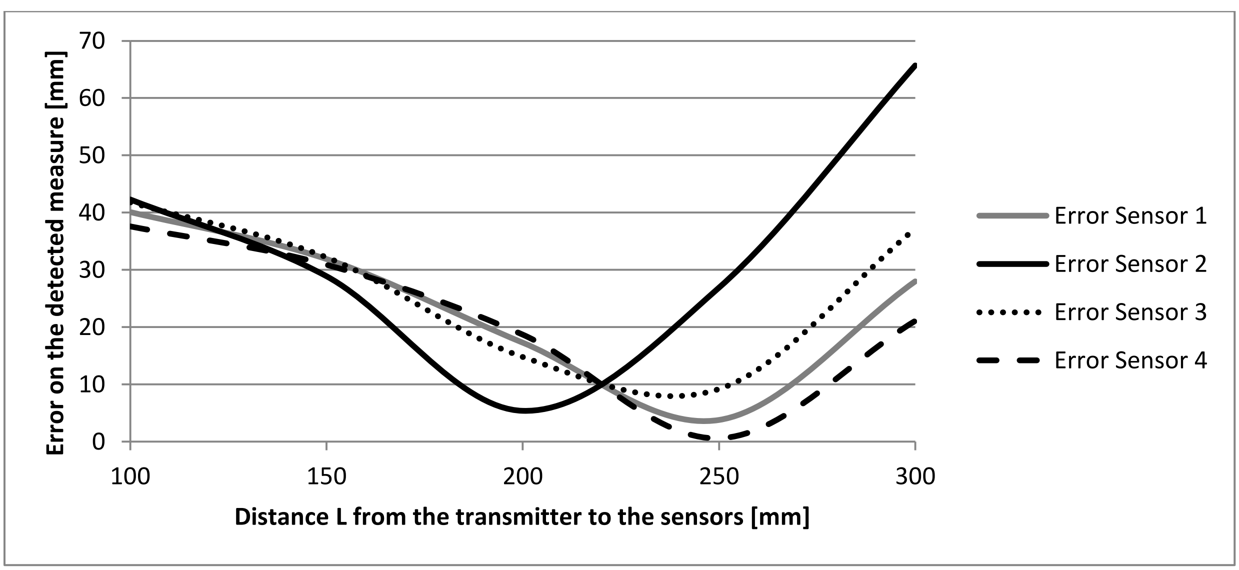


Figure 33 Absolute error on measurement using the transmitter as the reference

Figure 34 shows a comparison of the average errors obtained using either a sensor or the transmitter as a reference. From the experiment, it can be concluded that the lowest error is obtained when the sensor is used as a reference.

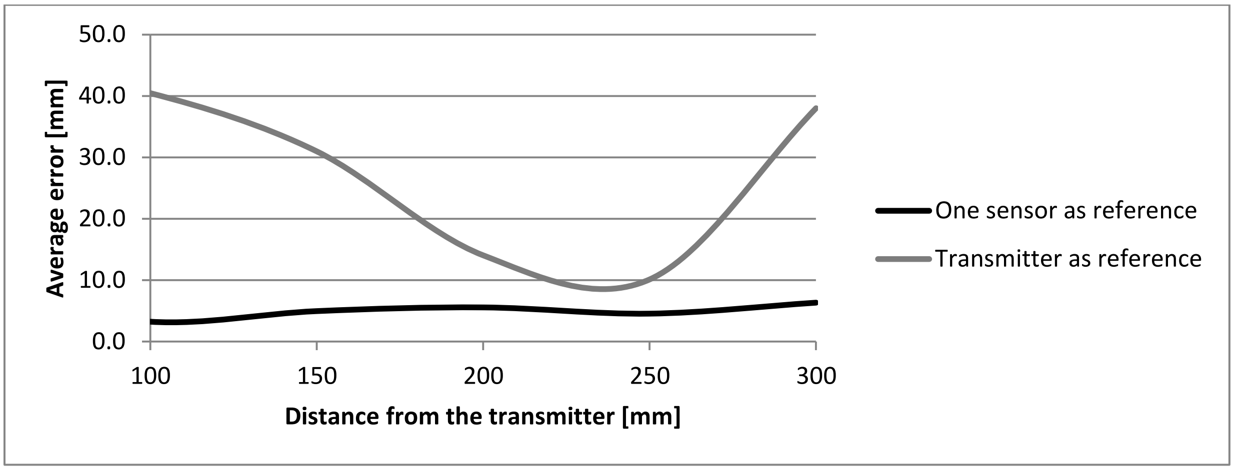


Figure 34 Average error using one sensor or the transmitter as reference

The software for the electromagnetic sensors also provides a manufacturer's estimated quality measurement. Figure 35 shows that the manufacturer's quality of the measurement reaches the highest values farther than 350mm away from the transmitter. However, as it can be seen in Figure 36, high manufacturer's quality values do not imply low error of the measurement.

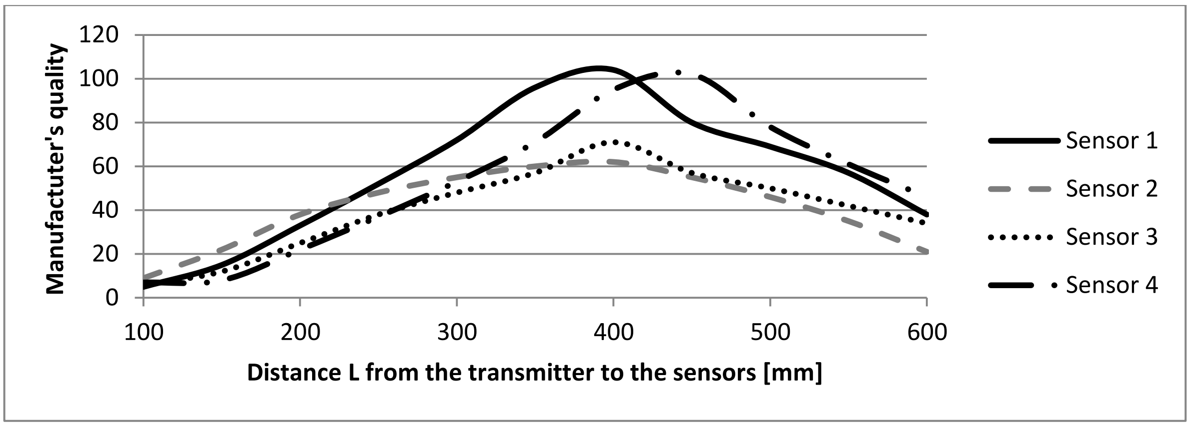


Figure 35 Manufacturer's quality for the four sensors

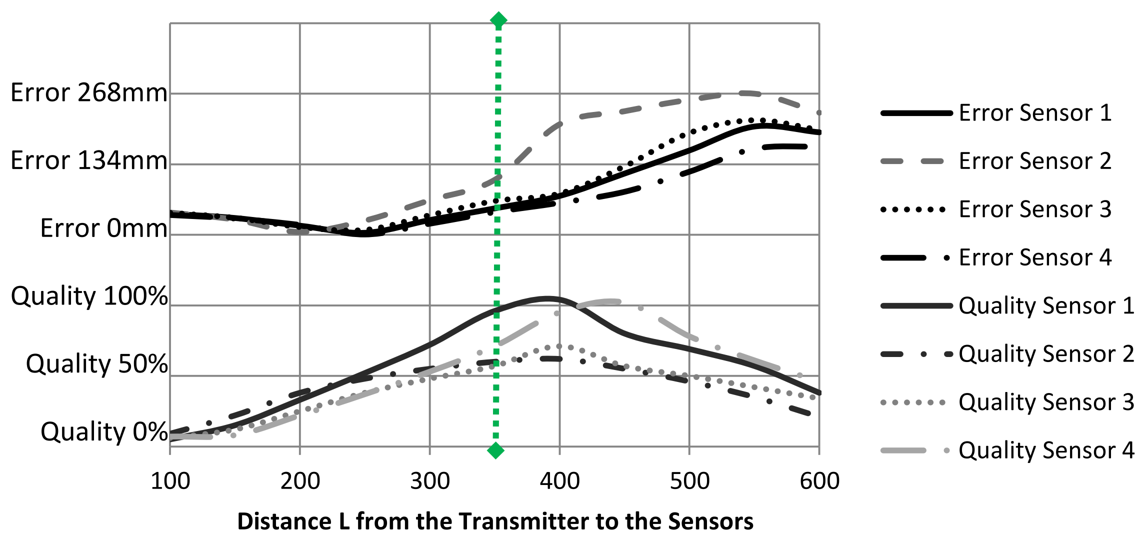


Figure 36 Error and manufacturer's quality for the four sensors

The data shown in figure 36 makes noticeable that once again, after 350mm away from the transmitter, the error on measurements are around 65mm (2.6") representing an error of 18%. The quality is at its maximum from 350mm to 450mm, area where the errors start to increase in size up to 140mm (5.5"). It was concluded from the data that the best range to keep track of the sensors is between 100mm to 300mm (4" – 11.8"). The experimental average error found is around 3.2mm (0.13") at 100mm and 21.8m (0.86"). These experimental errors are shown in Table XI.

Distance L	Average error	Average 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

Table XI Average error and quality at different distances L from the transmitter

CHAPTER 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 have benefits such as: standardized training avoiding the variance in instruction from other physicians, capability to recognize user's errors and correct them, reduced cost since no need of hiring supervising physicians.

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 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 see with an error less than one centimeter 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.

Finally, the technology that was evaluated for human motion tracking makes it possible to evaluate the physician’s actions. Therefore, a future simulator for CVC placement training is feasible using this technology for tracking the head, hands and instruments.

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APPENDIX A. List of Common Abbreviations

CVAD	Central Venous Access Device
CVC	Central Venous Catheter
D	Distance between the sensors
EJV	External Jugular vein
HITL	Human-In-The-Loop
IJV	Intra Jugular vein
L	Distance between the transmitter and the sensors
PICC	Peripheral Inserted Central Catheters
SCV	Subclavian vein
VR	Virtual Reality

APPENDIX B. Licensing of Images

Figure 1 Trendelenburg position from Chapter 1

Summary

Description	**فارسی:** پوزیشن ترندلنبرگ
Date	15 March 2013, 15:28:19
Source	Own work
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