

# TOWARDS A HYBRID VIRTUAL/PHYSICAL NUSS PROCEDURE SURGICAL SIMULATOR

Mohammad F. Obeid<sup>(a)</sup>, Eun-sil Heo<sup>(b)</sup>, Krzysztof J. Rechowicz<sup>(c)</sup>, Robert E. Kelly<sup>(d)</sup>, Frederic D. McKenzie<sup>(e)</sup>

<sup>(a),(b),(c)</sup>Dept. of Modeling, Simulation and Visualization Engineering  
Old Dominion University Norfolk, USA

<sup>(c)</sup>Virginia Modeling, Analysis and Simulation Center  
Old Dominion University Norfolk, USA

<sup>(d)</sup>Pediatric Surgery, Children's Hospital of The King's Daughters and Eastern Virginia Medical School, Norfolk, USA

<sup>(a)</sup>[mobei001@odu.edu](mailto:mobei001@odu.edu), <sup>(b)</sup>[heox002@odu.edu](mailto:heox002@odu.edu), <sup>(c)</sup>[krechowi@odu.edu](mailto:krechowi@odu.edu), <sup>(d)</sup>[robert.kelly@chkd.org](mailto:robert.kelly@chkd.org), <sup>(e)</sup>[rdmckenzen@odu.edu](mailto:rdmckenzen@odu.edu)

## ABSTRACT

Surgical simulation is embraced by many for training and skill transfer purposes of non-trivial minimally invasive procedures. Some systems utilize haptic feedback within an anatomically-correct virtual environment whereas others use manikins, synthetic components and box trainers. This paper explores the challenges and implications of reproducing the Nuss procedure on both a solely-virtual and a solely-physical environment. This work then describes a roadmap for a hybrid system that employs a best-of-both approach integrating both physical and virtual schemes to achieve a mixed reality implementation of the primary steps of the Nuss procedure.

Keywords: surgery simulator, mixed reality, hybrid simulation, Nuss procedure

## 1. INTRODUCTION

Over the past two decades, minimally invasive procedures (MIP) have influenced the popularity of conventional approaches with regards to scarring, recovery times and pain medication aspects. It is often argued, however, that such procedures pose a prolonged learning curve for most novice surgeons. Preoperative training and proper surgical planning can alleviate such limitations. In the early stages, such planning existed in the form of collaboration between radiologists and surgeons using three-dimensional representations of organs and body components constructed from MRI and/or CT images for preoperative planning such as for colonoscopy (Vining 1997) and craniofacial surgery (Altobelli, Kikinis et al. 1993). In principle, high fidelity surgical simulators can be employed for surgical training and education and proved to be an advantageous part of a teaching curricula (Satava 2001).

Today, a number of commercially available and under development simulators exist for most common endoscopic, laparoscopic, and, in general, minimally invasive procedures. SimSurgery's Educational Platform

for laparoscopic procedures (SimSurgery 2015), Symbionix's numerous mentors for laparoscopic, endoscopic, arthroscopic, endovascular and other procedures (Symbionix 2015), SurgicalScience's procedural simulation systems for cholecystectomy, appendectomy, suturing and anastomosis (Surgical Science 2015), and Mentice's Minimally Invasive Surgical Trainer (MIST) (Mentice 2015), are all examples of such simulation systems.

Others are developing simulation and training systems in medical robotics. Among those are projects that aim for skill transfer and training for operating the da Vinci surgical robot. Although Mimic's dV-Trainer (Mimic 2015) is a pioneer in this area, Simulate Surgical Systems' RoSS (Simulated Surgical Systems 2015) and Symbionix's Robotix Mentor (Symbionix 2015) are not far behind.

According to Milgram and Kishino (Milgram and Kishino 1994), the conventional view of a *virtual reality* (VR) environment is one where the user views, and interacts with, a completely synthetic world that consists of virtual objects. On the other extreme of the virtuality continuum, a *real environment* is one that consists solely of real objects. A display system that falls somewhere between the two and involves a merge of real and virtual worlds is referred to as *mixed reality* (MR). This concept of mixed reality is carried on in this work and will be used with the term *hybrid* interchangeably.

Many of the aforementioned surgical simulators use physical components when simulating external behaviors such as a tool insertion process, whereas others utilize haptic feedback. A simulator that integrates a physical component representing an anatomically correct part of the body (a manikin) with a virtual environment displayed on a monitor is referred to, in this work, as a *hybrid simulator*. This definition of a hybrid excludes simulators that use physical ports mounted on arbitrary objects like a box or hemisphere and focuses on those that use an anatomical manikin.

Pectus Excavatum (PE) is a congenital chest wall deformity that affects children and young adults exhibiting a sunken or funnel anterior chest wall (Huddleston 2004). In the Nuss Procedure, two small incisions are made on either sides of the chest to insert a pre-bent steel bar from the side of the chest to be placed and secured beneath the funneled area to elevate and support the sternum pushing out the sunken part of the ribcage. The surgeon uses a thoracoscope to monitor the procedure internally in addition to the external view of the patient's torso (Nuss and Kelly 2008).

The need to, pre-operatively, enhance surgical skills of trainees as well as alleviate risks of complications during surgery drove the development of a surgical simulator. The Nuss Procedure Surgical Simulator (NPSS), (Rechowicz, Obeid et al. 2014; Rechowicz, Obeid and McKenzie 2014), utilizes patient-specific data to create a computer generated virtual model of the patient and the deformity and allows the user to interact with the environment through a haptic interface. Simultaneously, an anatomically correct manikin was developed combining 3D-printed components with synthetic materials to create a physical simulator for the procedure. This work aims to compare the two implementations against relevant criteria derived from the nature of the surgery to identify potentials and weaknesses of each setup in order to pave the road for a hybrid model that combines the best of both.

## 2. RELATED WORK AND STATE OF THE ART

Relating to Milgram and Kishino's virtuality continuum model but in a more related context, ASERNIP-S's systematic review describes, among others, three types of surgical simulators: virtual reality (VR), physical, and hybrid (Sturm, Windsor et al. 2007).

### 2.1. Virtual Reality (VR) Simulators

In virtual reality surgical simulators, computer generated instruments are used to manipulate computer generated objects in a virtual environment through specially designed interfaces. A high-fidelity simulator of this type is usually expensive but provides objective performance measurements, error tracking and tactile (haptic) feedback.

Peterisk et. al. worked on reproducing haptic volume interactions for bone surgery simulations. Recently, VOXEL-MAN commercialized their fully-virtual Tempo and Dental simulators for training surgical access to the structures of the middle ear, and for training on dental procedures, respectively (Petersik, Pflesser et al. 2002; Voxel-Man 2015). A similar all-virtual surgical simulator was developed by Choi *et al.* for the phacoemulsification procedures of the cataract surgery (Choi, Soo and Chung 2009). Heng et. al. built a tailored force feedback device that compensates for all related forces within the surgical simulation for arthroscopic surgery (Heng, Cheng et al. 2004).

Many others have developed and commercialized VR simulators for endoscopic procedural tasks such as camera navigation, instrument manipulation, perceptual-

motor skills coordination, grasping, cutting, clipping, dissection, and suturing. SimSurgery's Education Platform (SimSurgery 2015), Surgical Science's LapSim (Surgical Science 2015), Symbionix's LapMentor (Symbionix 2015), and CAE Healthcare's LapVR (CAE Healthcare 2015) are such products for laparoscopic surgery. For other endoscopic procedures, Surgical Science's EndoSim (Surgical Science 2015), Symbionix's Bronch Mentor (Symbionix 2015), and CAE Healthcare's EndoVR (CAE Healthcare 2015) are available.

### 2.2. Physical Simulators

Physical (synthetic) models and box trainers use models of plastic, rubber and latex to render different organs and pathologies (Cisler and Martin 2006). This type is generally used as a low-cost, portable platform for part-task trainers but is limited in aspects such as time required to replace components, level of realism, haptic forces, and lack of inherent metrics of performance.

Delletec provides several synthetic components for simulating various surgical procedures including appendectomy, breast biopsy, laparoscopy, and many others (Delletec 2015). SimuLab offers synthetic and physical models and manikins for numerous open and laparoscopic surgeries as well as box trainer modules. TraumaMan is considered one of their popular systems (SimuLab 2015).

### 2.3. Hybrid Simulators

Hybrid simulators are a combination of physical simulators and VR simulators, where a physical object (usually a manikin) is linked to a computer program that provides visual images and/or feedback (Satava 2001). The virtual component, i.e., the computer program, produces patient responses and simulation dynamics, whereas the physical component provides the ability to interact with the patient's physical constructs.

Many systems have proven a more practical, realistic and efficient reproduction of surgical procedures when composed of an integration of a physical manikin with a virtual environment. Such a mixed reality implementation was developed by Li *et al.* for arthroscopic knee surgery simulation. In their system, they used an artificial knee joint from Pacific Research Laboratories. As the user manipulates the actual tools and arthroscopic camera used in the surgery, the display shows a synchronized 3D computer generated model of the joint.

Symbionix commercializes Arthro Mentor for arthroscopic training which combines fiberglass/polyurethane anatomical models (shoulder, knee and hip) with 3D images and a haptic interface, allowing the user to operate the actual instruments and the arthroscopic camera (Symbionix 2015). CAE Healthcare provides VirtaMed ArthroS for knee and shoulder arthroscopy training in a mixed reality environment that integrates anatomical rubber models of a knee or shoulder with a corresponding virtual environment, also allowing the user to train on the original surgical tools (CAE Healthcare 2015).

### 3. METHODS

Simulating a non-laparoscopic (involves instruments other than common laparoscopic graspers, scissors, dissectors and clip-appliers) minimally invasive procedure can be challenging due to the nature of the used surgical tools. Depending on the procedure, a physical constituent can be of great significance to enhance realism aspects. This section describes methods used to construct the fully-virtual NPSS and introduces the under-development fully-physical NPSS. The two schemes are then compared against critical tasks of the Nuss procedure to demonstrate where each setup adds more value.

#### 3.1. Nuss Procedure Tasks

In collaboration with surgeons who frequently perform the Nuss procedure, a task breakdown was performed for the surgery and a (high, medium, or low) evaluation of priority was assigned to all tasks and subtasks of the procedure. This evaluation reflects the importance of each subtask in the training context, i.e., the significance of a correct skill-transfer for that particular subtask. This task analysis was used as an assessment platform for the various constructs of the NPSS. Table 1 shows how each subtask is executed on both the virtual and the physical setting of the NPSS. An initial assessment of each implementation is done by displaying the one that is anticipated to perform more efficiently and satisfactory in bold).

#### 3.2. A Solely Virtual Setup

As thoroughly explained in (Rechowicz, Obeid et al. 2014) and (Chemlal, Rechowicz et al. 2014), a virtual version of the NPSS was developed by integrating a virtual environment with a haptic interface. A generic low polygon model of the patient's torso was adjusted to a skinny posture, a skeletal model based on the Visible Human Project (Ackerman 1998) was used to create the ribcage, the pericardium was modeled based on an anatomical atlas, and generic models of the lungs and the diaphragm were obtained from a 3D models repository. The main tool used in the procedure -the introducer- was modeled using orthogonal photographs. The virtual environment also includes a thoracoscopic camera that follows the surgical tool and shows the real-time dynamics including collisions, deformations and heart beating. As explained in (Rechowicz, Obeid and McKenzie 2014), the patient's model as well as the reproduced PE deforming are formed according to patient-specific data. Table 1 describes how the simulator performs each of the Nuss procedure tasks.

In the actual surgery, since the introducer's movement is limited at the insertion point within the selected intercostal space and by the room of motion inside the body, these constraints can be simulated in the haptic interface by applying corresponding forces that vary depending on the stiffness of the simulated tissue or surrounding organs. The haptic device's forces approximate a virtual pivot (Obeid, Chemlal et al. 2014) constraining the tool from motion in the local x- and y-

directions by applying high stiffness forces while allowing translation in the z-direction only for further insertion.

#### 3.3. A Solely Physical Setup

In a prototyped fully-physical version of the simulator, rapid prototyping, 3D printing and form casting techniques are utilized to create a physical manikin simulator of a patient's torso with a PE deformity. The skeletal model from the Visible Human Project (Ackerman 1998) is used to create a 3D model of a deformed ribcage. The ribs are then 3D-printed and mounted on the apparatus along with synthetic skin and muscle and incorporated with casted organs. The synthetic skin and muscle are replaceable to allow for repetitive training. A metal hinge is inserted into the sternum to introduce the PE deformity as an added elastic connector pulls the sternum posteriorly toward the spine. In addition to a small camera mounted on a steel rod for thoracoscopy, the user is able to operate the actual surgical tools including, among others: introducer, Kelly clamp, pectus bar, and bar flipper. Table 1 describes how the simulator performs each of the Nuss procedure tasks.

### 4. DISCUSSION AND NEW APPROACH

As can be observed in Table 1. Each setup varies in its successful implementation of different aspects of the procedure. In this section, the advantages and disadvantages of each setup will be discussed and a new hypothesized improved setup will be introduced.

#### 4.1. Merits and Limitations

For each of the two setups, some steps of the procedure are better and more accurately reproduced. In this section, the merits, advantages and limitations of each setup will be discussed to shed light on the areas where each setup contributes more in order to define areas of strength for each.

##### 4.1.1. Solely Virtual Simulator

Given the nature of a generic (3-DOF) haptic device's end-effector, no insertion mechanism can be performed without moving the stylus' natural pivot along. Therefore, although the force models for constraining the haptic device's motion and simulating collisions are a successful approximation of the tool's pivoting behavior, a discrepancy is present where the end-effector is always carried along causing the stylus' physical joint to be located, at some instances, at coordinates that correspond to the inside of the patient.

Furthermore, the virtual implementation of the simulator lacks visual cues such as an exterior visualization of intercostal spaces (tasks 2b, 2c, and 3 in Table 1). It is also not, or at least not easily, possible in such setup to utilize the haptic device to operate instruments such as a bar flipper, Kelly clamp, suture needle and umbilical tape (tasks 4 and 10 in Table 1).

In this setup, however, patient-specific modeling is used to create a planning platform where dimensions and parameters describing the patient's torso and deformity

are extracted from CT data to, consequently, tailor the models (task 2a in Table 1). Furthermore, the virtual environment allows for introducing surgical scenarios and complications to the procedure for training aspects. Another benefit from a virtual setup is the ability to accurately reproduce forces with the aid of the haptic device and associated physics-based models.

#### 4.1.2. Solely Physical Simulator

The physical setup clearly adds value to tasks that require the use of surgical instruments where fine movements are expected such as making an incision, creating a suture and securing the stabilizer. The reproduction of the mechanical behavior and pivoting motion of the surgical tools are flawless here as they, the tools, are inserted into the manikin just like they are in the actual surgery. Additionally, not only does the physical setup provide the user with visual cues regarding the external landmarks such as the intercostal spaces, deepest point of depression, and introducer's progress in the subcutaneous tunnel, but also the ability determine their location in a tactile manner.

In a physical setup, however, no real-time dynamics and interactions are present such as the beating heart, fluid emission and the possibility to puncture the pericardial sac by mistake (task 7b in Table 1). Although these can be added with some difficulty and expense, the system is also unable to introduce procedural complications and pre-modeled scenarios to the simulation which makes the training scope and resolution somewhat limited. Furthermore, this setup is not an efficient platform for patient-specific planning as it requires an offline, and a rather long, changeover. Therefore, an average or standardized set of parameters that describe the patient and deformity populations are assumed to suffice.

#### 4.2. A Hybrid Approach

From previous sections, the comparison between the two setups shows how each scheme has merits that the other cannot provide. In this section, a best-of-both approach will be undertaken to describe a design of a hybrid virtual/physical construction for the simulator.

Since the physical setup showed very strong potential for implementing aspects that are relevant to the external visual and tactile cues of the simulator, a 3D-printed ribcage with synthetic skin and muscle will be adopted in the new approach. This will allow for tool insertion, subcutaneous tunneling, popping into and out of the thoracic cavity, as well as making sutures and installing the stabilizer. Implementing this physical component in the hybrid simulator provides the ability to use the original surgical tools and to perform fundamental tasks such as making incisions and using the umbilical tape.

The thoracoscopic view of the patient, however, will convey from the virtual setup. Patient-specific modeling of the patient's PE deformity will be reproduced from a parameterized ribcage system explained in (Rechowicz,

Obeid and McKenzie 2014), the organs and tool movement inside the chest will be part of a virtual environment utilizing the haptic interface. However, to overcome the discrepancy introduced by the virtual setup regarding the pivoting motion of the tool, the generic haptic device is augmented with an extension that implements a mechanism to utilize the device's natural pivot, while allowing the tool to be inserted into the physical manikin.

At insertion, the haptic device prevents motion in all directions. As the user attempts to move the tool through the insertion point (in the z-direction), the tool (not the end-effector itself) slides through the developed extension. The tool's translational motion is monitored using a rotary encoder (potentiometer) which controls the surgical tool in the simulation. Upon collision with an organ in the simulation, the mechanism will trigger a rubber wheel to descend vertically pushing onto the tool; thus reproducing force that would hinder the tool's motion. In this implementation, the forces generated upon colliding with the organs and moving inside the chest are calculated according to a physics-based model that studies the force-displacement profile as measured from a constructed phantom. Information regarding the force's behavior over time or versus displacement and velocity is directly obtainable using this phantom.

The mechanism for haptic augmentation has been prototyped using 3D printed components and implemented on the Arduino platform. The methods used for developing this mechanism as well as the constructed phantom for force-displacement measurement are thoroughly explained in (Obeid, Chemlal et al. 2014).

To control the virtual thoracoscope, the user is able to choose between the first mode where the camera constantly follows the tip of the introducer as in the case for the fully-virtual setup, and the second mode where the user is able to control the thoracoscopic camera in real-time using a Wiimote. Since the hybrid setup utilizes a physical manikin, the Wiimote can be attached to a steel rod and inserted in any intercostal space the surgeon decides. The Wiimote's pitch, roll and yaw motions control the rotation of the virtual camera which is equipped with a 30° tilt as in the real surgery.

The dynamics involved in the simulated surgery will convey from the virtual setup. Physics-based interactions were modeled to deliver realistic behavior of the pericardium. To simulate the beating heart, a non-uniform scaling deformation of the pericardial sac was constructed to reproduce systole and diastole motions. The amount and shape of PE depression can be adjusted according to patient-specific data and the pericardial sac is pushed laterally to the left as severity increases. Additionally, a framework is implemented for puncturing detection to trigger blood or pericardial fluid emission, depending on puncturing depth.

Table 1: A comparison in implementation for the virtual and physical surgical simulators against the Nuss Procedure tasks. Training significance for each subtask is identified and the corresponding more efficient setup is marked in bold.

#	Task Description	Subtasks "High (H), Medium (M), Low (L) significance for training"	Virtual Simulator Approach	Physical Simulator Approach
1	Positioning patient appropriately	a. Patient placed in supine position with back against operating table. "M"	<b>Patient's avatar is positioned supine with arms spread and right side facing user.</b>	<b>Manikin is mounted down in correct position. Surgical drapes provided to simulate actual operation.</b>
		b. Patient's arms are spread. "M"		
2	Visualizing external landmarks:	a. Deepest part of sternum. "M"	<b>PE deformity is reproduced by affecting sternum, associated costal cartilage and external skin of patient's avatar with a deformation model with a falloff according to parameters collected from CT data.</b>	PE deformity created with a physical elastic force attached to xiphoid process. Elastic force holding the bottom half of the sternum may be pulled up to show a corrected chest.
		b. Intercostal spaces. "M"	Deepest depression can be visualized. However, tactile determination of landmarks is absent and intercostal spaces are not visible externally. AAL and MAL can only be approximated.	<b>Exterior landmarks can be located by visualizing and feeling through synthetic skin on 3D-printed ribcage. AAL and MAL can be approximated.</b>
		c. Anterior axillary line (AAL) and mid axillary line (MAL). "M"		
3	Visualizing and marking necessary incision areas:	a. Deepest point of sternum. "M"	<b>User interface is incorporated with marking tool to mark skin externally using haptic device (not implemented). Intercostal spaces not visible externally.</b>	<b>Synthetic skin may be marked with a marker. Intercostal spaces can be assigned externally.</b>
		b. Intercostal spaces horizontal to deepest point of sternum. "M"		
		c. Entry and exit sites outside pectoralis muscle. "M"		
4	Preparing bar	a. Measure patient's chest according to landmark indicated in 2c. "M"	<b>The bar can be bent to fit patient specific data and incorporated in the UI (not implemented).</b>	The bar is already bent to fit the ribcage of the manikin. Verbal and visual instructions are necessary.
		b. Determine length of the bar (Bar should be 1 inch shorter than measurement). "M"		
		c. Shape bar using bending device.		
		d. Check final shape with patient's chest. "M"		
		e. Mark each end of bar (incision areas). "M"		
5	Thoracoscopy	a. Incision made for thoracoscope. "H"	a. Incision for thoracoscope is assumed to already exist.	<b>a. Incision can be made on replaceable synthetic skin.</b>
		b. Inspect deepest part of sternum internally. "M"	b. Camera is available to visualize interior of virtual chest and semi-translucent thoracic cavity.	<b>b. A camera is mounted on a long steel rod and can be inserted to visualize interior of chest.</b>
		c. Surgeon's assistant guides thoracoscope, focusing on tip of introducer. "M"	c. Virtual camera follows the introducer's tip at all times according to haptic device's motion. A 30° angle is incorporated.	<b>c. Assistant can maneuver the camera for the best view.</b>
6	Subcutaneous tunnel	a. Small incisions are made on right entry site marked in task 3. "H"	a. Incisions can be made (not implemented).	<b>a. Incisions can be made on the synthetic skin as it is replaceable.</b>
		b. Using tonsil or Kelly clamp or finger, make a pocket subcutaneously outside of pectoralis muscle. "H"	b. Subcutaneous tunneling is achievable by eliminating force feedback in plane between skin and muscle. Approximated with friction. (not implemented)	<b>b. Necessary tools are available. An extra layer of synthetic muscle is present beneath the synthetic skin, allowing separation between them.</b>
		c. Introducer is used to puncture the pectoralis muscle through the intercostal muscle. "H"	<b>c. Virtual muscle can be punctured (not implemented).</b>	c. Synthetic muscle can be punctured as it is replaceable.

7	Substernal tunnel	a. With aid of thoracoscope, guide introducer under sternum avoiding puncturing heart. "M"	a. The camera follows tip of introducer. Targeted areas can be viewed by aiming introducer towards them.	<b>a. Maneuver camera to visualize targeted area. Synthetic organs in sight.</b>
		b. Determine correct tunneling plane by putting small force brushing downwards with introducer on undersurface of sternum. Separation of tissue indicates safe spot to proceed. "H"	<b>b. Pericardial sac can be seen beating in view, a thin layer can be identified between the pericardial sac and the sternum.</b>	b. Tunneling plane can be determined between synthetic pericardial sac and sternum. Tissue separation is observed.
		c. Gently dissect off the pleura and pericardium under the sternum with the guide of thoracoscope. "H"	<b>c. User is able to pry along defined plane to dissect tissue and make pathway while heart is beating (implemented but slow).</b>	c. Brushing motion may be performed similar to surgery.
		d. When tunneling is achieved, puncture through exit site, examining externally. "H"	<b>d. Puncturing can be done to exit from other side with associated force feedback (not implemented).</b>	<b>d. Puncturing is done through the other side of the synthetic muscle.</b>
		e. Pull tip of introducer out through established left incision site. "M"	e. Will require moving the external camera to left side and making another incision (not implemented).	<b>e. Introducer tip can be pulled from left incision.</b>
8	Sternal elevation	a. Once introducer is through both incision sites, lift introducer up holding from both sides for 10-15 seconds for three times to mold the chest. "M"	a. Sternal elevation can be achieved by moving the end-effector of the haptic device (not implemented).	<b>a. Introducer can be lifted for the required duration elevating the sternum.</b>
		b. Link an umbilical tape to tip of introducer, pull through chest while introducer is slowly withdrawn from the chest with end of the string still remaining on left. "M"	b. Tying an umbilical tape to the introducer and pulling it inwards can be very difficult to implement (not implemented).	<b>b. An umbilical tape can be linked to the introducer.</b>
9	Bar insertion and rotation	a. Link umbilical tape to bar prepared in task 2. "M"	Tying an umbilical tape to the bar and pulling it inwards can be very difficult to implement (not implemented).	<b>The bar can be inserted into the simulator in a similar manner as in the surgery and the provided camera can be used for monitoring the process.</b> <b>A Bar Flipper is provided to flip the bar.</b>
		b. Insert prepared bar into right incision site upside down through subcutaneous tunnel. "M"		
		c. With guide of umbilical tape, introduce bar through under-sternal chest cavity. "M"	User can change the held instrument into a pectus bar and insert it into chest using haptic device's end-effector (not implemented).	
		d. Use finger in the left subcutaneous tunnel to guide tip of bar. "M"	User can change held instrument into a Bar Flipper to rotate the bar (not implemented).	
		e. Without displacing bar, use Bar Flipper to rotate bar clockwise or counter-clockwise. "H"		
		f. Ensure that patient's chest looks corrected. "M"		
10	Bar fixation	a. Place stabilizer in the space in left subcutaneous tunnel. "M"	Stabilizer fixation, suturing and stitching is difficult to achieve on a virtual setup (not implemented).	<b>3D-printed ribs can be used for stabilization and can be replaced when necessary. User can visualize corrected pectus interior and exterior of the chest using the provided camera.</b>
		b. Fix stabilizer and bar using a fiber wire. "M"		
		c. Ensure thoracoscope is used to assess the bar's current location. "M"		

The hybrid setup of the simulator is, therefore, able to combine the merits of having a physical external manikin that allows for realistic tactile assessment of the torso and the use of actual surgical tools with the power of a virtual environment that integrates an interactive and realistic

patient-specific model of the patient's torso and deformation with the ability to generate accurate haptic force feedback. Complications and educational scenarios can be introduced to this setup to enhance training aspects.

## 5. CONCLUSION

Realistic simulation of a full surgical procedure is not a feasible goal with current technology. A more dominantly practical approach is to follow a task breakdown procedure of the surgery to identify the most relevant aspect to be included in the simulation. This paper presented this task breakdown for the Nuss procedure and, based on experts' opinion, identified the significance of each task.

This paper then compared a fully-virtual platform for simulating the procedure that utilizes a virtual environment setup integrated with a haptic interface, to a fully-physical manikin-based platform for the simulation that uses a 3D-printed ribcage and synthetic body components. The comparison resulted with an identification of the areas where each setup is more powerful and allowed for a preliminary structure of a hybrid virtual/physical Nuss procedure surgical simulator.

Following this work, the hybrid simulator will be put to evaluation and assessment by surgical experts and feedback will be reported in a validation study.

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## AUTHORS BIOGRAPHY

**Mohammad F. Obeid** is a Ph.D. student and graduate Teaching/Research Assistant at the Modeling, Simulation and Visualization Engineering (MSVE) Department at Old Dominion University in Norfolk, Virginia. He received his BS degree in Industrial Engineering from the German-Jordanian University in Amman, Jordan in 2011; and his MS degree in Modeling and Simulation Engineering from Old Dominion University in Norfolk, Virginia in 2013. Currently, he is involved with research projects in virtual/augmented reality applications for simulated, surgical and computer assisted interventions. His research interests include medical modeling and simulation, surgery simulation, biomedical engineering and virtual environments.

**Eun-sil (Helen) Heo** was born in Busan, Korea. Ms. Heo received her B.S. in Mechanical Engineering and M.E. in Modeling and Simulation, both from Old Dominion

University (ODU) in Norfolk, Virginia USA. She was a Graduate Research Assistant in the Modeling, Simulation and Visualization Engineering (MSVE) Department at ODU. After graduation in 2015, she joined Children's Surgical Specialty Group-Orthopedic Surgery and Sports Medicine/ Plastic Surgery at Children's Hospital of The King's Daughter as a Clinical Research Associate.

**Krzysztof Rechowicz** is a Research Assistant Professor at the Virginia Modeling, Analysis and Simulation Center of Old Dominion University. He also serves as a researcher and university representative at the Commonwealth Center for Advanced Manufacturing. He previously served as a Postdoctoral Research Associate at Old Dominion University from 2012 to 2014. In 2006, Dr. Rechowicz received his M.Eng. jointly with his B.Eng. in Mechanics and Machine Construction from the Warsaw University of Technology. He went on to receive his Ph.D. in Engineering with a Concentration in Modeling and Simulation from the Old Dominion University in 2012. Dr. Rechowicz's research interests center on applications of virtual and augmented reality, visualization and adequate user interfaces to medicine and manufacturing. Some of his past projects include the development of a haptically-enabled virtual surgical simulator and planner for a minimally surgical procedure that repairs a congenital chest wall deformity. Furthermore, he designed a surgical tool for removing chest implants without the need of larger skin openings. He has also applied his research experience to solve real world problems of the manufacturing industry, and his work has been sponsored by companies like Rolls-Royce, Sandvik and Newport News Shipbuilding. He has worked on the development of a flexible augmented reality system for integrating digital design and process information with a worker's physical environment for feedback and control of manufacturing processes with special emphasis on user's safety and user interface. He also provided visualization for special manufacturing processes which allowed to better understand influence of process variables on its outcome.

**Dr. Robert E. Kelly, Jr., M.D.** received his medical degree from The Johns Hopkins University in 1985. He completed his General Surgery Residency at Vanderbilt University School of Medicine and his Pediatric Surgery Fellowship at Children's Hospital of Buffalo. Dr. Kelly also completed an ECMO and Surgical Research Fellowship at UCLA School of Medicine. In 1994, Dr. Kelly joined Children's Surgical Specialty Group-Pediatric Surgery and has been the Chairman of the Department of Surgery at Children's Hospital of The King's Daughters since 1998. He is also a Professor of Clinical Surgery and Pediatrics in the Department of Surgery at Eastern Virginia Medical School. Dr. Kelly lives in Norfolk, Virginia with his wife, Dr. Cynthia Kelly, and their three children.

**Frederic (Rick) D. McKenzie, Ph.D.** was born in Kingston, Jamaica. Dr. McKenzie has a B.S. in engineering, M.S. in computer engineering, and a Ph.D. in computer engineering all from the University of Central Florida in Orlando, Florida U.S.A. Currently, he is the Department Chair in the new Modeling, Simulation and Visualization Engineering (MSVE) Dept. and a joint faculty member in the Department of Electrical and Computer Engineering (ECE) at Old Dominion University in Norfolk, Virginia U.S.A. In addition, Dr. McKenzie is the director of the Medical Imaging, Diagnosis, and Analysis (MIDA) Laboratory, Adjunct Associate Professor of Eastern Virginia Medical School (EVMS) in the School of Health Professions, and Graduate Faculty Scholar at University of Central Florida (UCF) in the School of Electrical Engineering and Computer Science. Before coming to Old Dominion University, he spent 6 years in the simulation industry at Science Applications International Corporation (SAIC) as a senior scientist. Dr. McKenzie's research has been in medical modeling and simulation, human behavior representation, and simulation architectures often focusing on aspects of scientific visualization and virtual reality.