# USE OF BIOMECHANICAL MOTION ANALYSIS AND PELVIC SURGERY SIMULATOR FOR THE PREVENTION OF SURGICAL ERRORS IN MID-URETHRAL SLING ANTI-INCONTINENCE SURGERY

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by
MD ARIFUZZAMAN ARIF

M. S., University of Missouri-Kansas City, USA, 2019
B.Sc., Khulna University of Engineering & Technology, Bangladesh, 2014

Kansas City, Missouri
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Md Arifuzzaman Arif, Candidate for the Doctor of Philosophy Degree

University of Missouri–Kansas City, 2023

# ABSTRACT

More than 200 million surgeries are performed annually worldwide in which preventable complications occur in up to 22 percent of these surgeries, with permanent disability rates between 0.4 - 0.8 percent. Resident surgeons are more likely to commit surgical errors as they start their surgical career with less mastery and surgical skills. Yet other than close supervision in the operating room, there is no accepted way to teach a young surgeon how to prevent surgical errors.

This work discusses a method that was focused on identifying and modeling individual surgical errors to improve the training of individual surgeons and complement systems approaches, and thus lead to effective error prevention. This technique involved a combination of virtual and physical anatomic models, simulation of surgical injury, and kinematics of both surgeon and surgical instrument to identify, model and describe surgi-

cal errors quantitatively. This study targets a complex, high-risk step of the Midurethral Sling surgery which is highly effective in reducing stress urinary incontinence. This surgery involves the insertion of a strip of mesh underneath the urethra and the surgeon is tasked with blindly guiding a sharp steel trocar behind the pubic symphysis and past the bladder, bowel, and major blood vessels. If the trocar is not guided properly through its passage (from vagina to the suprapubic skin), it can lead to several injuries, such as injury to the bladder or urethra (4.9%), injury to the bowel (0.1%), and injury to external iliac vessels (2.0%).

This work effectively integrates the concepts and theories from both biomechanical engineering and medicine (surgery), including MRI segmentation, development of subject-specific virtual and physical models, motion capture technology, testing cadaveric specimens, multi-body modeling, musculoskeletal modeling and simulation.

Three MUS physical pelvic floor models were developed by segmenting the pelvic bones and organs from MR images of three patients with stress urinary incontinence. Segmented pelvic bone structure was 3D printed and the open space between the bone was filled with thermo-ballistic gel to provide the haptic feedback associated with soft tissue during the retropubic trocar passage. Vital injuries during the midurethral sling Surgery (MUS) can be avoided by maintaining constant contact between the trocar tip and pubic bone, yet this is challenging for a teaching surgeon to monitor during this blind procedure. A force-sensing trocar was developed by modifying the retropubic trocar with a load cell which can distinguish on-bone and off-bone movement during the procedure. Two expert and three novice surgeons performed retropubic trocar passage on the MUS physical pelvic floor model using the modified trocar. Bio-fidelity of the MUS physical model was assessed by analyzing the force variables in the expert passages performed on a thiel-embalmed cadaver and the MUS physical model, using this force-sensing trocar. Test-retest analysis was conducted to analyze the force-sensitivity of this proposed model-trocar system using trocar passages performed on the MUS physical model two weeks apart. Post-hoc analyses were performed to compare the expert vs. novice performance on the physical model. Three expert and three novice surgeons participated in the kinematic study where both the surgical instrument (trocar) and surgeon body movements were tracked. Both the surgical instrument and surgeon body were equipped with retroreflective markers to facilitate the motion tracking during this procedure, using OptiTrack Flex 13 motion capture system. Multibody kinematic models were developed in MSC ADAMS to analyze the surgical instrument kinematics. Musculoskeletal models were developed using OpenSim to analyze the surgeon body kinematics during the retropubic trocar passage. Simulated trocar passage (from the vaginal incision point to the exit point at rectus fascia) was separated into 4 stages for the purpose of analysis. Mixed model analysis was used to analyze the trocar trajectories, temporal data, and surgeon upper extremity kinematic variables obtained from the retropubic passages performed by each participant.

Paired sample t-tests revealed no statistically significant differences on the outcome force variables between trocar passages performed on cadaver and MUS physical model, suggesting adequate bio-fidelity of this physical pelvic model. Test-retest analysis also exhibited no significant difference between the testing sessions on any of the outcome variables. Independent sample t-tests revealed significantly larger amplitude of maximum force development, larger maximum rate of force development and shorter time to reach the maximum force in the expert participants than the novices. Simulated trocar passages in the multibody models revealed that the experts completed 27 error-free passages and 18 bladder error passages (40%). Novices completed 18 error-free passages, 4 bladder error passages and 23 anterior error passages, resulting in an overall error rate of 60%. Mixed model analysis revealed that the trocar tip trajectories were significantly different between the error free passages and the bladder error passages in the anterior-posterior and caudal-cephalad directions for both left and right shoulder passages. The incidence of the anterior error passages was significantly higher in the novices for both left and right directions. Experts had significantly longer mean trial duration and path length, compared to the novices. Mixed model analysis was also used to analyze the total trocar path variation which indicated that 48% of variation was attributed to the novices, where only 14% path variation was attributed to the experts. Mixed model analysis of the surgeon body kinematic variables revealed that the bladder contact trials were significantly associated with higher starting wrist dorsiflexion, less final elbow flexion and greater range of motion in both wrist dorsiflexion and elbow flexion at stage 3. Anterior versus posterior passage analysis performed on stage 1 indicated this incidence is significantly associated with less elbow flexion. Expert versus novice analysis revealed that novices had significantly higher range of motion in elbow flexion, but less range of motion in wrist dorsiflexion and arm pronation during stage 1, compared to the experts. However, stage 2 exhibited less range of motion with arm pronation and less range of motion with shoulder flexion in the novices.

This study suggests high test-retest reliability and adequate bio-fidelity of the modified trocar used on our MUS 3D surgery simulator. This innovative trocar can be used both in surgical simulation and in the operating room to help the novice stay on the bone, and to help the attending monitor safe surgery. Kinematic analysis of the surgical instrument movement indicated that the novice passages were predominantly anterior to the pubic bone. In addition, significantly higher trocar path variation in the novices suggests that they were not able to follow a consistent trocar path between trials. Surgeon upper extremity kinematics indicate that expert participants exhibited more consistency with the distal joints (wrist and forearm), while the novices mostly focused at the proximal joints (elbow). Monitoring the temporal and kinematic characteristics of trocar, and the surgeon body kinematics provides useful insights into the types of errors occurred during retropubic trocar passage and has the potential to provide insight into proper education of surgical trainees. This is the first study that incorporated motion capture technology with a high-fidelity 3D pelvic surgery simulator to track the surgical instrument and surgeon body movements during the MUS procedure. Methods used in this study has the potential to be used for monitoring the sling placement in the operating room, accelerate the learning experience of novice through insights from surgeon kinematics, thus lead to effective error prevention in the midurethral sling surgery.

## APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Science and Engineering, have examined a dissertation titled ”Use of Biomechanical Motion Analysis and Pelvic Surgery Simulator for the Prevention of Surgical Errors in Mid-urethral Sling Anti-Incontinence Surgery”, presented by Md Arifuzzaman Arif, candidate for the Doctor of Philosophy degree, and hereby certify that in their opinion it is worthy of acceptance.

Supervisory Committee


Antonis P. Stylianou, Ph.D., Committee Chair and Primary Discipline Advisor
Division of Energy, Matter, and Systems

Majid Bani-Yaghoub, Ph.D., Co-discipline Advisor
Division of Computing, Analytics & Mathematics

Gregory W. King, Ph.D., P.E.
Division of Energy, Matter, and Systems

Zahra Niroobakhsh, Ph.D.
Division of Energy, Matter, and Systems

Gary Sutkin, M.D.
Department(s) of Biomedical and Health Informatics, Obstetrics and Gynecology

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# CHAPTER 1

# INTRODUCTION

## 1.1 Surgical Errors

In recent years, preventable surgical complications have received increasing attention among various types of medical errors. Surgical errors are generally defined as potentially preventable mistakes made during the surgical procedure which could be avoided through advanced training and proper execution of the procedure, better technique or by maintaining a protocol. Preventable surgical errors have the potential for the most direct and serious consequences. In more than 200 million surgeries performed annually worldwide, preventable errors occur in 3 to 22% of the cases. Permanent mortality or disability rates range between 0.4% and 0.8% [1–3].

Surgical errors are commonplace, and both technical and cognitive errors can lead to surgical injuries. Errors of judgement, omission, wrong order, and technique can lead to poor surgical outcomes, decreased patient satisfaction, re-operation, permanent injury, or even death, and subsequent litigation [4, 5]. These errors can plague even the most experienced surgeons. However, the novice or resident surgeons are certainly more concerned about avoiding surgical errors [6,7]. Resident surgeons usually begin their surgical careers with less experience and mastery of surgical skills after finishing their surgical training program and are more likely to commit surgical errors.

The Institute of Medicine's 1999 publication "To Err is Human: Building a Safer Health System" led to the widespread public recognition of the problems associated with medical errors and their potential to cause patient harm [8]. Recent data also suggests that preventable medical errors have actually increased, even though the overall awareness of the problem has increased. Many of the medical errors occur in the operating room are preventable. Many surgical errors may not lead to patient harm directly. However, they should not be ignored as minor medical errors, since even minor inconsequential errors can accumulate into major errors. We have an imperative to increase patient safety by making the surgeries safer. To accomplish this goal, our target is to maintain the rate of surgical errors at an As Low as Reasonably Possible (ALARP) level of safety [4].

## 1.2 How to Prevent Surgical Errors

Current efforts implemented into practice to reduce surgical errors mainly focus on systems approaches. Systems approaches are widely used in high-stake environments, such as aeronautics and aviation, to reduce human errors [9]. Systems approaches commonly used in surgical error prevention are checklists, preoperative timeouts, and improving hand-offs between intraoperative and postoperative teams [10]. These systems approaches implemented to reduce surgical errors proved to be successful to an extent. However, because of the complexity of the medical systems and multifaceted contributing causes, even the best systems and checklists can not ensure 100% effectiveness and prevent injuries from an erroneous movement [11].

In addition, technical surgical errors are mainly associated with inadequate surgical experience. There is no accepted way to teach novice surgeons how to prevent surgical errors, except close supervision in the operating room. Even in today's era where patient safety is highly encouraged, lead surgeon is mostly responsible for such surgical errors. Therefore, in addition to making efforts in filling gaps in the existing systems approaches, large scale training of the novice surgeons should be encouraged to improve the individual surgical skills. Individualized approaches can focus on individual errors and are also required to lower the surgery-specific error rates [12, 13]. Therefore, a system needs to be established, combined with both systems and individualized approaches, to reduce the surgical errors in a step-by-step manner.

While systems and individualized approaches are both paramount, it is highly important to improve our granular understanding of the finite technical aspects of specific surgeries which are poorly defined. This will be helpful in understanding individual surgical errors. For example: there is no standard way available to describe an intraoperative error (e.g. laceration of the interior vena cava), patient-specific risk factors (e.g. adhesive disease or obesity), or consequences (e.g. lengthening of the surgery duration). In addition, there is inadequate description of individual surgeon and surgical instrument movements that cause the surgical injury [14]. For example, when a surgeon perforates the bowel with scissors during an enterolysis, it is necessary to understand whether the tips of the scissors were angled correctly or the bite of the scissors was too large. In addition, it is also important to understand from where the error has been associated: the wrist, lower hand, upper hand or shoulder level? or, a combination of different levels? The error might have been resulted in from exerting too much force from surgeon's wrist during performing the procedure with scissors. It is obvious that a combination of factors might have been involved with the causation surgical errors and it requires better descriptions and definitions of the surgical procedure to better our understanding of a particular surgery.

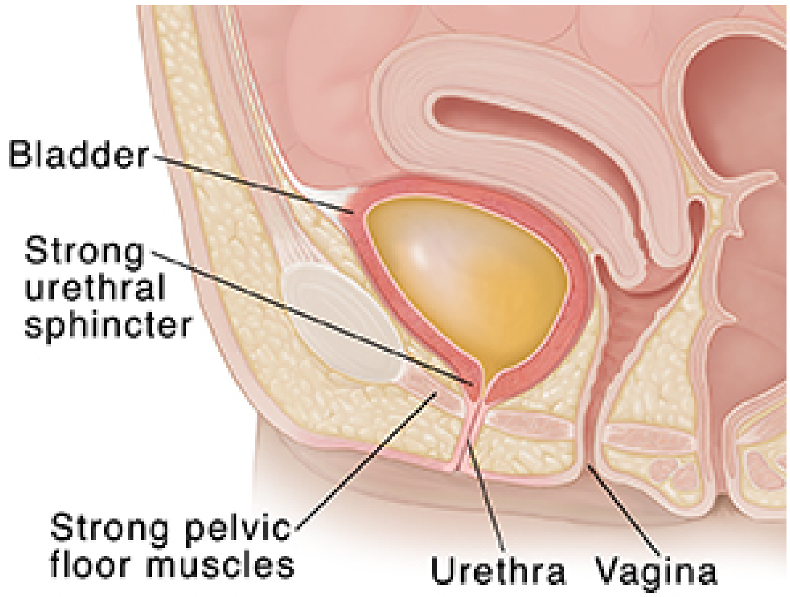
### 1.3 Stress Urinary Incontinence (SUI) - Problem

Stress urinary incontinence (SUI) is defined as ”leakage of urine” associated with physical exertion. ”Physical exertion” refers to the activities such as sneezing, coughing or physical exercise that increase the stress or pressure in bladder to stimulate the loss of urine. Stress urinary incontinence is a common problem among women, specially the elderly women. One in every three women over 45 years suffer from this problem [15].

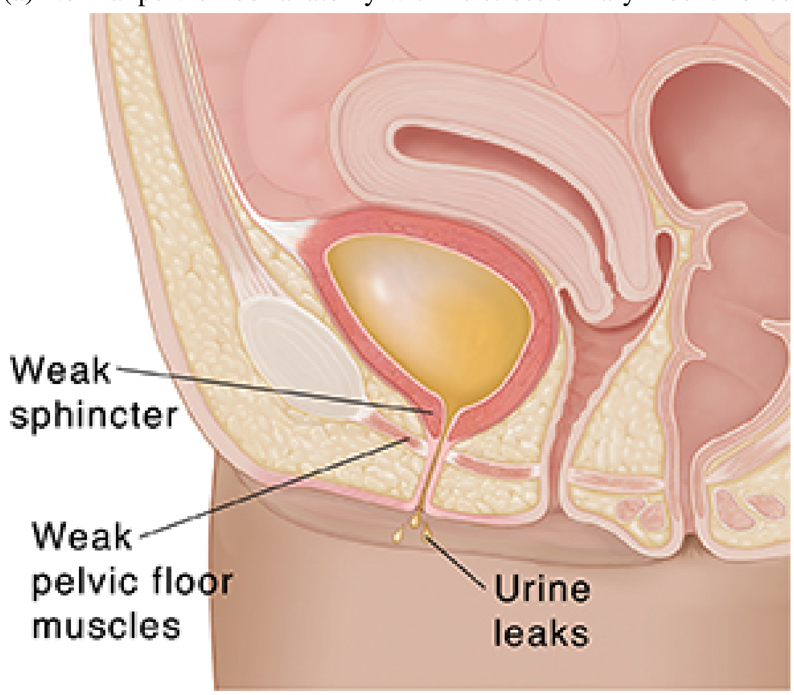
Stress urinary incontinence or bladder weakness is usually resulted in from weakening of the muscles or sphincter that support the pelvic floor (Figure 1). In women, pelvic floor support structures can be weakened or damaged during pregnancy by carrying the extra weight or natural hormonal changes. Prolonged child-birth or extra baby weight can cause more damage to pelvic floor muscles. Many women naturally develop stress urinary incontinence with aging, since the pelvic floor muscles become weaker after menopause with the hormonal changes in the body.

### 1.4 Midurethral Sling Surgery (MUS) - Solution

This condition can be treated by conservative strategies, such as lifestyle changes, pelvic floor muscle exercises, or by using medical devices such as vaginal pessaries. Surgery is recommended when the conservative strategies are not successful or the patient needs surgery for another pelvic condition (e.g. prolapse). Stress urinary incontinence surgery addresses weakened pelvic floor supports around the urethra. Surgical




(a) Normal pelvic floor anatomy with no stress urinary incontinence




(b) Weakened pelvic floor with stress urinary incontinence

Figure 1: Pelvic Floor Anatomy and Stress Urinary Incontinence

techniques to treat SUI include placing bulking agents, mid-urethral sling, autologus fascia pubovaginal sling, and colposuspension. [16].

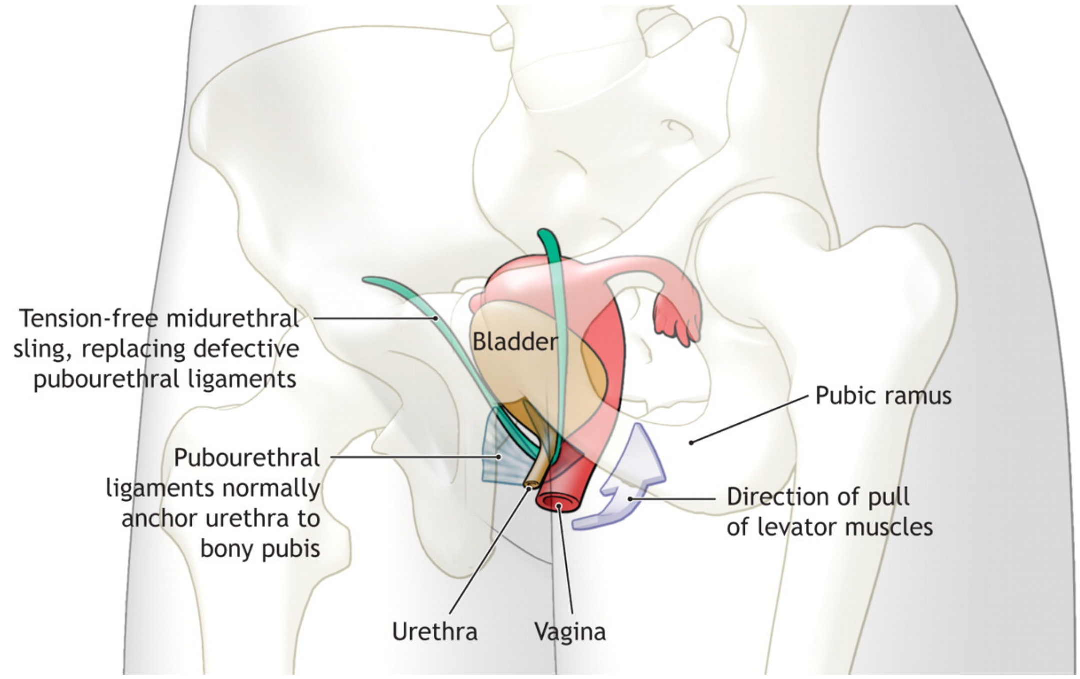



Figure 2: Relationship between mid-urethral sling and urethra

Mid-urethral sling procedure (MUS) is the most common and successful surgical intervention to treat SUI, in which a U-shaped sling tape is installed underneath the urethra to provide additional support (Figure 2). This procedure is also known as a tension-free or trans-vaginal tape (TVT) procedure. Primarily, there are three types of surgical techniques to treat the SUI condition surgically, Retropubic, Transobturator, and single-incision sling approach (Figure 3).

In the retropubic sling approach, insertion of the needle is performed through the retropubic space blindly from the vagina to the abdomen using two suprapubic incisions.

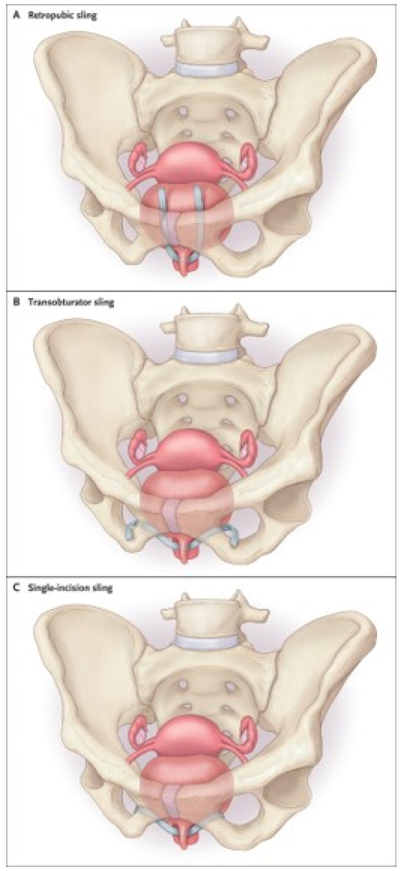



Figure 3: Different variations of midurethral sling

Cystoscopy is recommended to ensure if there is any perforation of the bladder or urethra during this procedure. Transobturator sling approach is a minimally invasive sling procedure where the sling mesh is inserted through a horizontal plane between two obturator foramina, under the middle of the urethra and exits through two groin incisions. The ends of the mesh tape are tunnelled percutaneously without any suture fixation, using a tunneller. Single-incision or mini-sling approach uses a shorter piece of mesh and only require a single vaginal incision.

The transobturator and retropubic sling approaches are both highly effective in terms of short-term rates of subjective cure and have similar risk ratio. Although the transobturator sling approach is associated with lower rates of bladder perforation, voiding dysfunction, suprapubic pain, and vascular injury than retropubic slings, it shows a higher rate of groin pain and repeat surgery after 5 years. Mini-slings approach is less effective, but the rate of complications associated with mini-slings are similar to the retropubic and transobturator approaches [16–20].

### 1.5 Complications due to MUS

The Midurethral Sling (MUS) surgery is an appropriate selection for modeling individual surgeon error. Approximately 170,000 MUS surgeries are performed annually in the United States [21]. This number is likely to increase since our population is aging. MUS surgery is highly effective in reducing stress urinary incontinence and involves the insertion of a strip of mesh underneath the urethra (Figure 4). To perform the MUS surgery, the surgeon must guide a sharp steel trocar blindly behind the pubic symphysis and past the bladder, bowel, and major blood vessels (Figure 5). The surgeon is required to possess excellent bimanual dexterity and the ability to envision a blind 3D space (Figure 4). In addition, the surgeon also needs excellent knowledge of the complex anatomy of the periurethral and perivesical spaces [22, 23].

The MUS surgery is ideal for simulation as the surgery is performed largely the same way each time and it has a well-established error rate. Most complications are associated with one discrete step: the retropubic passage of the sharp steel trocar from the vagina to the suprapubic bone. If the trocar is not guided appropriately, disastrous

Figure 4: Trocar insert shows the retropubic location with reference to the bone landmarks

complications can occur, such as injury to the bladder or urethra (4.9%), bowel (0.1%), and blood vessels such as the external iliac (2.0%) [24]. Such complications can turn an elective minor surgery into a costly hospital course that may involve blood transfusions, a bowel resection, a colostomy, even sepsis and death [25]. Novices are understandably anxious about performing MUS surgery.

### 1.6 Expert Vs. Novice Surgical Skills

Surgical residents or novice surgeons are more likely to commit surgical errors since they start their surgical career with less mastery or surgical skills. Yet other than close supervision in the operating room, there is no accepted way to teach a young surgeon on how to prevent surgical errors [26]. We have an imperative to make surgery safer. Current efforts largely focus on a systems approach to ensure surgical safety, which is commonly used in other high-stakes environments, such as aeronautics and aviation, to prevent human errors. The adoption of a 'Culture of Safety' in the operating room environment has resulted on error reduction which is modest at its best. However, even

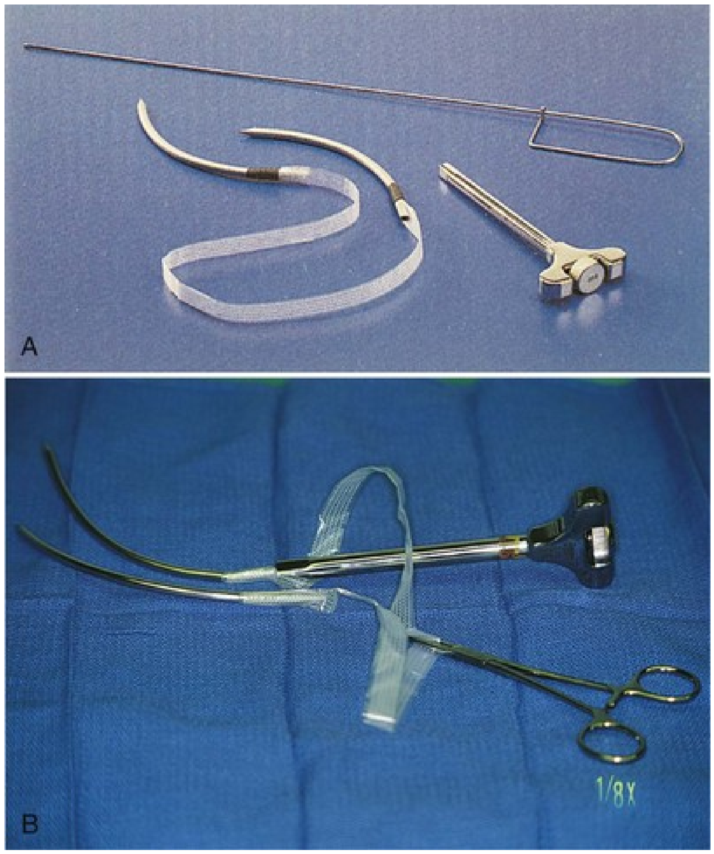



Figure 5: Surgical Instrument (Trocar) used in the Midurethral Sling surgery

the best systems and checklists cannot prevent injury from an erroneous movement, as the lead surgeon bears responsibility of such errors. Approaches aimed at preventing individual errors are necessary to effectively lower the surgery-specific error rates. While large-scale error prevention should focus on improving the training of surgeons to complement systems approaches, we must first understand individual surgical errors. This relies on a granular understanding of the finite technical aspects of individual surgeries.

## 1.7 Why Kinematics Analysis is Important?

Surgical error prevention correlates with surgeon kinematics and previous studies linked surgeon kinematics to surgeon experience. Several other studies have also linked surgeon experience to error prevention. Previous studies have analyzed gross surgeon movement, but have not focused on correlation between surgeon movement and surgical errors [27–30]. Experienced surgeons learn error prevention over time, on live patients, through mastery of their movements (kinematics). When novice residents are supervised in the OR by a teaching surgeon, they are monitored and corrected for improper kinematics so that over the time, the resident can naturally perform the steps correctly and reduce errors. A combination of factors is involved when it comes to the analysis of causation of surgical errors in a specific surgery, such as surgeon body kinematics, surgical instrument kinematics, variation in force exerted on surgical instruments during the procedure etc. Several questions can be asked linking these factors to the technical aspects of an individual surgery and the mechanisms of injury/surgical error: For example, when a surgeon perforates the bowel with scissors while performing an enterolysis, 1. Was the tip of surgical instrument (Scissors) angled incorrectly? (Surgical instrument kinematics); 2. Did the surgical error happen at the level of wrist, elbow, or shoulder? (Surgeon Kinematics); 3. Did the surgeon exert too much force while performing the surgery (during the use of scissors)? (Force Variability).

Surgical mastery or surgical experience, and error prevention skills correlate with improved kinematics of surgeon and surgical instrument. Kinematic studies have not been performed to study individual surgeon error. This study work targets the biomechanics of individual surgeons by quantifying the movements of a surgeon and the trocar. This study used a combination of virtual and physical anatomic models, simulation of the MUS procedure, and analysis of surgeon and trocar kinematics to ultimately prevent surgical errors.

## 1.8 Research Questions/Hypothesis

In this study, it has been hypothesized that surgical error related to suboptimal surgeon biomechanics can be quantified, predicted, and avoided by discrete changes in the kinematics of surgeon's shoulder, elbow, wrist, and the surgical instrument's spatio-temporal characteristics.

## 1.9 Objectives of Our Study

Multiple anatomic variations of a 3D pelvic simulator and motion analysis have been used to identify and prevent surgical errors during one high risk step of a prototype surgery, the Midurethral Sling (MUS) procedure. The general hypothesis stated above has been tested with the following objectives:

- Objective 1: Create a high-fidelity pelvic surgery simulator capable of identifying surgical errors involved in one surgery, the Midurethral Sling procedure.
- Objective 2: Develop a force sensing trocar (surgical instrument) to track the force variability during the procedure and analyze the bio-fidelity of the physical anatomic model.

- Objective 3: Identify the kinematics of the surgical instrument during the simulated surgical procedure.
- Objective 4: Identify the upper extremity kinematics of surgeon during simulated surgical procedure.

## 1.10 Significance of Research

Young surgeons lack in experience and mastery of skills while they enter the operating room after their basic surgical training. There is no such technique available to teach them not to commit surgical errors, except close supervision. High-fidelity, virtual and physical anatomic models are available and have been integrated into simulation using actual surgical instruments [31–35]. High-fidelity simulation models have been accepted by the surgical trainees [36]. However, widespread application of the high-fidelity physical anatomic models and surgical simulation in the operating room with a view to improving surgical skills and the overall effectiveness of the existing physical anatomic models are not consistent [37, 38]. Therefore, low-cost, high-performance surgical simulators are required that can reflect complex surgical procedures with high-fidelity. The individualized approach is novel for three reasons: 1. A focus on modeling individual surgeon error; 2. Correlation of surgeon gross motor movement with surgical errors.2. Correlation of surgical instrument temporal characteristics and force variability with surgical errors.

Motion capture technology has been increasingly used in measuring gross motor movements in recent years, but correlating surgeon and surgical instrument kinematics with surgeon error is novel. In terms of model development techniques and training methods, there is also high potential for applying this methodology to other high-risk surgeries, including fixation of the sacroiliac joint near the lateral femoral cutaneous nerve, sagittal split mandibular osteotomy near the inferior alveolar neurovascular bundle, and thoracic spine osteotomy near the spinal cord.

## 1.11 Description of the Dissertation

This work emphasized on understanding individual surgeon's role in causing a surgical error, and therefore complement the existing systems approaches. In order to accomplish this goal, a novel method has been proposed that can define individual surgeon and surgical instrument movements responsible for a surgical error. This methodology used a combination of virtual and physical anatomic models, simulation of surgical injury or erroneous surgical procedure, and kinematics of both surgical instrument and surgeon upper extremity to describe and define individual surgical errors.

The materials and methods used for analyzing the force-sensitivity during trocar passage, assessment of biofidelity, surgical instrument kinematics and surgeon body kinematics are described in chapter two. Chapter three details the results obtained from force-sensing trocar passages, simulated trocar passage in multi-body ADAMS models, and inverse kinematics simulation in OpenSim. The fourth chapter covers all the discussion of the results presented in chapter three.

CHAPTER 2

# METHODS

## 2.1 Imaging for Subject-specific Pelvic Floor Models

### 2.1.1 Magnetic Resonance Images (MRI)

Physical pelvic floor models were developed from segmentation of high-resolution magnetic resonance images (MRI) of female patients with stress urinary incontinence. Three female patients were recruited by an expert urogynecologist based on varying interspinous differences (142 mm, 140 mm, and 117 mm) and all three patients had a positive cough stress test. MRI images of female pelvis were taken in the sagittal, coronal and axial plane with 0.5 mm slice thickness, using a 1.5 Tesla GE Sigma system. Five different image sequences were considered: T2, Water, Fiesta, In-Phase and Out-Phase.

Segmentation of MR images was performed using 3D Slicer (slicer.org) using both manual and automated segmentation technique. Manual segmentation was employed for soft tissue structures with non-uniform boundary thickness and intensity (external iliac blood vessel, urethra and vaginal skin). For manual segmentation, a Wacom Cintiq Interactive Pen Display (Wacom Company, Ltd., Tokyo, Japan) tablet was used. Automated segmentation technique (Robust Statistics Algorithm and Grow-cut Algorithm) was used for pelvic floor structures with uniform boundary thickness and homogeneous intensity for entire length (bladder and uterus). A combination of both manual and automated segmentation was used to segment pelvic bone. Robust Statistics tool parameters used for automated segmentation are as follows: Approximate Volume (mL) - 250, Intensity

Homogeneity - 0.25, Boundary Smoothness - 0.25, Max Running Time (min) - 10. A preliminary study was previously conducted to segment the entire pelvic floor including muscles, blood vessels, and peritoneum membrane [39,40]. For this study, we considered only the pelvic bone, bladder, bowel, uterus, external iliac vessel, urethra and vaginal skin. We have used high resolution T2 MR image sequences for the segmentation of bowel, urethra and vaginal wall. In-Phase MR image sequence was used for the segmentation of external iliac blood vessel, and a part of bowel and urethra. All five image sequences were used for pelvic bone, bladder, uterus and vaginal skin, and later merged to finalize the output geometries.

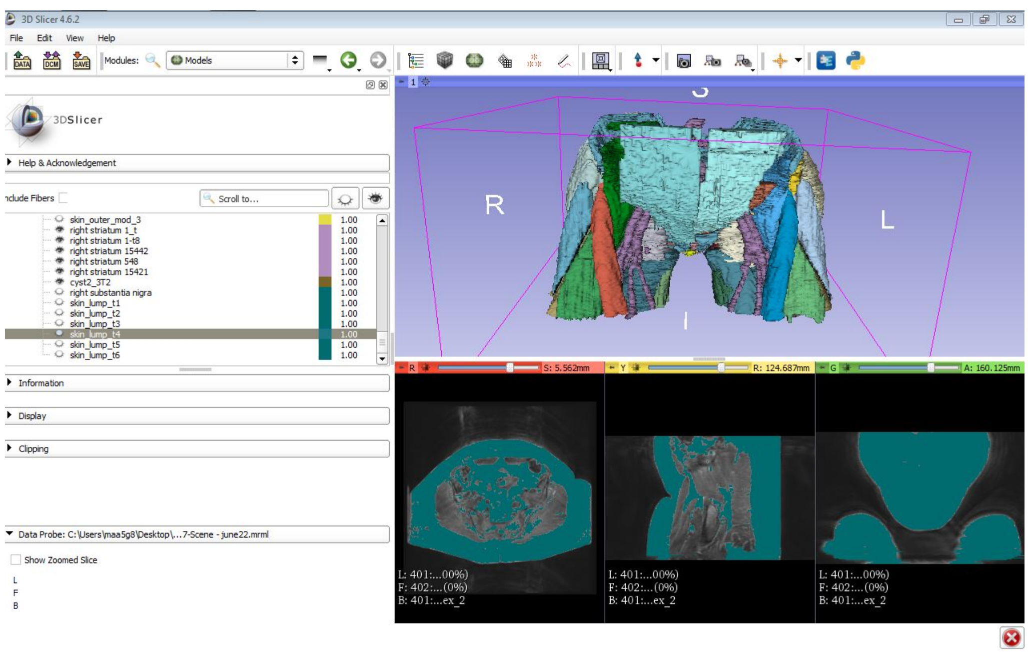



Figure 6: Pelvic MRI segmentation using 3D Slicer

After segmentation of individual geometries, 3D slicer's ModelMaker algorithm was used to visualize the shell models of segmented structures. Smoothing and decimation parameters were 0.20 and 0.25 respectively. After review and correction of segmented structures, 3D geometries were exported as as .stl files and considered for further post-processing.

### 2.1.2 Post-processing and Virtual Model

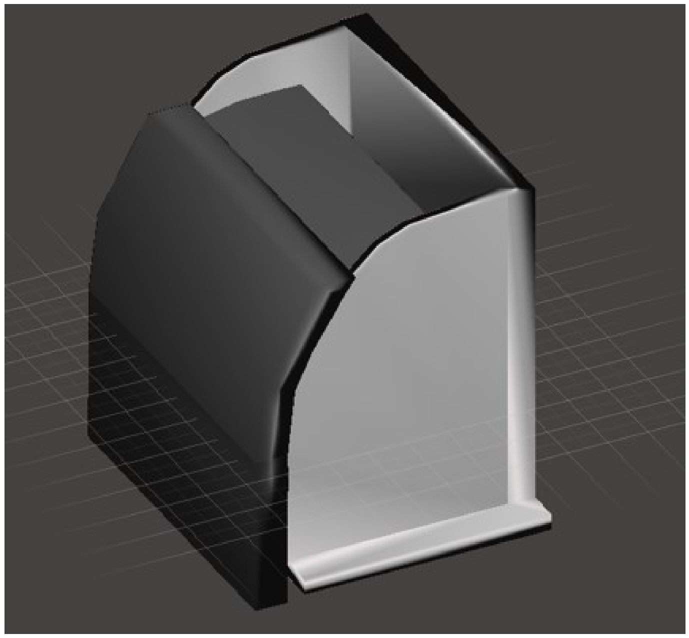
After exporting 3D geometries from 3D Slicer, geometries were post-processed in MeshLab (meshlab.net). Geometries were post-processed for reduction of noise, artifacts and file size.

A simplified version of the pelvic floor model was developed using Altair InspireTM. Boundaries of the pelvic floor model were determined using the pelvic bone, vaginal skin, and the most posterior point of bladder. Pelvic floor model included an additional cover part to facilitate the casting of physical experimental model. Inside boundary of the cover plate matches the outer surface of vaginal skin (Figure 7).

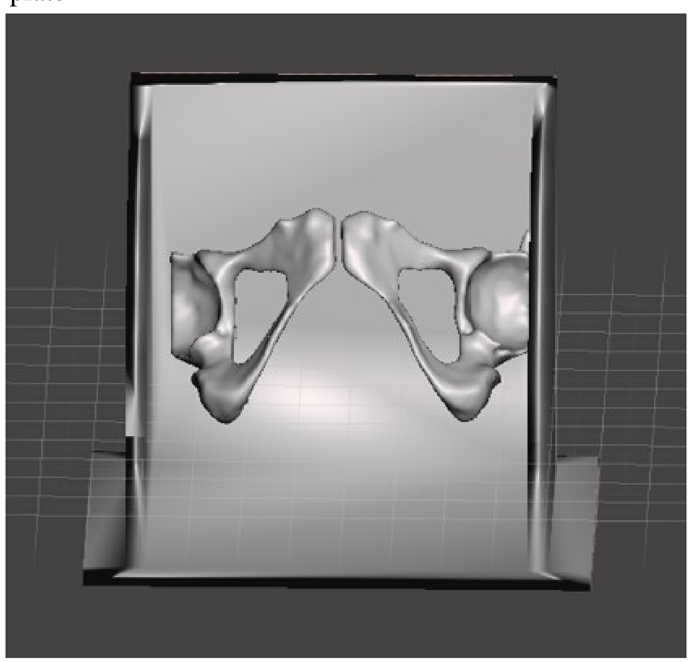
## 2.2 Physical Experimental Model

### 2.2.1 3D Printing & Thermo-ballistic Gel

ABS plastic has been used to manufacture the MUS Physical Pelvic Models using a Dimension bst 1200 series 3D printer. The empty space inside the model was filled with ballistic gel. Ballistic gel is a synthetic, clear, and non-toxic material than can mimic human tissue (soft-tissue medium) and provide the haptic feedback during surgical procedure. A preliminary study on the MR image segmentation technique and subject-specific physical pelvic model development has been previously published [39–41].



(a) CAD model of experimental pelvic model with cover plate



(b) CAD model of experimental pelvic model

Figure 7: Simplified Computer Aided Design of pelvic floor model

### 2.2.2 Ballistic Gel Preparation & Physical Model Casting

The thermo-ballistic gel is melted separately using a range oven and poured into the ABS plastic model through a casting process. The steps to prepare and cast ballistic gel for the experimental physical model are as follows:

- A kitchen range oven (or a roaster oven) has been used to melt the ballistic gel separately. Usually ballistic gel comes in large-sized blocks (approximately $5 \times 11 \times 17$ inches) which was sliced into smaller blocks (1 - 2 inches). Then, sliced gel blocks were taken to the oven using an aluminum tray to start the melting process.
- Ballistic gel blocks were melted at around 200° F. Temperature was maintained carefully to protect the ABS plastic base of MUS pelvic model and it usually takes 8 - 10 hours to complete the controlled melting process.
- The ABS plastic model consists of two distinct parts: the base and cover plate. Before pouring the molten material, the cover plate was fastened with base using duct tape. Molten material (gel) was poured into the mold through the gap between base and cover (open space on top).
- The mold was allowed to cool overnight (8 - 12 hours) after the gel was poured. Then, the cover was carefully and slowly removed from the solidified gel block.
- Model was examined to see if any pocket was created. If there was a pocket on top, it was filled with extra molten gel. A heat gun was used to remove the bubbles from the surface of the gel block, and make the surface smooth and clean.

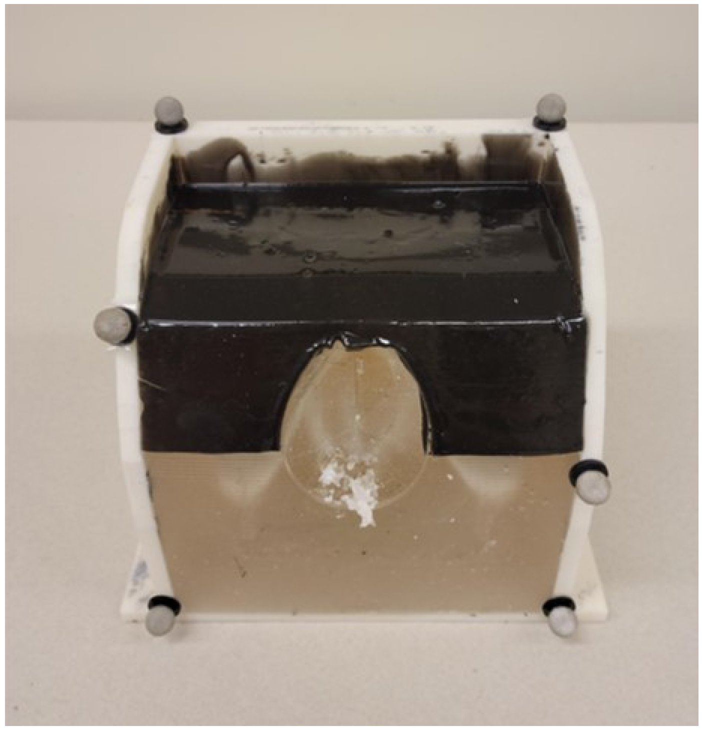


Figure 8: 3D printed MUS model filled with ballistic gel and pigmented

#### 2.2.3 Pigmented latex layer preparation

The pigmented layer preparation steps are as follows:

- A pigmented latex layer was created to stay on the upper part of the MUS model so that the subjects could not see through the model. Smooth-On Dragon Skin 20 Part A and Part B were mixed in 1:1 ratio and Smooth-On Silc Pig was added to it.

- The upper part of the MUS model was painted with this mixture and allowed to stay for 4 hours to get solidified and create a pigmented latex layer. At this point, MUS model was ready to be used for the experiments.

## 2.3 Development of Force Trocar

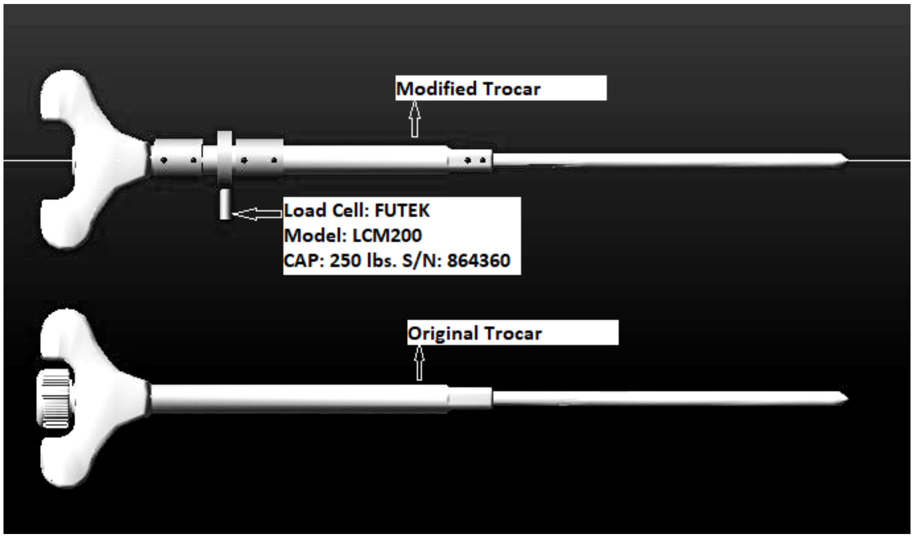
A force-sensing trocar has been developed to measure the force variation during retropubic trocar passage on the high-fidelity 3D pelvic floor model. Retropubic trocar (Ethicon, 810041BL) was modified using a load cell (Futek LCM200) and the original dimensions of the trocar were retained. The modifield surgical trocar can track the uni-directional force exerted on the trocar using a custom-built LabView program (National Instruments, Inc.). Force data was collected with a sampling frequency of 100 Hz. This modified trocar can track the contact between instrument and the pelvic bone during the MUS procedure. The development process of force-sensing trocar and bio-fidelity testing have been previously published [42].

## 2.4 Experiment for Model Biofidelity

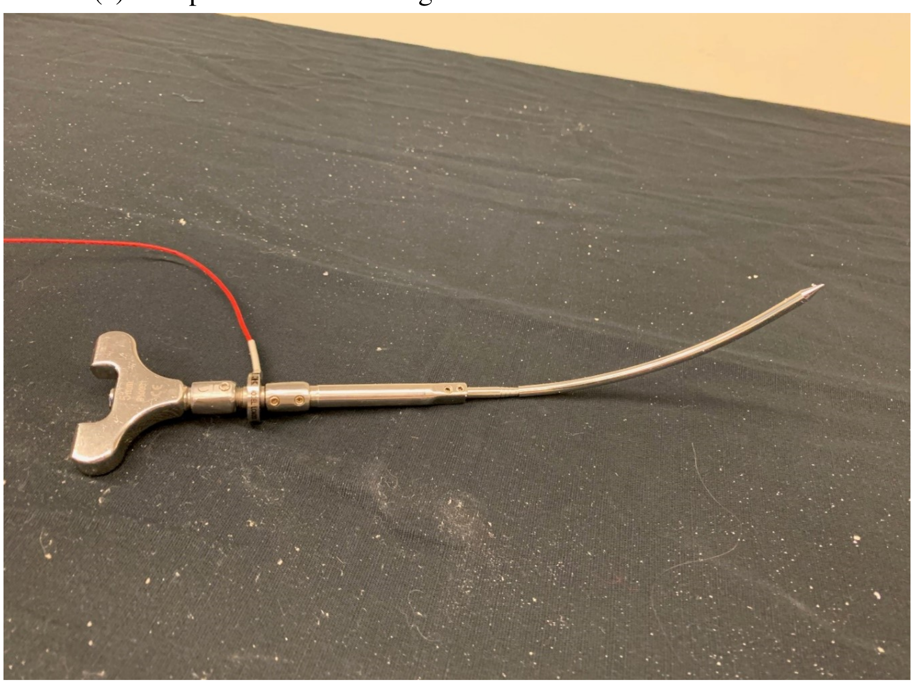
### 2.4.1 Biofidelity and force-sensitivity testing - Subjects

Five subjects, including two experts and three novice surgeons, participated in this study that involved retropubic passage of the modified trocar on the physical pelvic floor model. Prior to testing, an expert surgeon formed two peri-urethral tunnel on the model. This experiment included two parts:

- Test 1 - Biofidelity: Test 1 was conducted to analyze the biofidelity of MUS model. Two expert surgeons performed retropubic passage on a thiel-embalmed cadaver using the force trocar and also performed this procedure on physical pelvic model on the same day. Bio-fieldity of our physical pelvic floor model was determined by comparing force variables between MUS model and the cadaver.




(a) Comparison between original trocar and the modified trocar



(b) Trocar modified with a load cell

Figure 9: Force sensing trocar

- Test 2 - Test-retest for force sensitivity: Two expert surgeons and three novice surgeons performed retropubic trocar passages on MUS model two weeks apart to determine the force-sensitivity of our proposed trocar-model system. They performed six trocar passages and again performed additional six trocar passages two weeks later. Each session included three passages on both patient left and patient right side, and the left and right passages were performed sequentially.

Variables used to analyse the force variability during trials were as follows:

Table 1: Variables used to analyse force variability during trials

| Variables | Definition | Notation | Units |
|---|---|---|---|
| Maximum Force | Overall maximum force generated during trial | Fmax | Pounds (lb.) |
| Force RMS | Root-mean-squared value of force | FRMS | Pounds (lb.) |
| Standard Deviation of force | Measure of dispersion in force during trial | FSD | Pounds (lb.) |
| Force-generating Duration | Total time in which trocar generated more than 2 lbs. of force | Tforce | Seconds (s) |
| Time to maximum force | Time elapsed between first increase of force greater than 2 lbs. and maximum force | TMaxF | Seconds (s) |
| Average rate of force production | slope of a least-squares line fit to force data between onset of force production and maximum force | Mavg | lb./s |
| Maximum rate of force production | Maximum value of instantaneous slope calculated between onset of force production and time of maximum force | Mmax | lb./s |

*Note: 2 lbs. force was chosen based on the visual observation of all surgeons that they made contact between trocar tip and bone above this threshold force value.

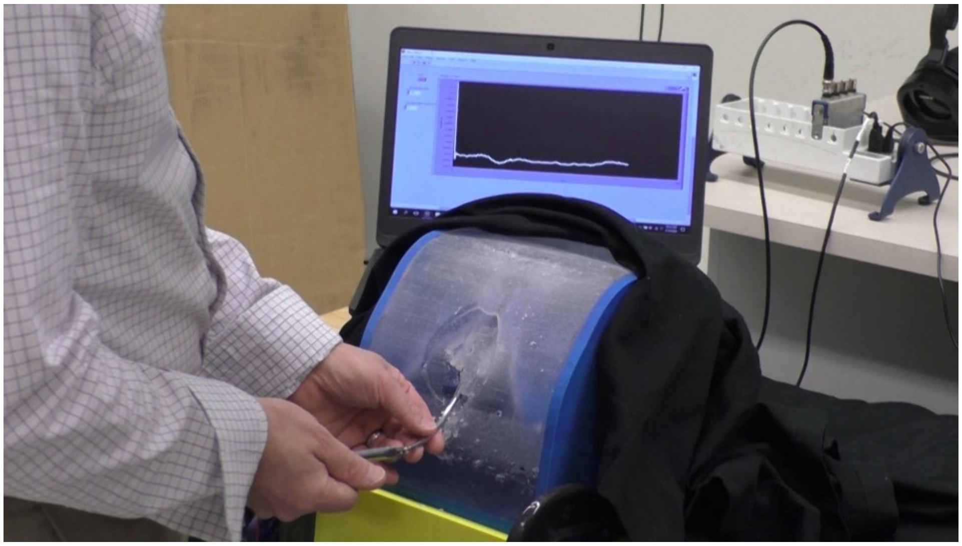


Figure 10: Experimental setup for testing with force-sensing trocar

#### 2.4.2 Biofidelity and force-sensitivity testing - Data Analysis

All preliminary analysis of the force data was performed using MATLAB R2020 (The Mathworks, Inc., Natick, MA, USA). Statistical Analysis was performed with IBM SPSS Statistics Version 26 (IBM Corporation, Armonk, NY, USA). Paired sample t-tests were performed within the expert surgeons on all outcome variables between the model and cadaver trials to assess the biofidelity of our physical pelvic model. Paired sample t-tests were performed on all outcome variables between the testing sessions to assess the reliability of our model-trocar system. Independent sample t-tests were performed on all outcome variables to compare between expert and novice surgeons.

## 2.5 Surgical Instrument (Trocar) and Surgeon Kinematics

### 2.5.1 Kinematics - Research Study Design

Modification of the Surgical Instrument: In this study, participants used a Gynecare TVT trocar (model 810041B), with the mesh tape removed, to perform retropubic trocar passage on physical pelvic floor models. TVT trocar model was connected to a Gynecare TVT introducer model 810051 (Ethicon, Inc, Somerville, NJ, USA). An additional 3D printed rigid body was attached to the trocar introducer. Seven retrorefelctive motion capture markers (8 mm) were mounted on this rigid body to track the instrument trajectory during trocar passage.

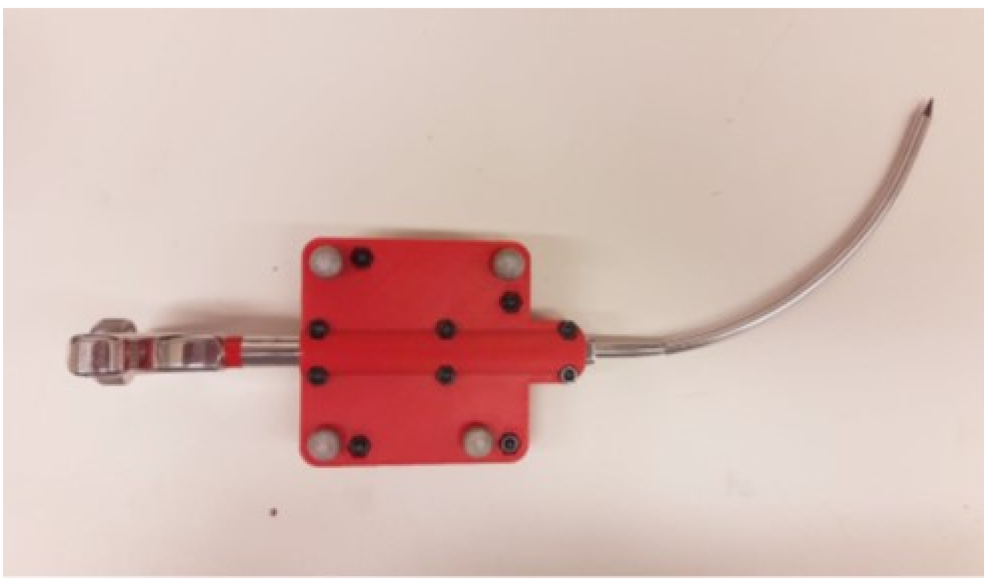


Figure 11: Retropubic trocar fitted with marker sleeve

Physical Pelvic Model Tracking: Six motion capture markers were mounted on the physical pelvic model that facilitated tracking the location of experimental model's bones, bladder, bowel, and blood vessels. The experimental configuration of the MUS model also included a wedge base with a five-degree tilt. This wedge-shaped base provides the required tilt angle for the pelvis and allows the surgeon to get a better view of the urethra and periurethral tunnel. This was introduced to the experimental setup based on recommendations made by expert surgeons who participated in the biofidelity study [42]. Both the physical MUS model and the wedge-shaped base were fastened to a height-adjustable table so that each subject can choose the desired height during the procedure. The experimental configuration was positioned securely and quickly using fast clamps.

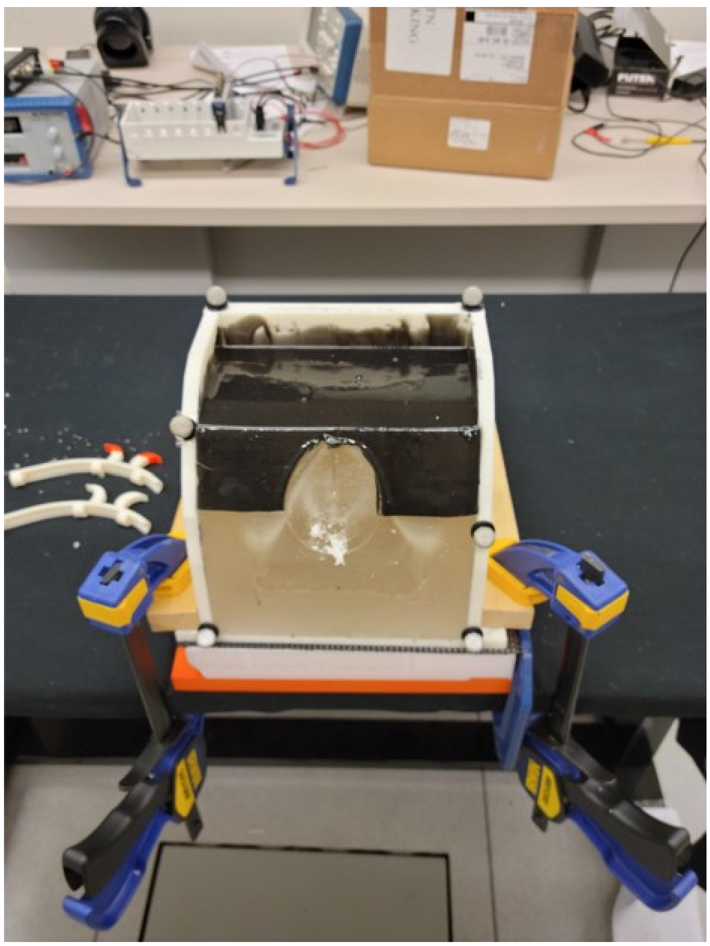


Figure 12: Experimental setup for physical model attached with wedge and table

Figure 13: Experimental setup for trocar and surgeon kinematics

Marker Placement on Surgeon Body: A custom marker set was used to track surgeon kinematics. This custom marker set consists of 81 markers including both upper and lower extremity. For the upper extremity, the Vicon Upper-body Plug-in gait marker set was used, along with 10 marker clusters (chest, back, upper-arm, lower-arm, wrist on both left and right side). For lower extremity, markers were chosen from OptiTrack Motive Biomech (57) marker placement system. All the body markers were placed on a velcro suit worn by the subjects. This custom marker set (marker labels, definition and location of individual markers) has been described in Appendix A. In addition to surgeon kinematics, a set of anthropometric measurements was collected for each subject. Anthropometric measurements included body mass, height, shoulder offset, elbow width, and wrist width.

Data Collection: All the motion capture markers were tracked using an OptiTrack Flex 13 motion capture system equipped with twelve cameras. For each retropubic trocar passage performed by the participants, three dimensional trajectories of all refelctive markers were collected at a frame rate of 120 Hz using the Motive motion capture software (NaturalPoint Inc, Corvallis, OR, USA). The trocar and experimental physical pelvic model fitted with reflective motion markers are shown in figure 11 & 12.

Subjects: Three expert and three novice surgeons participated in this study. The inclusion criteria for the expert participants was to have performed at least 100 retropubic midurethral sling surgeries. The inclusion criteria for novice surgeons was that all participants were Obstetrics and Gynecology residents with no previous experience with the midurethral sling procedure. The study protocol was approved by the Institutional Review Board (IRB), and all subjects approved and signed informed consent forms.

Experiment: All participants were provided with pre-experiment readings and instructions on how to pass the trocar safely. Peri-urethral tunnels were made on experimental MUS models by an expert surgeon before the experiment. Participants were instructed to maintain contact with the pubic ramus and to aim at avoiding injuries to vital organs, as they performed the trocar passage. They were also instructed to exit the trocar tip through rectus fascia. However, they were not specifically told that they would require to keep the passage posterior to the suprapubic bone.

A total of six MUS models (3 subject-specific patient models, each having 2 versions) was used for each subject. To compensate for the wear and tear caused by repetitive trocar passage, each patient model was printed in two copies. Each subject performed five trocar passages on each of the three physical pelvic floor models, for a total of 15 trials per participant. The order of the model usage and side of the trocar passages were randomized for each participant. As the trocar tip progressed, subjects were able to see only the trocar handle, similar to the blind MUS procedure performed in the operating room. Subjects were not provided with any feedback during the procedure and if an error was about to occur, it was allowed to happen. For each participant, all the trials were performed in a single experiment session.

Data post-processing: All the motion capture data collected (trocar, model and surgeon) were post-processed and filtered using the Motive motion capture software post-processing utility. Post-processing of the marker data included trimming, labeling markers, filling gaps, fixing swaps and filtering.

Power Analysis: An a priori power analysis was performed using cystotomy as the outcome of interest. Cystotomy is a common complication associated with retropubic midurethral sling placement. If a 40.9% incidence of cystotomy is assumed for novices [43] and a 5.0% incidence of cystotomy for experts [44] with significance set at 0.05, and 90% power to detect a difference, then this study requires a sample of 27 trocar passes for each group.

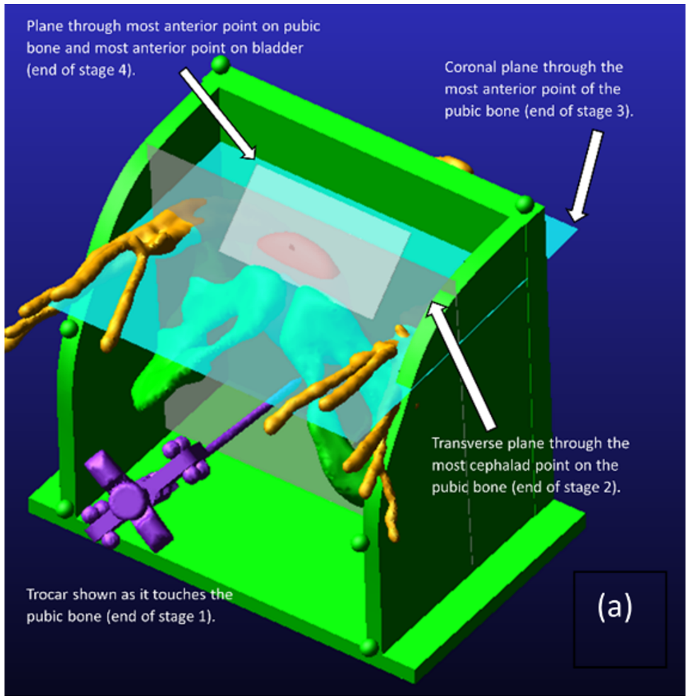
Figure 14: Surgeon, equipped with motion capture markers, performing the retropubic passage on MUS model

### 2.5.2 Trocar Kinematics - Analysis

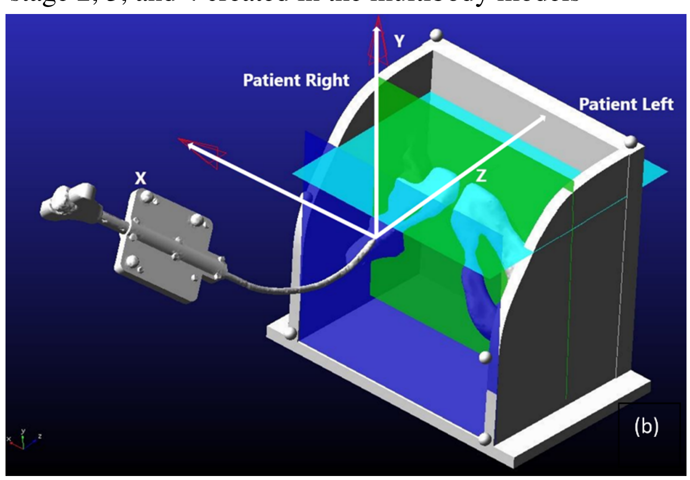
Multi-body Modeling: Three dimensional motion capture data from the trocar and MUS model were exported and imported as an input to the Multi-body models for further analysis. Trocar-model kinematic models were developed in a multi-body modeling framework, ADAMS (MSC Software Corporation, Santa Ana, CA). These models included the 3D geometries of the physical MUS model and the surgical instrument (trocar). In addition, the major blood vessels and the bladder segmented from the MRI sequences were also imported to the multi-body model. MRI derived pelvis geometries were aligned with the corresponding pelvis of the physical MUS model using least squares fit. The surgical trocar along with the fitted rigid body was scanned using a handheld 3D scanner (Artec EVA, Senningerberg, Luxembourg) and 3D geometry was imported to the multi-body model. Motion capture data of trocar and model from the experimental trials was used as an input to drive the kinematic analysis. This procedure allowed us to simulate each retropubic trocar passage performed on the physical models in the multibody environment. These models facilitate the visualization and analysis of trocar movement corresponding to the pelvic floor structures, since the blood vessels and the bladder structures have been overlayed in the MUS model now. The trocar passage has been defined using 4 stages according to the location of the trocar tip.

- Stage 1: from vaginal incision point to pubic bone contact point.
- stage 2: from first bone contact point to the most cephalad point along the posterior surface of the pubic bone.
- stage 3: from the most cephalad point to the most ventral point of the pubic bone.
- stage 4: from the most ventral point of the pubic bone to the rectus fascia.

Landmark-oriented planes have been created that correspond to the end of stages 2, 3, and 4. These planes in the multibody models can identify when the trocar tip crossed those planes (Figure 15). A right handed coordinate system has been defined at the starting point (0,0,0) which is the location where the trocar tip enters the model. This point also corresponds to the entry point of the periurethral tunnel (most distal point relative to the pubic bone). Trocar tip locations were identified corresponding to the planes defined and pelvic floor structures, through the simulated trocar passage of each trial. For each trial, the outputs of the trocar kinematic analysis were: trocar tip location throughout the




(a) Landmark-oriented planes corresponding to the end of stage 2, 3, and 4 created in the multibody models




(b) The location where the trocar tip entered the model, corresponding to the most distal part (the entry point of) the periurethral tunnel

Figure 15: Multibody model used for kinematic analysis. Includes the surgery simulator, trocar, and landmark planes

passage (time-series of trocar tip trajectory), time intervals of each of the four stages, contact or penetration between trocar and bladder or iliac blood vessels, and total path length. The simulated passage revealed whether the surgeon followed a trocar trajectory anterior or posterior to the pubic symphysis. The correct trocar passage is posterior to the pubic symphysis. Total path length was defined as the cumulative length of the path traveled by the trocar tip in 4 stages. Time zero was defined at the beginning point of stage 1. Separate analyses were conducted for trocar passage towards the patient right and patient left shoulder.

In this study, all three directions of trocar tip trajectories were analyzed and the following comparisons were conducted: 1. Bladder contact versus no bladder contact in all 4 stages, 2. Bladder contact versus no bladder contact in stage 3, since bladder contact occurs in stage 3. The trocar trajectory was compared between bladder contact and no bladder contact in all 4 stages to identify the overall differences during the procedure, and separate analysis was done for stage 3 to determine the stage when bladder perforation actually takes place, 3. Anterior versus posterior passage in stage 1, since anterior trials technically do not have any stage 2, stage 3, or stage 4. Bladder contact versus no bladder contact trials were also compared in terms of stage duration. Expert versus novice analysis was performed by comparing trocar tip trajectories, stage duration times and variation of the troacr tip trajectory.

Statistical Analysis: Mixed model analysis was used to analyze the output variables to account for the repeat measures from each participant. Mixed model analysis was chosen to account for repeated experiments from 6 different participants. Temporal variables and trocar trajectories were treated as outcome variables while bladder, and anterior passage errors were treated as explanatory variables. Participants were treated as random effects to account for the repeated measures. All statistical analysis was done in SAS 9.4 (SAS Institute Inc, Cary, NC).

## 2.6 Surgeon Kinematics - Analysis

Musculoskeletal Modeling: Musculoskeletal models were developed to analyze the surgeon body kinematics using OpenSim, an open-source software to create and analyze dynamic simulations of human movement [45, 46]. A generic OpenSim model was scaled to subject-specific OpenSim model for each subject using the anthropometric measurements, markers placed on bony landmarks and joint centers. This model has 17 degrees of freedom in the upper body and torso, and 20 degrees of freedom in the lower body [47]. OptiTrack Flex 13 motion capture system captured the 3D positions of reflective markers placed on surgeon's upper extremities. Surgeon kinematic data was post-processed, exported and used as an input to the OpenSim Models to recreate the surgeon body kinematics for each trial. A freely available toolbox MOtoNMS (matlab MOtion data elaboration TOolbox for Neuromusculoskeletal applications) was used for post-processing of kinematic data and prepare .trc files for running inverse kinematic simulation in OpenSim Musculoskeltal Modeling software [48].

Inverse kinematics simulation was run using the scaled subject-specific OpenSim models integrated with surgeon kinematic data which allowed calculation of flexion/extension, abduction/adduction, and internal/external rotation angular time series for shoulder, elbow, and wrist joints. Time series were truncated and divided into 4 stages ending with the following events as defined in the analysis of trocar kinematics: (1) contact with pubic bone; (2) the most cephalad point of the pubic bone; (3) the most ventral point of the pubic bone; and (4) the rectus fascia. In each stage, trocar passages were assessed in terms of towards and away from the bladder trials, starting and ending angles, minimum and maximum angles, and angular range of motion (ROM).

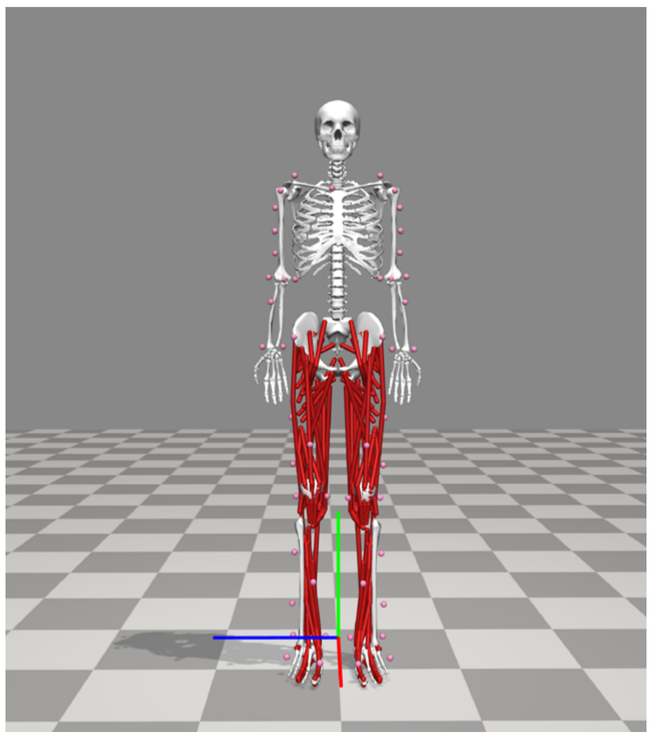


Figure 16: Musculoskeletal model developed in OpenSim to analyze surgeon kinematics

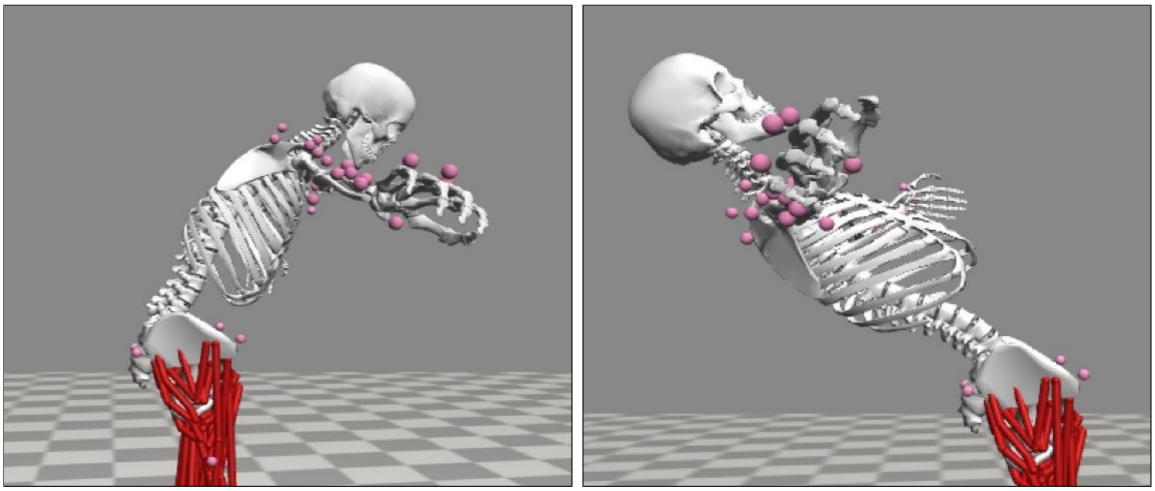
Data Analysis: Linear mixed modeling has been used to compare surgeon kinematics between bladder contact versus no bladder contact trials, anterior versus posterior trocar passage relative to pubic bone, and expert versus novice surgeons. Separate analyses were conducted for trials towards or away from the bladder. The direction of passages were defined according to the gripping hand and shoulder direction (left or right passages).

Analysis has been done separately on left and right passages and on gripping hand side for beginning and ending kinematic joint angles at 4 stages. Gripping side was defined as the hand side that grips the t-handle, and supporting side is the contra-lateral. The gripping side were not always the same as the dominant side of the subject. For example, a subject might change their grip based on the side of trocar passage. Movement directions of the upper extremity joint angles (Kinematic variables) computed from the OpenSim analysis have been demonstrated in the figures 17-26. Upper extremity joint angles were defined as follows :

- Wrist deviation
  - Full radial deviation: -25° (Radial flexion of the wrist or radial deviation refers to the movement of the hand and wrist towards the thumb of the forearm)
  - Wrist straight: 0° (Neutral position)
  - Full ulnar deviation: 35° (Ulnar deviation of the wrist or ulnar flexion refers to the movement of the hand and wrist towards the little finger of the forearm)
- Arm Pronation
  - Full pronation: 0° (Pronation is a rotational movement of the forearm that causes the palm to face posteriorly or downwards)
  - Neutral: 45° (Thumb is approximately vertical up in the air)
  - Full supination: 90° (Supination refers to the motion of turning the palm anteriorly, or upwards)

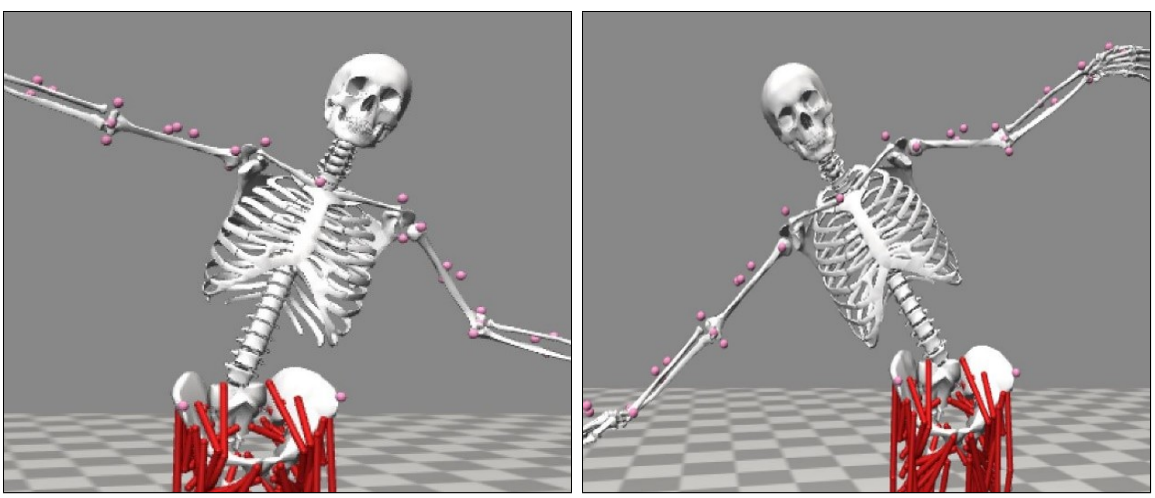
- Wrist dorsiflexion
  - Full dorsiflexion: -70° (Dorsiflexion of the hand/wrist involves lifting the hand up towards the top of the forearm)
  - Neutral: 0° (Neutral position of the wrist)
  - Full palmar flexion: 70° (Palmar flexion to the radioulnar joint is described as the motion in which the palmar aspect of the hand moves toward the forearm in the sagittal plane)
- Elbow flexion
  - Full extension: 0° (Elbow extension involves increasing the angle between the upper arm and forearm)
  - Full flexion: 150° (Flexing the forearm at the elbow joint involves reducing the angle between the forearm and the upper arm at the elbow joint)
- Shoulder Adduction
  - Full abduction: -120° (The humerus moves upward and laterally towards the side, away from the body, in the plane of the scapula)
  - Neutral: 0° (arm is straight down at rest)
  - Full adduction: 90° (Descending motion of the humerus towards the body from the abduction, in the plane of the scapula.)

The overall methodology used in this project, from imaging to the development of computational models, has been demonstrated using figure 27.



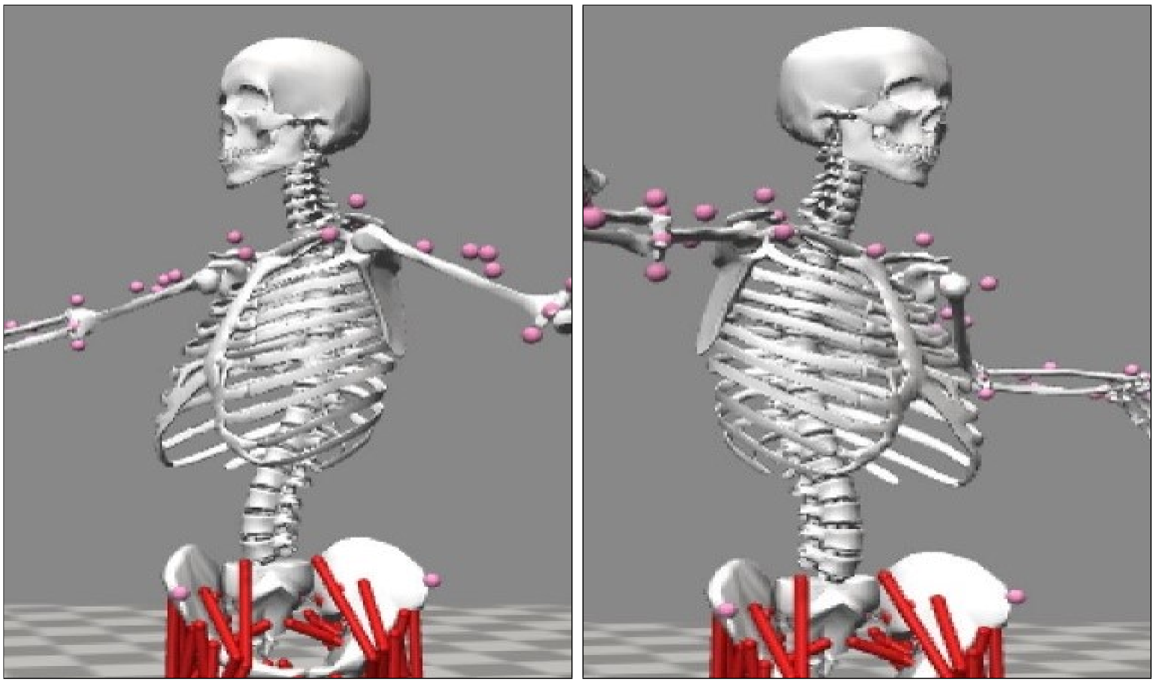
(a) (b)

Figure 17: Lumbar Extension (-90° Froward & 90° Backward)



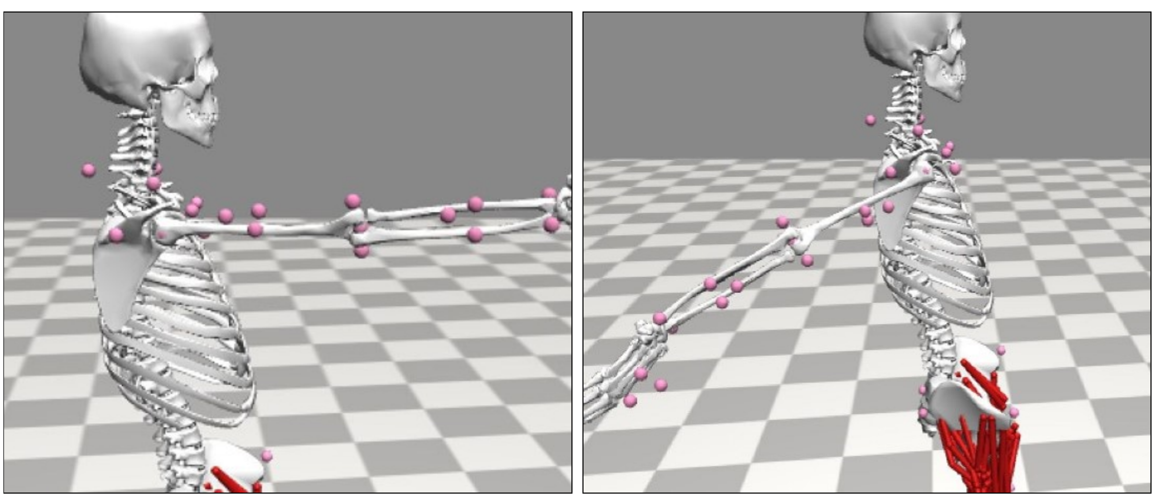
(a) (b)

Figure 18: Lumbar Bending (-90° to the Left & 90° to the Right)



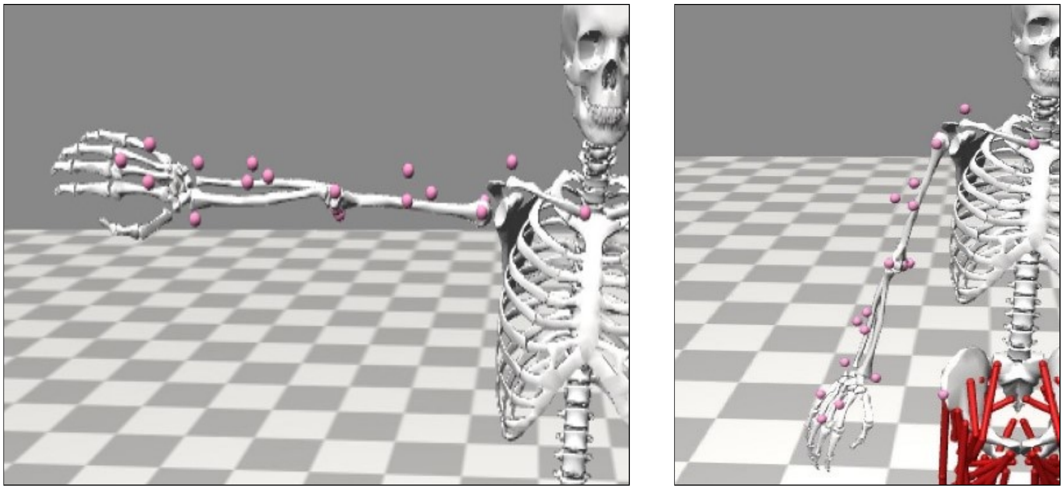
(a) (b)

Figure 19: Lumbar Rotation (-90° to the Right & 90° to the Left)



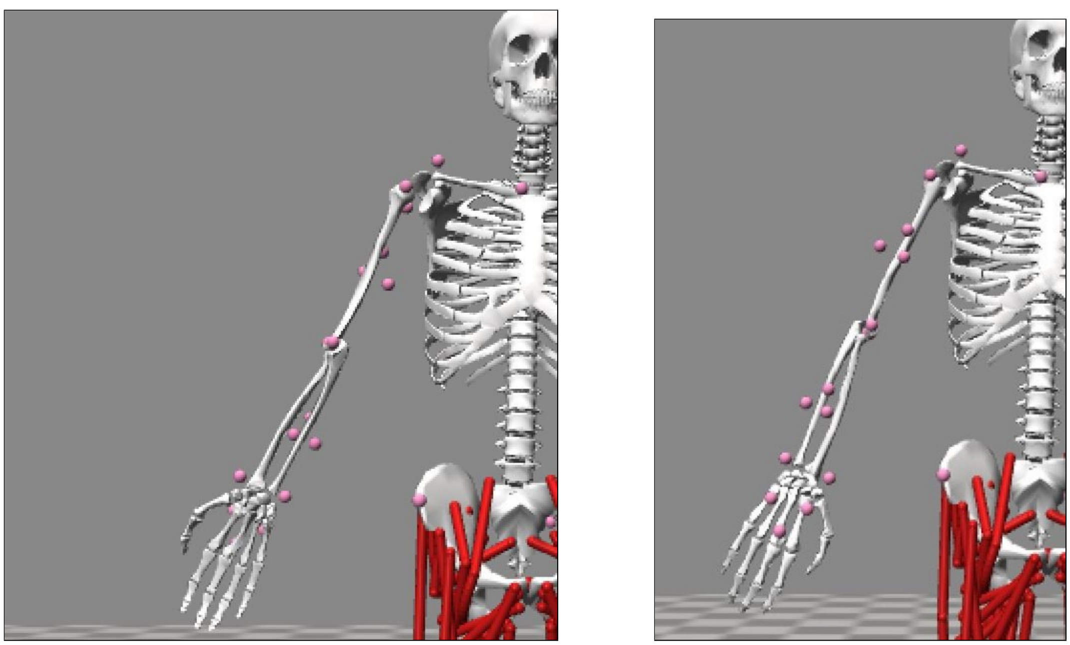
(a) (b)

Figure 20: Arm Flexion - Right (-90° Flexion Backward & 90° Flexion Backward)



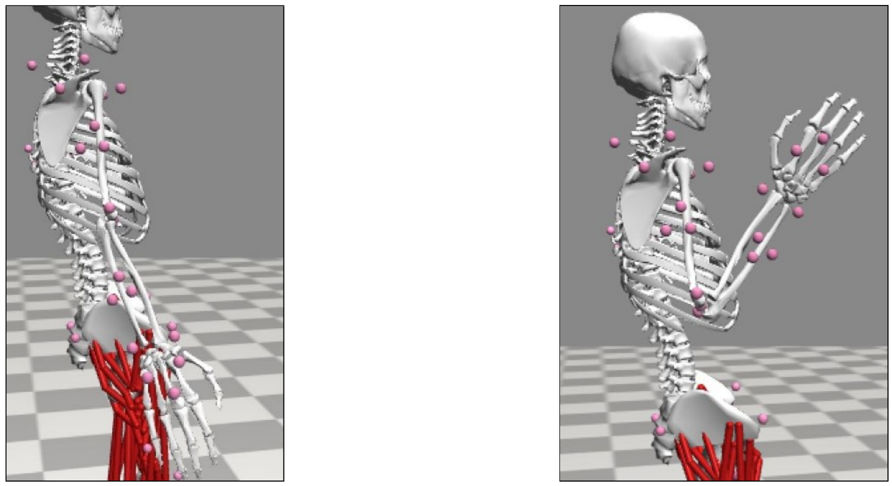
(a) (b)

Figure 21: Arm Adduction - Right (-120° Full Abduction & 90° Full Adduction)



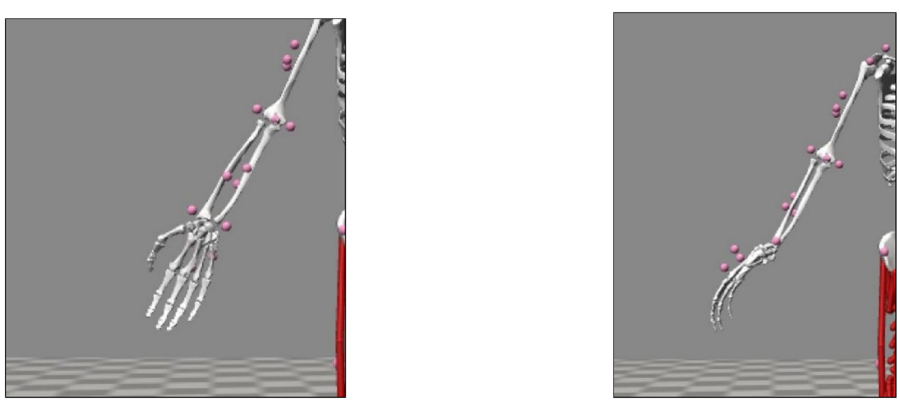
(a) (b)

Figure 22: Arm Rotation - Right (-90° External & 90° Internal)



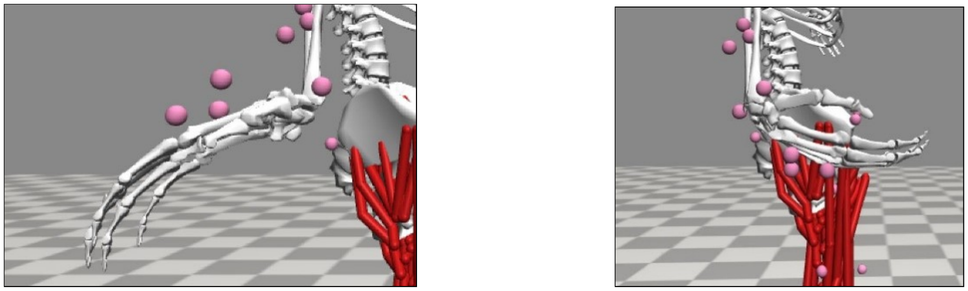
(a) (b)

Figure 23: Elbow Flexion - Right (0° Full Extension & 150° Full Flexion)



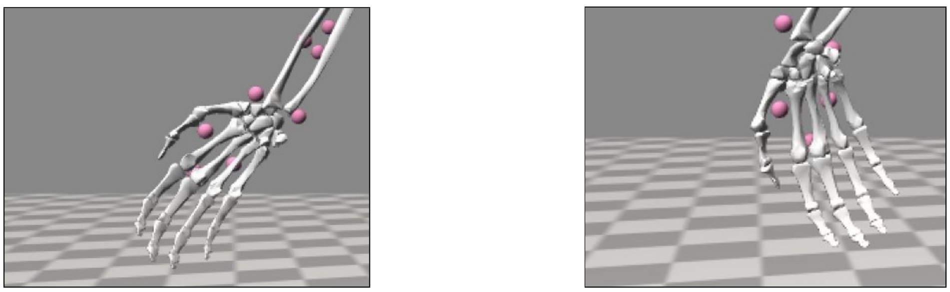
(a) (b)

Figure 24: Elbow Pronation Supination - Right (0° Full Pronation & 90° Full Supination)



(a) (b)

Figure 25: Wrist Flexion - Right (-70° Full Dorsiflexion & 70° Full Flexion)



(a) (b)

Figure 26: Wrist Deviation - Right (-25° Deviation towards Thumb & 35° Deviation to the Little Finger)

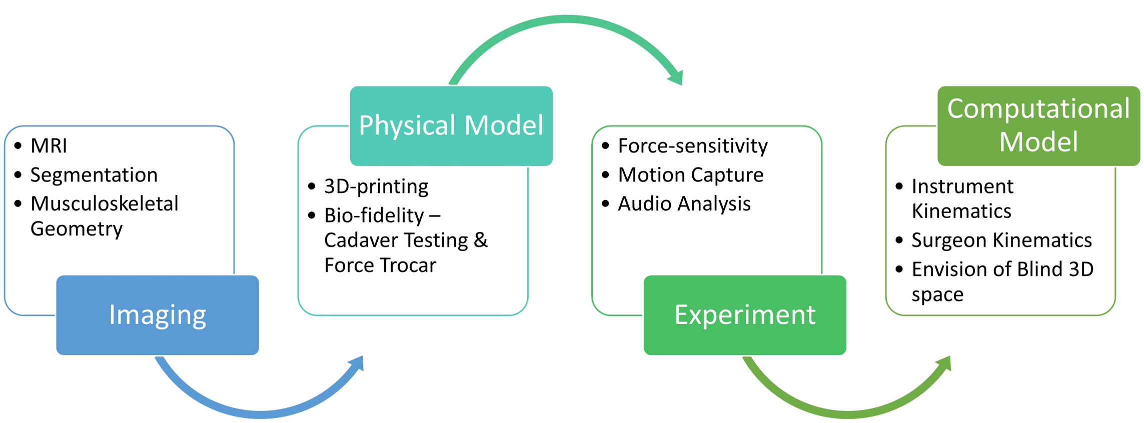



Figure 27: Description of methods used in this study

# CHAPTER 3

# RESULTS & ANALYSIS

## 3.1 Force-sensing Trocar

### 3.1.1 Cadaver vs. Model Bio-fidelity

Paired sample t-tests between the cadaver and MUS physical pelvic model trials showed no statistically significant differences on the outcome variables considered, except force-generating Duration (Tforce). The cadaver had a significantly higher force-generating Duration (Tforce) than the model (11.7 seconds vs 6.9, p = 0.048), which was the only exception. Outcome values and p-values have been presented in Table 2.

Table 2: Cadaver vs. MUS Model Biofidelity Analysis

| Variable | Units | Cadaver (N = 2) Means (SDs) | Model (N = 2) Means (SDs) | p-Value |
|---|---|---|---|---|
| Fmax | Pounds (lb.) | 51.6 (12.4) | 43.5 (14.1) | 0.548 |
| FRMS | Pounds (lb.) | 24.3 (7.2) | 21.1 (12.0) | 0.615 |
| FSD | Pounds (lb.) | 17.0 (4.0) | 14.5 (6.0) | 0.587 |
| Tforce | Seconds (s) | 11.7 (3.1) | 6.9 (1.5) | 0.048* |
| TMaxF | Seconds (s) | 6.8 (2.9) | 3.1 (3.2) | 0.072 |
| Mavg | Pounds per Second (lb./s) | 8.8 (10.6) | 10.8 (3.1) | 0.646 |
| Mmax | Pounds per Second (lb./s) | 134.7 (38.4) | 119.0 (22.4) | 0.621 |

Figure 28 refers to a representative trial showing force over time, with least squares fit line, duration of bone contact, and maximum force denoted. This graph shows visually how each phase of the curve corresponds with the steps of trocar passage. Figure 29 shows a comparison of forces tracked in cadaver and MUS model retropubic passages

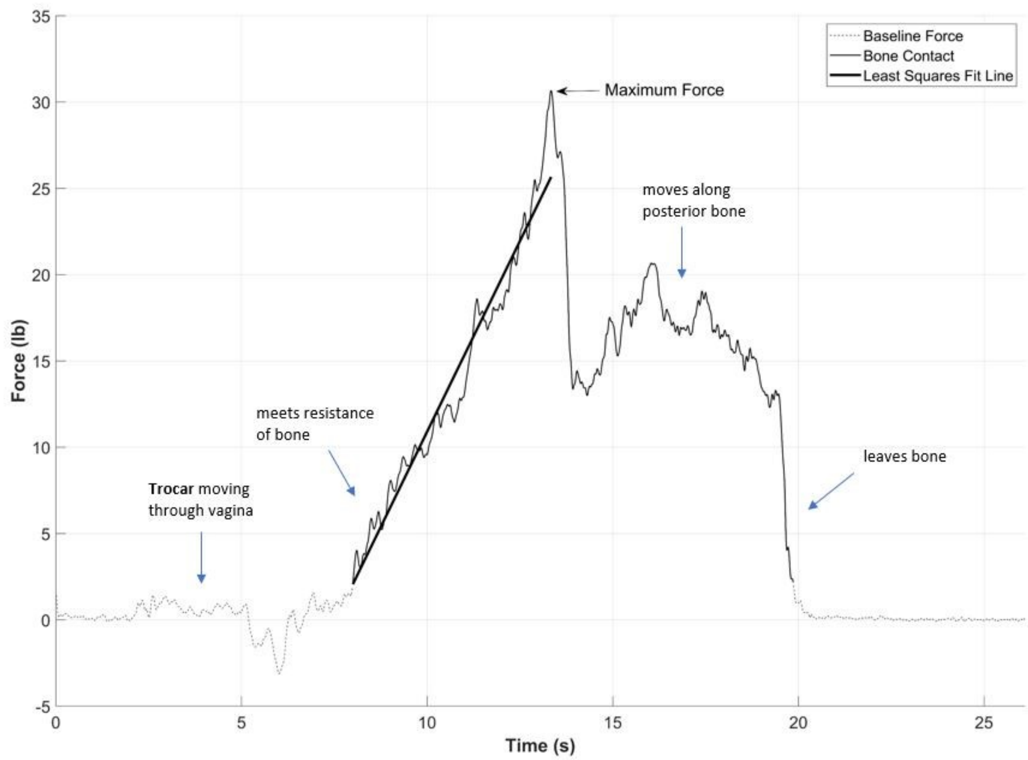



Figure 28: Representative trial to show the force profile during the retropubic passage performed using the force-sensing trocar

using the modified trocar.

### 3.1.2 Test-retest reliability

Two expert and two novice surgeons were included in the test-retest analysis. Paired sample t-tests showed no statistically significant differences between the testing sessions for individual surgeons for any of the outcome variables compared. Table 3 shows the values of outcome variables along with p-values in the test-retest module. ”Force-generating duration (Tforce)”, ”Time to maximum force (TMaxF)” and ”Average rate of force production (Mavg)” were higher in the first session and other force variables

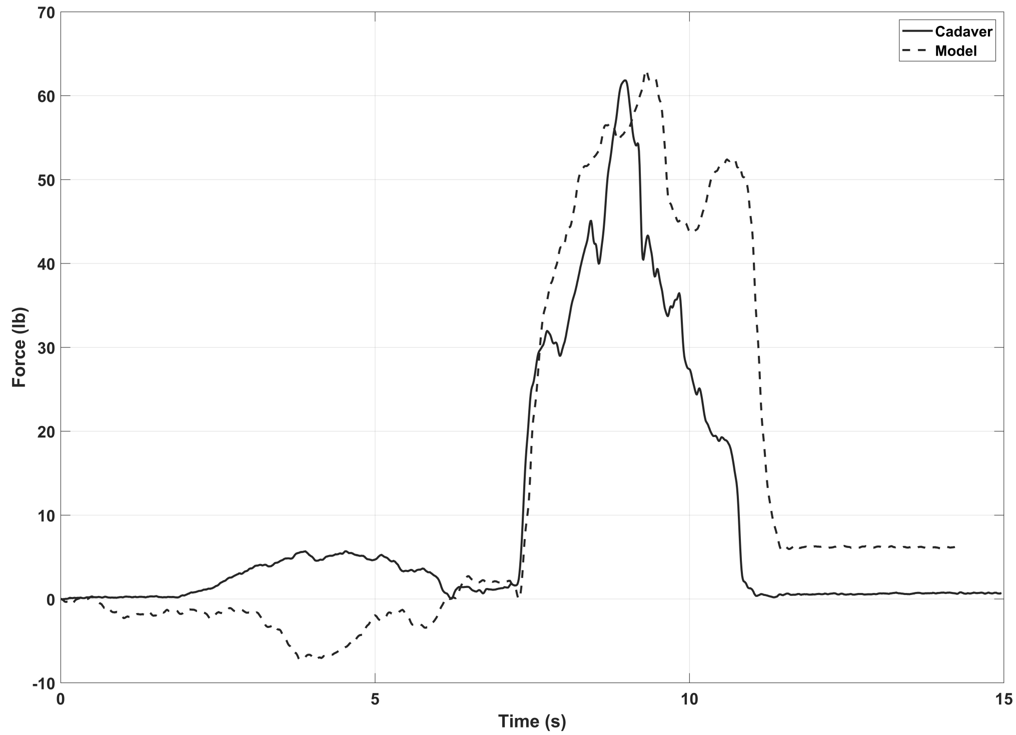



Figure 29: Representative comparison between cadaver and MUS model force profile during the retropubic passage

were found to be higher in the second session. However, these force variables did not reach statistical significance.

### 3.1.3 Expert vs. Novice Analysis

Expert vs. Novice comparison included two expert and three novice surgeons. Independent sample t-tests performed on the outcome variables showed that the expert surgeons, compared to novices, generated larger amplitude of maximum force during the trocar passage (51.2 lbs. vs 22.7 lbs., p =0 .03), shorter time to reach maximum force

Table 3: Test-retest analysis, performed 2 weeks apart

| Variable | Units | Session 1 (N=4)<br>Means (SDs) | Session 2 (N=4)<br>Means (SDs) | p-Value |
|---|---|---|---|---|
| Fmax | Pounds (lb.) | 31.0 (16.0) | 39.5 (24.0) | 0.224 |
| FRMS | Pounds (lb.) | 14.0 (11.0) | 19.1 (11.7) | 0.296 |
| FSD | Pounds (lb.) | 9.7 (6.2) | 11.7 (7.0) | 0.051 |
| Tforce | Seconds (s) | 14.3 (9.3) | 9.6 (2.4) | 0.314 |
| TMaxF | Seconds (s) | 7.0 (4.8) | 4.4 (3.3) | 0.089 |
| Mavg | Pounds per Second (lb./s) | 6.1 (5.6) | 4.1 (3.1) | 0.392 |
| Mmax | Pounds per Second (lb./s) | 78.4 (50.2) | 148.0 (118.5) | 0.150 |

development (2.7s vs. 9.5s, p = 0.03), and larger maximum rate of force development (171.5 lb./s vs. 54.0 lb./s, p = 0.01), as shown in table 4.

Table 4: Expert vs. Novice Analysis

| Variable | Units | Novice (N = 3)<br>Means (SDs) | Expert (N = 2)<br>Means (SDs) | p-Value |
|---|---|---|---|---|
| Fmax | Pounds (lb.) | 22.7 (7.9) | 51.2 (7.0) | 0.026* |
| FRMS | Pounds (lb.) | 10.2 (3.9) | 24.5 (6.9) | 0.055 |
| FSD | Pounds (lb.) | 6.8 (2.7) | 15.9 (4.0) | 0.052 |
| Tforce | Seconds (s) | 15.7 (3.6) | 7.8 (1.4) | 0.067 |
| TMaxF | Seconds (s) | 9.5 (1.7) | 2.7 (2.6) | 0.034* |
| Mavg | Pounds per second (lb./s) | 2.0 (0.5) | 9.1 (1.3) | 0.057 |
| Mmax | Pounds per second (lb./s) | 54.0 (22.2) | 171.5 (5.6) | 0.006* |

### 3.2 Surgical Instrument Kinematics

Expert surgeons performed 27 error-free passages (60%) and 18 error passages (40%) where the trocar contacted the bladder. On the other hand, novice surgeons performed 18 error-free passages (40%) and 27 error passages (60%). Among 27 error passages performed by the novices, trocar contacted the bladder in 4 error passages (8.9%), and trocar passed anterior to the pubic symphysis in 23 error passages (51.1%). This resulted in an overall error rate of 60% for the novices. Neither experts nor novices made contact with the bowel or the iliac blood vessels in any of the trials.

### 3.2.1 Bladder Contact versus no Bladder Contact

Excursions have been measured in the coordinate system described in the methods section. Here, the negative values in the medial-lateral direction represent excursions towards the patient left side and the positive values represent excursions to patient right side. Negative values in the anterior-posterior direction represent excursions posterior to the coordinate origin, and negative values in the caudal-cephalad direction represent excursions caudal to the origin. Similarly, positive values in the anterior-posterior direction represent excursions anterior to the coordinate origin, and positive values in the caudal-cephalad direction represent excursions cephalad to the origin.

Tables 5-8 summarize the excursions of the trocar tip in all three directions by each stage. There was no statistically significant difference in the excursions between error-free and bladder error trials.

However, when analyzing the trocar tip trajectories across all 4 stages, significant statistical differences have been observed between the bladder contact trials and no bladder contact trials for both passages towards the patient right and patient left shoulder direction. For the passages towards the left shoulder direction, significant differences were observed in all three directions (Medial-Lateral, Anterior-Posterior, and Caudal-Cephalad). However, passage towards the patient right shoulder direction exhibited significant differences in the Anterior-Posterior and Caudal-Cephalad directions, but not in

Table 5: Excursions of the trocar tip in all three directions for stage 1

| Stage 1: Passage towards left Shoulder | | | | |
|---|---|---|---|---|
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | -8.70 (9.17) | 16.95 (27.72) | -11.36 (9.72) | 6.96 (10.83) |
| Anterior-Posterior | -29.19 (20.82) | 2.84 (4.01) | -25.56 (11.96) | 0.81 (1.79) |
| Caudal-Cephalad | -0.59 (1.64) | 48.86 (19.71) | -0.73 (2.04) | 51.13 (14.73) |
| | | | | |
| Stage 1: Passage towards right Shoulder | | | | |
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | -8.54 (16.81) | 8.89 (8.94) | -4.34 (4.85) | 11.26 (10.64) |
| Anterior-Posterior | -27.26 (16.19) | 4.96 (10.21) | -24.55 (11.94) | 10.12 (13.25) |
| Caudal-Cephalad | -0.23 (0.59) | 54.56 (23.17) | -0.04 (0.16) | 62.41 (24.86) |

Table 6: Excursions of the trocar tip in all three directions for stage 2

| Stage 2: Passage towards left Shoulder | | | | |
|---|---|---|---|---|
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | -3.42 (34.63) | 8.24 (33.09) | -19.95 (16.10) | -4.81 (14.12) |
| Anterior-Posterior | -27.62 (21.59) | -15.26 (25.79) | -20.22 (14.29) | -0.61 (12.97) |
| Caudal-Cephalad | 39.86 (11.32) | 71.23 (9.65) | 45.04 (7.11) | 76.66 (6.77) |
| | | | | |
| Stage 2: Passage towards right Shoulder | | | | |
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | -1.80 (19.24) | 7.45 (19.81) | 4.21 (8.31) | 15.46 (10.76) |
| Anterior-Posterior | -24.66 (17.42) | -10.92 (20.74) | -21.22 (14.56) | -6.03 (18.84) |
| Caudal-Cephalad | 38.90 (9.34) | 70.48 (9.92) | 42.23 (7.45) | 75.67 (7.23) |

Table 7: Excursions of the trocar tip in all three directions for stage 3

| Stage 3: Passage towards left Shoulder | | | | |
|---|---|---|---|---|
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | -8.22 (36.00) | 3.56 (39.28) | -21.99 (20.43) | -11.71 (18.90) |
| Anterior-Posterior | -17.77 (21.71) | 12.79 (23.22) | -4.52 (13.02) | 22.16 (13.18) |
| Caudal-Cephalad | 70.25 (9.48) | 90.94 (11.88) | 75.59 (7.02) | 90.18 (13.84) |
| | | | | |
| Stage 3: Passage towards right Shoulder | | | | |
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | 3.50 (20.79) | 11.66 (21.41) | 10.75 (11.28) | 20.28 (9.84) |
| Anterior-Posterior | -12.15 (20.24) | 17.14 (19.19) | -9.09 (19.38) | 18.77 (11.86) |
| Caudal-Cephalad | 70.44 (9.72) | 89.44 (14.77) | 75.21 (7.73) | 89.44 (10.79) |

Table 8: Excursions of the trocar tip in all three directions for stage 4

| Stage 4: Passage towards left Shoulder | | | | |
|---|---|---|---|---|
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | -6.43 (35.44) | -2.41 (37.65) | -19.78 (22.32) | -15.30 (21.62) |
| Anterior-Posterior | 12.93 (23.25) | 20.78 (27.46) | 22.37 (13.22) | 32.01 (15.23) |
| Caudal-Cephalad | 87.37 (10.90) | 89.78 (11.06) | 87.82 (12.03) | 91.40 (11.54) |
| | | | | |
| Stage 4: Passage towards right Shoulder | | | | |
| Direction | Bladder Contact | | No Bladder Contact | |
| | Min (mm) | Max (mm) | Min (mm) | Max (mm) |
| Medial-Lateral | 7.25 (21.76) | 11.96 (21.65) | 14.05 (12.61) | 17.67 (11.97) |
| Anterior-Posterior | 17.06 (19.31) | 25.37 (20.18) | 18.93 (11.77) | 27.74 (14.00) |
| Caudal-Cephalad | 86.44 (13.20) | 90.69 (12.36) | 86.64 (11.63) | 89.31 (10.81) |

the Medial-Lateral direction. Table 9 represents the Mixed model analysis results for trocar tip trajectories with and without bladder contact for all 4 stages (Stages 1 - 4).

Table 9: Mixed model analysis results for trocar tip trajectories with and without bladder contact, Stages 1 - 4

| Passage towards left shoulder | | | |
|---|---|---|---|
| Direction | Bladder contact<br><br>Mean (SD) - mm | No bladder contact<br><br>Mean (SD) - mm | Significance<br><br>($\alpha = 0.05$) |
| Medial-Lateral | 1.3 (32.1) | -13.1 (18.1) | 0.001* |
| Anterior-Posterior | -11.4 (26.4) | -3.8 (19.0) | 0.010* |
| Caudal-Cephalad | 61.5 (25.9) | 63.4 (24.9) | <0.001* |

| Passage towards right shoulder | | | |
|---|---|---|---|
| Direction | Bladder contact<br><br>Mean (SD) - mm | No bladder contact<br><br>Mean (SD) - mm | Significance<br><br>($\alpha = 0.05$) |
| Medial-Lateral | 3.1 (19.4) | 11.7 (11.3) | 0.105 |
| Anterior-Posterior | -5.7 (24.6) | -6.9 (19.4) | <0.001* |
| Caudal-Cephalad | 62.0 (25.7) | 65.5 (26.5) | <0.001* |

* Statistically Significant ($\alpha = 0.05$)

Note: Means and standard deviations (SD) represent the mean and standard deviation of the slope of the regression lines. All the units are in millimeters (mm).

When we analyzed the trocar tip trajectories for only stage 3, which corresponds to the passage from the most cephalad point to the most ventral point of the pubic bone, significant statistical differences were observed between bladder contact and no bladder contact trials for both left and right shoulder passages. In this case (Stage 3), significant differences were observed between the bladder contact and no bladder contact trials in both the Anterior-Posterior direction and Caudal-Cephalad direction, but not in the

Medial-Lateral direction. Table 10 represents the Mixed model analysis results for trocar tip trajectories with and without bladder contact for stage 3 only.

Table 10: Mixed model analysis results for trocar tip trajectories with and without bladder contact, Stage 3 Only

Passage towards left shoulder

| Direction | Bladder contact<br>Mean (SD) - mm | No bladder contact<br>Mean (SD) - mm | Significance<br>($\alpha = 0.05$) |
|---|---|---|---|
| Medial-Lateral | -0.5 (38.7) | -19.7 (21.5) | 0.099 |
| Anterior-Posterior | -4.1 (24.5) | 5.0 (15.3) | <0.001* |
| Caudal-Cephalad | 81.2 (11.8) | 84.8 (11.7) | <0.001* |

Passage towards right shoulder

| Direction | Bladder contact<br>Mean (SD) - mm | No bladder contact<br>Mean (SD) - mm | Significance<br>($\alpha = 0.05$) |
|---|---|---|---|
| Medial-Lateral | 9.5 (16.8) | 15.0 (11.0) | 0.316 |
| Anterior-Posterior | 3.4 (21.0) | -3.0 (18.2) | 0.039* |
| Caudal-Cephalad | 82.4 (12.9) | 86.5 (9.2) | <0.001* |

* Statistically Significant ($\alpha = 0.05$)

Note: Means and standard deviations (SD) represent the mean and standard deviation of the slope of the regression lines. All the units are in millimeters (mm).

### 3.2.2 Anterior Passage versus Posterior Passage

Analysis of the trocar tip trajectories has shown significant difference in the incidence of the anterior passage between the expert and novice surgeons for the passages in both patient left and right shoulder directions. In the patient left shoulder direction, the incidence of anterior passage was 0% and 64% ($p < 0.001$), for experts and novices, respectively. In the patient right direction, the incidence of the anterior passage was 0%

and 39% (p = 0.001), for the experts and novices, respectively.

Table 11: Mixed model analysis results for trocar tip trajectories and total path length, for posterior versus anterior passages, Stage 1 Only

Left Passage

| Direction | Posterior passage Mean (SD) - mm | Anterior passage Mean (SD) - mm | Significance ($\alpha = 0.05$) |
|---|---|---|---|
| Medial-Lateral | -9.1 (23.7) | -13.4 (12.8) | <0.001* |
| Anterior-Posterior | -5.9 (21.6) | 3.4 (17.2) | <0.001* |
| Caudal-Cephalad | 62.8 (25.2) | 51.1 (19.4) | <0.001* |
| Total Path Length | 272.4 | 304.2 | 0.262 |

Right Passage

| Direction | Posterior passage Mean (SD) - mm | Anterior passage Mean (SD) - mm | Significance ($\alpha = 0.05$) |
|---|---|---|---|
| Medial-Lateral | 8.5 (15.4) | 12.6 (10.8) | 0.003* |
| Anterior-Posterior | -6.4 (21.5) | -17.6 (26.5) | <0.001* |
| Caudal-Cephalad | 64.2 (26.2) | 49.0 (18.2) | <0.001* |
| Total Path Length | 242.1 | 345.3 | 0.0005* |

* Statistically Significant ($\alpha = 0.05$)

Note: Posterior versus anterior passage analysis represents the relationship of trocar tip to the pubic symphysis, with posterior representing the correct, error-free pathway. Means and standard deviations represent the mean and standard deviation of the slope of the regression lines. All the units are in millimeters (mm).

There was no significant difference in stage 1 duration between anterior and posterior passages (1.9 vs 2.2 seconds, respectively, p = 0.261 for left shoulder passes and 1.7 vs 1.9 seconds, respectively, p = 0.366 for right shoulder passes). Significant differences were observed in trocar tip trajectories (all three directions) between anterior and posterior passages, for both passages towards patient left and right shoulder. Total path length was greater in the anterior passage, but the difference was significant only in the passages towards patient right shoulder. Table 11 represents the mixed model analysis results for trocar tip trajectories and total path length, for posterior versus anterior passages in stage 1 only. This analysis only includes stage 1, since the anterior passages technically don't have stages 2,3 and 4.

#### 3.2.3 Temporal Analysis

Significant statistical differences have been observed in the duration of left and right passages of the trocar in stages 1,2, and 3. Expert and novice passages were significantly different in terms of duration in stages 1 and 3. Novices exhibited significantly greater duration in Stage 1, while the experts exhibited greater duration in Stage 3.

There was a significant difference in the stage 2 duration between the bladder error trials and error free trials, where bladder error trials showed significantly longer duration. Since anterior trocar passages do not exhibit stages 2,3, and 4, those trials were not considered for this analysis.

There was no significant difference in stage 1 duration between error-free posterior passages and anterior error passages. Analysis of the total variation in total path length among all expert and novice surgeons has revealed that 48% of variation is attributed to novice surgeons, where 14% variation is attributed to experts, and 38% is attributed to the residuals.

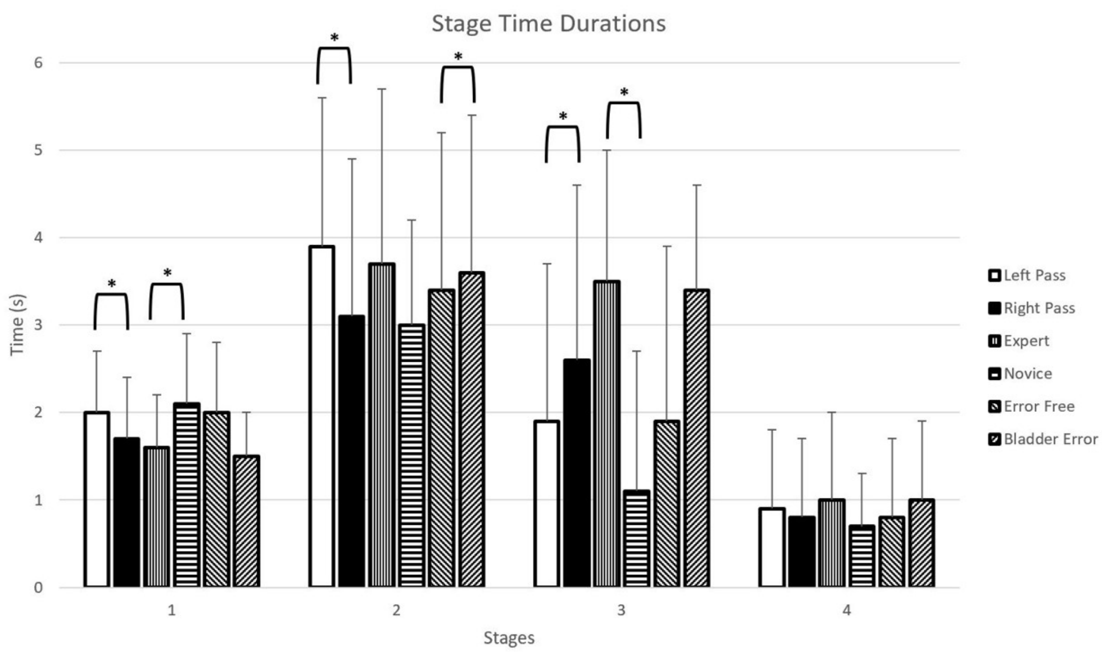



Figure 30: Durations for each stage, posterior passes only

## 3.3 Surgeon Body Kinematics

### 3.3.1 Bladder Error

In this study, participants performed 62 passages posterior to the pubic bone and 23 passages anterior to the pubic bone. 5 trials were not considered because of missing data on surgeon body tracking markers. For the bladder error analysis only the posterior passages were considered and surgeons made contact with bladder on 20 occasions among the 62 posterior passages. Surgeons did not make contact with bladder in 42 posterior passages (i.e. bladder error free trials).

For this analysis, stage 3 was mainly analyzed, since all bladder contact occurred during stage 3. Among the 32 posterior passages towards the bladder, trocar tip contact with the bladder was significantly associated with more higher starting wrist dorsiflexion

Table 12: Surgeon gripping arm kinematics in trocar passages towards the bladder, Stage 3, comparing contact with bladder versus no contact

| | No bladder contact (N=23) | Bladder contact (N=9) | p-value |
|---|---|---|---|
| Arm Pronation | | | |
| Start | 65.77 (7.73) | 52.15 (10.08) | 0.18 |
| End | 68.99 (4.52) | 68.34 (7.02) | 0.94 |
| Min | 58.52 (9.75) | 46.18 (11.41) | 0.19 |
| Max | 72.14 (4.48) | 73.65 (7.16) | 0.86 |
| Range | 12.86 (7.66) | 15.42 (8.47) | 0.65 |
| | | | |
| Wrist deviation | | | |
| Start | -8.76 (4.10) | -0.12 (5.35) | 0.11 |
| End | -9.78 (3.93) | -14.29 (4.87) | 0.32 |
| Min | -14.82 (4.17) | -15.71 (4.68) | 0.79 |
| Max | -4.08 (6.03) | 2.92 (6.72) | 0.13 |
| Range | 10.56 (4.90) | 16.80 (6.00) | 0.14 |
| | | | |
| Elbow Flexion | | | |
| Start | 69.11 (8.46) | 79.39 (11.05) | 0.35 |
| End | 60.81 (8.12) | 39.49 (10.22) | 0.033 |
| Min | 62.71 (8.35) | 62.06 (9.82) | 0.93 |
| Max | 76.45 (5.35) | 81.33 (8.19) | 0.61 |
| Range | 12.87 (5.12) | 20.45 (5.58) | 0.035 |
| | | | |
| Wrist dorsiflexion | | | |
| Start | -9.03 (8.56) | -27.32 (9.58) | 0.01 |
| End | -6.46 (10.25) | -7.02 (11.12) | 0.93 |
| Min | -12.99 (10.26) | -28.10 (11.21) | 0.038 |
| Max | 1.51 (10.44) | -2.31 (11.31) | 0.57 |
| Range | 14.01 (9.44) | 27.48 (10.11) | 0.022 |
| | | | |
| Shoulder Adduction | | | |
| Start | -13.13 (3.67) | -13.28 (3.86) | 0.94 |
| End | -12.08 (1.95) | -10.52 (2.38) | 0.46 |
| Min | -12.98 (3.59) | -11.21 (2.91) | 0.49 |
| Max | -9.93 (3.37) | -12.91 (3.59) | 0.13 |
| Range | 3.52 (1.40) | 3.41 (1.59) | 0.93 |

(-27.32 vs -9.03 degrees, p=.01), less final elbow flexion (39.49 vs 60.81, p=.03), and greater ROM in both wrist dorsiflexion (27.48 vs 14.01, p=0.02), and elbow flexion (20.45 vs 12.87, p=0.04) in the gripping arm during Stage 3. Table 12 summarizes these results. These differences at the wrist and elbow were not significant in the passages away from the bladder. Bladder contact was not associated with other gripping arm kinematics, such as wrist deviation, arm pronation, or shoulder adduction.

Note: All values in table 12 are described as mean (SD). Means presented in the table are least squares means from mixed model analysis.'Towards the bladder' is defined as right-hand grip, passage towards the left shoulder; or, a left hand grip, passage towards the right shoulder. Here, p-values are obtained from linear mixed model analysis comparing marginal means (not shown), which eliminate repeated measures for each participant.

### 3.3.2 Anterior Passage

Anterior versus posterior trocar passage to the bone analyzed during Stage 1 was significantly associated with smaller elbow flexion. This includes less starting elbow flexion (88.84 vs 95.25 degrees, $p < 0.01$), ending elbow flexion (84.14 vs 93.86, $p < 0.01$), minimum (78.89 vs 89.01, $p < 0.01$), and maximum (92.65 vs 99.81, $p < 0.01$) elbow flexion.

Anterior passage was also associated with smaller starting shoulder flexion (21.53 vs 26.83 degrees, $p < 0.01$) and maximum shoulder flexion (24.34 vs 28.72, $p = 0.02$). Table 13 summarizes all the comparison between anterior versus posterior passes in terms of surgeon upper extremity kinematics considered. There were no significant differences in wrist flexion, except for smaller ROM in anterior passages.

Table 13: Surgeon gripping arm kinematics in trocar passages, Stage 1, comparing posterior passage versus anterior

| | Posterior pass (N=62) | Anterior pass (N=23) | p-value |
|---|---|---|---|
| Wrist dorsiflexion | | | |
| Start | -22.73 (7.04) | -22.23 (7.58) | 0.90 |
| End | -25.60 (7.28) | -19.73 (7.89) | 0.17 |
| Min | -32.84 (7.00) | -25.66 (7.52) | 0.07 |
| Max | -14.57 (7.37) | -13.55 (7.92) | 0.80 |
| Range | 18.26 (2.48) | 12.29 (3.11) | 0.03 |
| | | | |
| Elbow Flexion | | | |
| Start | 95.25 (6.96) | 88.84 (7.13) | <0.01 |
| End | 93.86 (5.22) | 84.14 (5.46) | <0.01 |
| Min | 89.01 (6.21) | 78.89 (6.42) | <0.01 |
| Max | 99.81 (6.64) | 92.65 (5.81) | <0.01 |
| Range | 10.67 (1.44) | 13.98 (1.87) | 0.054 |
| | | | |
| Shoulder Flexion | | | |
| Start | 26.83 (6.17) | 21.53 (6.34) | 0.01 |
| End | 23.97 (5.97) | 21.50 (6.10) | 0.16 |
| Min | 21.68 (6.21) | 18.96 (6.34) | 0.14 |
| Max | 28.72 (5.95) | 24.34 (6.10) | 0.02 |
| Range | 6.94 (1.07) | 5.85 (1.41) | 0.40 |

Note: All values in table 13 are described as mean (SD). Means presented in the table are least squares means from mixed model. The difference in angles is the difference between marginal means, based on a mixed model accounting for the correlation from the repeated measures for each participant; therefore, the difference in angle is not equal to the difference between arithmetic means.

### 3.3.3 Experts vs Novices

Novices, compared to experts, had larger ROM during Stage 1 in elbow flexion (14.61 vs 8.35 degrees, $p < 0.01$), but smaller ROM in wrist dorsiflexion (13.31 vs 20.33, p=0.02) and arm pronation (4.75 vs 38.46, $p < 0.01$). During Stage 2, novices exhibited smaller ROM with arm pronation (6.08 vs 32.43, $p < 0.01$) and shoulder flexion (4.73 vs 10.24, $p < 0.01$), as compared to the experts. Table 14 summarizes these results. There was no contact between the trocar and the bowel or the blood vessels in any of the trials.

Note: N = 44 for stage 1; N = 21 for stages 2,3,4 as 21 novice passages were anterior to the suprapubic bone, and thus did not have a stage 2,3, or 4. Means presented in the table 14 are least squares means from mixed model analysis.

Table 14: Surgeon gripping arm kinematics in trocar passages, all stages, comparing expert versus novice participants

| | Expert ROM (n=41) | Novice ROM (n=44) | p-value |
|---|---|---|---|
| Stage 1 | | | |
| Wrist deviation | 21.72 (2.02) | 19.53 (1.95) | 0.44 |
| Wrist dorsiflexion | 20.33 (2.71) | 13.31 (2.68) | 0.02 |
| Elbow flexion | 8.35 (1.89) | 14.61 (1.88) | <0.01 |
| Pronation | 38.46 (7.47) | 4.75 (7.43) | <0.01 |
| Shoulder flexion | 6.85 (1.19) | 6.51 (1.18) | 0.81 |
| Shoulder adduction | 3.50 (0.69) | 4.39 (0.68) | 0.22 |
| Stage 2 | | | |
| Wrist deviation | 20.55 (4.58) | 11.76 (5.19) | 0.13 |
| Wrist dorsiflexion | 27.37 (4.02) | 16.73 (4.82) | 0.07 |
| Elbow flexion | 17.98 (3.10) | 12.54 (3.43) | 0.14 |
| Pronation | 32.43 (4.60) | 6.08 (5.62) | <0.01 |
| Shoulder flexion | 10.24 (0.85) | 4.73 (1.19) | <0.01 |
| Shoulder adduction | 4.42 (0.71) | 3.56 (0.82) | 0.35 |
| Stage 3 | | | |
| Wrist deviation | 9.74 (3.71) | 7.02 (4.02) | 0.49 |
| Wrist dorsiflexion | 15.02 (6.39) | 14.55 (6.86) | 0.94 |
| Elbow flexion | 15.50 (3.48) | 11.22 (3.80) | 0.27 |
| Pronation | 14.27 (4.65) | 6.41 (5.12) | 0.15 |
| Shoulder flexion | 5.94 (1.67) | 5.66 (1.88) | 0.89 |
| Shoulder adduction | 3.69 (0.97) | 3.52 (1.07) | 0.88 |
| Stage 4 | | | |
| Wrist deviation | 3.37 (1.31) | 3.01 (1.45) | 0.81 |
| Wrist dorsiflexion | 3.61 (1.25) | 5.81 (1.51) | 0.22 |
| Elbow flexion | 5.30 (1.34) | 4.98 (1.60) | 0.86 |
| Pronation | 6.89 (2.33) | 2.00 (2.61) | 0.09 |
| Shoulder flexion | 3.92 (1.12) | 2.39 (1.25) | 0.25 |
| Shoulder adduction | 2.41 (0.94) | 2.09 (1.03) | 0.75 |

# CHAPTER 4

# DISCUSSION

## 4.1 Force-sensing Trocar

### 4.1.1 Biofidelity

In this study, a novel force-sensing retropubic trocar has been developed that facilitated measurement of force variability during retropubic trocar passage on our MUS 3D midurethral sling surgery simulator. Our Cadaver vs. Model Biofidelity analysis indicated good agreement between force variables measured on MUS physical model and on a thiel-embalmed cadaver and this suggests adequate biofidelity of the MUS physical model. In addition, the test-retest analysis revealed no significant difference in any of the force variables measured, suggesting adequate consistency and stability of our novel model-trocar system.

These results can be translated into important clinical implications. Retropubic trocar passage is a blind procedure with potential risk of injuries to visceral organs and blood vessels, and the force-sensing trocar would allow the teaching surgeon to monitor contact between trocar and bone while the novice surgeon performs the procedure on MUS pelvic model. In order to perform a safe passage, the primary target is to ensure that the tip of trocar maintains contact with suprapubic bone (hug the bone). In the university operating rooms, this procedure is primarily performed by the residents with little to no experience and there is a lack of pelvic surgical simulators with adequate biofidelity. Since high-fidelity and physical anatomic models are well-accepted by the surgical trainees [34–

36], Ob-Gyn residents can use our MRI-derived, high-fidelity MUS pelvic model as a training platform to practice retropubic midurethral sling procedure. In addition, our novel model-trocar system will allow the surgeons to verify contact between bone and trocar while performing the retropubic trocar passage. Thus, our novel model-trocar system can provide maximal resident experience to the Ob-Gyn residents for retropubic MUS, while ensuring patient safety.

Currently, there is no existing simulation model related to the midurethral sling surgery that allows the teaching surgeon to monitor contact between trocar tip and bone. Yip et el used piezo-resistive material to create a pressure transducer that can measure surface contact pressure of a retropubic trocar as it makes contact with bone [49]. Schrope et el incorporated a load cell into an abdominal wall trocar to measure force during insertion on a simulation model [50]. This study also included an accelerometer and electrical impedance measurement. As opposed to the abdominal wall trocar insertion, maintaining contact with bone is paramount to perform a safe procedure during the midurethral sling surgery.

#### 4.1.2 Surgical Simulation Performance and Expertise

In order to establish a relationship between the simulation performance and expertise, both the expert and novice surgeons are required to participate. It is also paramount to analyze the link between surgical skill and outcomes on a simulation of high-risk surgical procedures. This study measures construct validity of a midurethral sling simulation model which is novel. In general, the expert participants performed better on the MUS surgical simulation model, as they generated greater forces and reached maximum force in a shorter time period compared to the novices. Maintaining continuous contact between pubic bone and trocar tip is critical to perform this procedure successfully. Expert surgeons are believed to perform better because of their greater maximum amplitude of force, as a higher force is generated when the surgeon reaches bone resistance by contact. Significantly shorter time to reach maximum force can indicate how efficiently experts follow the bone while maintaining contact to meet bone resistance. In addition, experts also revealed significantly larger maximum rate of force development than the novices, which can also be attributed to their mastery and expertise through controlled surgical simulation of retropubic trocar passage. It is not still clear if these outcome variables can be translated into an improved clinical outcome. However, the retropubic trocar modified with the load cell can be used to monitor a novice's progress as they learn how to perform the retropubic passage blindly and maintain constant contact with the pubic bone.

### 4.1.3 Limitations

The main limitation of this study is a small sample size. Although our results suggest adequate test-retest reliability and construct validity, Type II and I errors are possible, respectively. In a future study, an entire residency program can be considered for testing along with the experts. For this study, the retropubic troacr was modified with a load cell that can measure force only in line with the trocar's longitudinal axis. The current setup of modified retropubic trocar can provide us with the visual representation of trocar contact with bone through the forces measured along trocar's longitudinal axis. This setup does not account for the forces generated along the axis oblique to trocar's longitudinal direction. In order to incorporate forces in other directions, a larger load cell would be required. This might result in interference with normal gripping of the retropubic trocar by the surgeons. Our current setup of retropubic trocar modified with the small load cell does not interfere with normal gripping and guiding while performing the retropubic trocar passage.

## 4.2 Surgical Instrument (Trocar) Kinematics

### 4.2.1 Hypotheses and Error Rates

We hypothesized that error-free trocar passages would have significantly different overall trocar tip trajectories than both passages with bladder contact and passages directed anterior to the suprapubic bone. The trajectories of the trocar tip were significantly different in all three anatomic directions, towards both the left and right shoulder, with only one exception, as confirmed by our results. Contrary to our hypotheses, trocar tip excursions did not differ significantly between bladder contact and error-free passages. The novices in our study committed more overall errors, including bladder contact and anterior passage, than the experts. Although we hypothesized that novices would specifically incur more bladder error trials than experts, bladder contact occurred in 40% of expert posterior passages and 18.2% of novice posterior passages. These bladder error rates may not be indicative of the true error rate in the novice participants because of so many anterior passes. If both errors are included, the error rate in the novices is 60%.

Duration differences between experts and novices were inconsistent. The longer duration of the novice surgeon in Stage 1 may be attributed to their experience in navigating the bone and making the first contact. Trocar tip progresses towards the close vicinity of the bladder during stage 3 and bladder contact error occurs during this stage.

We suspect that expert surgeons took longer in stage 3 to avoid contacting the bladder.

### 4.2.2 Bladder Errors

These results may have only limited implications for teaching surgical novices retropubic trocar passage and can help the attending surgeon monitor for safe passage stage by stage and intervene when the trocar is being deviated in the wrong direction. Our results indicate that when bladder contact occurs, overall trocar tip trajectory in the anterior-posterior and caudal-cephalad direction is different. However, the differences in the trajectory are challenging for a teaching surgeon to monitor just by watching the trocar handle itself. Since the trocar tip excursions were no different between bladder error and no bladder error trials, recognition and intervention by the attending surgeon is likely not possible prior to making contact with the bladder. We suspect that the statistical significance of trocar tip excursions was not achieved by themselves, since the distances associated with retropubic passage stages are very small.

### 4.2.3 Bladder & Stage 3

We analyzed Stage 3 separately because we hypothesized that bladder contact is more likely to occur during this stage. We found that during stage 3, the caudal-cephalad and anterior-posterior trajectories of the trocar were significantly different in the bladder error trials compared to the error-free trials. Stage 3, when the trocar has made an anterior turn, cephalad to the suprapubic bone, is when bladder contact occurred in all of our trials. This suggests that a trocar trajectory deviating anteriorly and cephalad during this stage is more likely to make a contact with the bladder. However, because the distance between the pubic bone and the bladder is very small, excusions by themselves did not reach statistical significance level. Even though the differences in excursions in the medial-lateral direction during stage 3 did not reach statistical significance level, the excursions suggest that if the trocar is deviated medially the likelihood of contact with the bladder is higher. As in our model, the midline was associated with less clearance between the bone and the bladder.

#### 4.2.4 Anterior Passage Errors

More than half of passes by the novices in our study were anterior to the supra-pubic bone. By contrast, no expert passes were anterior. We suspect that this is because although we provided all participants with ’pre-op’ reading materials, we did not specifically instruct them during the trial to pass posteriorly, nor did we correct the novices when they did so. This suggests that if we don’t give the novice this specific instruction or check their position when the trocar makes contact with the bone, they are more likely to make an anterior pass. Expert surgeons understand the haptic difference between pushing the trocar cephalad against the bone in an anterior pass compared to pulling against the bone in a posterior pass.

In analyzing anterior versus posterior passes, we compared only Stage 1, which is relevant for the teaching surgeon watching that initial stage of the trocar passage. In anterior error passages, the trajectory in the cephalad direction was significantly different than error free posterior passages, and there was also higher deviation from the midline towards the lateral side in anterior passes. Again, observing the trocar handle does not provide much evidence that this is happening, since the excursions are not significantly different, suggesting that the attending should pause the surgery at the end of Stage 1 and confirm that the trocar tip is oriented posterior to the pubic bone. The teaching surgeon, in addition to confirming the location of the trocar, can suspect an anterior pass if the trocar moves less towards the patient's head and more laterally.

### 4.2.5 Experts vs. Novices

Our mixed model analysis showed that the novice group produced the most variation in trocar trajectory. This indicates that experts are more consistent in following the same trocar pathway trial after trial. The novices in our study were very inexperienced. In addition, novices were not provided with any instruction to stay posterior to suprapubic bone. We also suspet that approach angle prior to contact with the suprapubic bone may have something to do with moving the trocar anterior or posterior. Expert surgeons have a better sense of bone contact with the tip of the trocar compared to the bone contact with the shaft of the trocar. In addition, they are likely to understand the sensation of pushing the trocar forward and feeling the bone.

### 4.2.6 Results in the Context of What is Known

Several studies looked into error rates between novices and experts [2, 51, 52]. The rate of consequential error varies with the type and complexity of the surgery, and the level of expertise and skill of the surgeon. Surgical trainees typically commit twice as many technical errors as expert surgeons [52, 53]. Similarly in midurethral sling surgery, error rates among novice surgeons are higher in comparison with experts [54, 55]. No studies have been conducted to observe and analyze the trocar trajectory during the MUS procedure to distinguish between expert and novice surgeons in terms of temporal and spatial characteristics. This study demonstrates that certain temporal and spatial aspects of the trocar can be related to errors during the MUS procedure. There are no previous studies that observed anterior passage errors during MUS. That can be attributed to the fact that most studies looked at surgery outcome errors from surgeries and therefore no anterior passages would be observed since such a passage would have been addressed by repeating the trocar passage. Our study indicates that inexperienced surgeons may have a hard time navigating the trocar cephalad to the pubic bone after initial trocar contact with the pelvis.

#### 4.2.7 Strength & Limitations

A major strength of our study was the use of a high-fidelity simulator and the use of a 3D motion capture system that allowed visualization of the trocar inside the area of interest. Limitations include the large number of trials performed by a small number of subjects. Furthermore, we did not separate analyses based on surgeons using their right or left hand. Our study is also limited in its ability to assist the teaching surgeon in helping the novice avoid a bladder injury during trocar passage, since the trocar handle is the only observable available to the teaching surgeon, and the trajectory of the trocar tip is difficult to predict based on its location and angle of the trocar handle.

## 4.3 Surgeon Body Kinematics

### 4.3.1 Principal Findings

In this exploration of the surgeon kinematics, or motion in terms of position, velocity and acceleration, of simulated retropubic trocar passage, we found associations between quantified surgeon kinematics and surgical errors. Trocar contact with the bladder was associated with wrist dorsiflexion and elbow flexion, but not with internal wrist deviation or arm supination. These associations were only significant for passages in the direction - ’towards the bladder’. Anterior passage occurred solely by novice surgeons and was associated with less elbow flexion and less shoulder flexion.

### 4.3.2 Experience and Surgeon Kinematics

Expert surgeons in our study used a greater range of motion (ROM) in both the wrist and forearm, compared to novices. In contrast, the novices had a greater ROM at the elbow than the experts. All participants were following a target, namely the contour of the suprapubic bone. Experience with mastering one’s kinematics impacts how a surgeon uses their upper extremity muscles to follow a target, specifically by maximizing the use of more distal muscles to exert fine control over the motion of the instrument. Our expert participants used more distal muscles (wrist or forearm) to follow the bone; by contrast, novices used the elbow, including more proximal muscles. This is analogous to an experienced basketball player employing a greater ROM in their wrist when shooting a 3-pointer [56].

Novice wrist dorsiflexion ROM in stage 1 was limited, which reflects this principle that keeping a tight, or narrow ROM, or plantar-flexed wrist when approaching the bone results in less adaptation to the contour of the bone and deviation anteriorly.

### 4.3.3 Results in the Context of What is Known

Surgeon gripping arm kinematics revealed that bladder contact was not associated with arm pronation or wrist deviation. In order to minimize the risk of bladder contact, common MUS teaching advises against pronation or medial wrist deviation [57]. Participants are instructed to keep the T-handle parallel to the ground and aim towards the ipsilateral shoulder at all times [58]. We are not aware of any teaching to avoid anterior error, but we hypothesized that larger elbow flexion would be associated with the trocar passage anterior to the suprapubic bone. The anterior error was not associated with the greater wrist plantarflexion, which would have guided the trocar's trajectory anteriorly.

Previous studies have studied gross surgeon movement during simulation, most commonly with laparoscopy [59, 60]. However, these studies have not focused on correlating surgeon movement with error [27]. It is reasonable that error prevention correlates with surgeon kinematics since several studies relate the surgeon kinematics to the surgeon's experience [61–64]. Several other studies link surgeon experience to error prevention [65–68]. Experienced surgeons learn error prevention over time, on live patients, through mastery of kinematics. The midurethral sling surgery is an example where being a novice correlates with higher injury rates, such as cystotomy.

### 4.3.4 Kinematics and Teaching Trocar Passage

Our results should be interpreted with caution in terms of monitoring a learner's kinematics during retropubic trocar passage. It is reasonable to expect that altering a resident's wrist, elbow, and shoulder flexion might avoid error, but it is also reasonable to expect that internal wrist deviation and arm pronation towards the bladder would result in bladder contact, which we did not find in our results. The preferred way to be certain that a resident is passing the trocar appropriately is to place one's hands on either on the trocar or on the resident's hands [26], and verify that the trocar is both posterior and maintaining contact with the bone.

By contrast, applying our kinematic results to training simulations will help them master retropubic trocar passage more quickly. Simulation is an ideal way for a learning surgeon to practice using their wrist and forearm (distal muscles, as opposed to their elbow and shoulder) to maintain contact with the suprapubic bone. For example, in simulation a resident could be shown how a slight palmerflexion of the wrist and flexion of the elbow can help to maneuver the trocar around the bone and how by contrast, dorsiflexion of the wrist and extension of the elbow can lead the trocar tip towards the bladder.

### 4.3.5 Research Implications & Future Directions

The field of kinematics, which describes motion in terms of position, velocity and acceleration, is an ideal method for studying the link between surgeon motion and intra-operative error. Furthermore, MUS is an excellent prototype for studying how kinematics relate to surgical error, as it involves a high-risk blind step with well-characterized error rates. We recommend future study on altering surgeon kinematics, either through training or using intraoperative kinematic guides, to avoid cystotomy. Our findings can also be used to study robotic advancement of a retropubic trocar, using a robot with joints similar to a human upper arm.

Motion capture methodology can also be applied to study common errors in other blind surgical procedures, such as laceration of the lateral femoral cutaneous nerve in external fixation of the sacroiliac joint procedure, injury to the inferior alveolar neurovascular bundle during sagittal split mandibular osteotomy, spinal cord injury during thoracic spine osteotomy, or something as ubiquitous as inferior vena cava injury during umbilical veress needle insertion.

#### 4.3.6 Strengths and Limitations

Our study strengths include the use of a validated motion tracking system to correlate surgeon kinematics with error during simulated retropubic trocar passage. Limitations also include a relatively small sample of participants, although we had enough trials to satisfy our a-priori power analysis. We did not analyze other markers of body position, such as the height of the shoulder, which would have been different for a participant who employed dropping their shoulder or bending their knees. The finding that anterior passage was associated with less elbow flexion and less shoulder flexion may be explained by this. Additionally, we could not use kinematic data for some of the trials due to technological limitations, most commonly when one would cover a portion of the trocar rigid body with their hand and block the camera's view of the markers.

Although our simulation model was anatomically accurate, it lacked the bladder's dynamic characteristics during live surgery, such as tissue deformation in response to contact with the trocar or due to patient breathing. We did not learn about contact between the trocar and the bowel or the blood vessels, as this did not occur in any of the trials

Finally, this study focused on the kinematics of the surgeon did not explore how to direct OR learners. Further study is needed to measure how instructions based on these kinematic findings would translate to safer surgery.

# CHAPTER 5

# CONCLUSION

## 5.1 Force-sensing Trocar

In summary, this study demonstrated a surgical simulation model that incorporates a retropubic trocar modified with a load cell, and a 3D pelvic model. This innovative trocar can be used both in surgical simulation and in the operating room, and essentially help the attending surgeon to monitor contact between trocar and bone. This model-trocar system also established the pathway for the next study which incorporated analysis of surgical instrument kinematics and surgeon body kinematics. In a future study, surgeon body kinematics can be correlated with trocar force generated. It is possible that the surgeon who exerts more force can show greater wrist pronation, and these information regarding comparison between surgeon kinematics and trocar force variables can be into surgical training. A future study could also test the role of force in injury to vital organs. Future research could also incorporate the sterilized version of this trocar in the operating room and measure variables such as surgeon confidence, learner cognitive load, and patient injuries such as bladder perforation. Small load cells can be attached to instruments used in other surgeries that use bones as landmarks, such as chest tube insertion, rib plating, or percutaneous placement of a vertebral screw, and provide visual feedback of force exerted during the procedure.

## 5.2 Trocar Kinematics & Temporal Characteristics

In conclusion, our study using motion capture analysis to follow the trajectory of the retropubic trocar in relation to the position of the pubic bone and bladder showed that retropubic trocar tip trajectory is different in passages where the tip contacts the bladder compared to error free passages, and novice surgeons produce more varied trocar trajectories than experts.

Further research should concentrate on developing a biomechanics based approach on avoiding errors. Future research using motion capture analysis should analyze trocar handle trajectory and rotation, and test if a surgeon not holding the handle, such as the teaching surgeon, can recognize abnormal trajectories and intervene before bladder contact occurs.

## 5.3 Surgeon Body Kinematics

In conclusion, using motion capture technology, we showed that bladder contact during simulated MUS is associated with more wrist dorsiflexion and less elbow flexion, but not by internal wrist deviation or arm supination. Anterior passage is associated with less elbow and shoulder flexion. Expert surgeons exerted control with the wrist and forearm, novices at with the elbow. Our findings can be used to design MUS simulations to help novices master the kinematics necessary to avoid both the bladder and anterior passage errors, and have direct implications for robotic control of the retropubic trocar.

APPENDIX A

INFORMATION

### A.1 Upper Extremity Custom Marker Set

Upper body custom marker placement system used in this project for kinematic data collection and joint center calculation has been explained in this section.

Table 15 describes the markers positioned on the subject"s head. Head markers (4) can be placed using a headband or the motion capture suit cap.

Table 15: Head markers

| Marker Label | Definition | Position on subject |
|---|---|---|
| LFHD | Left front head | Left temple |
| RFHD | Right front head | Right temple |
| LBHD | Left back head | Left back of head (defines the transverse plane of the head, together with the frontal markers) |
| RBHD | Right back head | Right back of head (defines the transverse plane of the head, together with the frontal markers) |

Table 16 describes the markers positioned on the subject's torso. Table 16 & 17 describe the markers positioned on the subject's upper body, left and right upper limb respectively. Upper body custom marker set also consists of a series of cluster markers, along with the conventional markers placed on upper extremity.

Table 16: Torso markers

| Marker Label | Definition | Position on subject |
|---|---|---|
| C7 | 7th cervical vertebra | On the spinous process of the 7th cervical vertebra |
| T10 | 10th thoracic vertebra | On the spinous process of the 10th thoracic vertebra |
| CLAV | Clavicle | On the jugular notch where the clavicles meet the sternum |
| STRN | Sternum | On the xiphoid process of the sternum |
| LCC1 | Left chest cluster marker 1 | Left chest - cluster |
| LCC2 | Left chest cluster marker 2 | Left chest - cluster |
| LCC3 | Left chest cluster marker 3 | Left chest - cluster |
| RCC1 | Right chest cluster marker 1 | Right chest - cluster |
| RCC2 | Right chest cluster marker 2 | Right chest - cluster |
| RCC3 | Right chest cluster marker 3 | Right chest - cluster |
| LBC1 | Left back cluster marker 1 | Left scapula - cluster |
| LBC2 | Left back cluster marker 2 | Left scapula - cluster |
| LBC3 | Left back cluster marker 3 | Left scapula - cluster |
| RBC1 | Right back cluster marker 1 | Right scapula - cluster |
| RBC2 | Right back cluster marker 2 | Right scapula - cluster |
| RBC3 | Right back cluster marker 3 | Right scapula - cluster |

Table 17: Left upper limb markers

| Marker Label | Definition | Position on subject |
|---|---|---|
| LSHO | Left shoulder | On the acromion-clavicular joint |
| LUAC1 | Left upper arm cluster marker 1 | Left upper arm - cluster |
| LUAC2 | Left upper arm cluster marker 2 | Left upper arm - cluster |
| LUAC3 | Left upper arm cluster marker 3 | Left upper arm - cluster. Equivalent to LUPA (On the upper lateral 1/3 surface of the left arm, place asymmetrically with RUPA) |
| LELB | Left elbow | On the lateral epicondyle |
| LHME | Left elbow | Left humerus medial epicondyle |
| LLAC1 | Left lower arm cluster marker 1 | Left lower arm/Forearm - cluster. Equivalent to LFRM (On the lower lateral 1/3 surface of the left forearm, place asymmetrically with RFRM) |
| LLAC2 | Left lower arm cluster marker 2 | Left lower arm/Forearm - cluster |
| LLAC3 | Left upper arm cluster marker 3 | Left lower arm/Forearm - cluster |
| LWRA | Left wrist marker A | At the thumb side of a bar attached to a wristband on the posterior of the left wrist, as close to the wrist joint center as possible. |
| LWRB | Left wrist marker B | At the little finger side of a bar attached to a wristband on the posterior of the left wrist, as close to the wrist joint center as possible. |
| LWC1 | Left wrist cluster marker 1 | Left wrist/finger - cluster |
| LWC2 | Left wrist cluster marker 2 | Left wrist/finger - cluster. Equivalent to LFIN (Just proximal to the middle knuckle on the left hand) |
| LWC3 | Left wrist cluster marker 3 | Left wrist/finger - cluster |

Table 18: Right upper limb markers

| Marker Label | Definition | Position on subject |
|---|---|---|
| RSHO | Right shoulder | On the acromion-clavicular joint |
| RUAC1 | Right upper arm cluster marker 1 | Right upper arm - cluster |
| RUAC2 | Right upper arm cluster marker 2 | Right upper arm - cluster |
| RUAC3 | Right upper arm cluster marker 3 | Right upper arm - cluster. Equivalent to RUPA (On the lower lateral 1/3 surface of the right arm, place asymmetrically with LUPA) |
| RELB | Right elbow | On the lateral epicondyle approximating the elbow joint axis |
| RHME | Right elbow | Right humerus medial epicondyle |
| RLAC1 | Right Lower Arm Cluster Marker 1 | Right lower arm/Forearm - cluster. Equivalent to RFRM (On the lower lateral 1/3 surface of the right forearm, place asymmetrically with LFRM) |
| RLAC2 | Right Lower Arm Cluster Marker 2 | Right lower arm/Forearm - cluster |
| RLAC3 | Right Lower Arm Cluster Marker 3 | Right lower arm/Forearm - cluster |
| RWRA | Right wrist marker A | At the thumb side of a bar attached symmetrically with a wristband on the posterior of the right wrist, as close to the wrist joint center as possible |
| RWRB | Right wrist marker B | At the little finger side of a bar attached symmetrically with a wrist band on the posterior of the right wrist, as close to the wrist joint center as possible. |
| RWC1 | Right wrist cluster marker 1 | Right wrist/finger - cluster |
| RWC2 | Right wrist cluster marker 2 | Right wrist/finger - cluster. Equivalent to RFIN (Just below the middle knuckle on the right hand) |
| RWC3 | Right wrist cluster marker 3 | Right wrist/finger - cluster |

Table 19: Subject Antropometric Measurements Collected

| Name | Description | Measure Left | Measure Right |
|---|---|---|---|
| Body Mass | Patient mass. | _____ kg | |
| Height | Patient height. | _____ mm | |
| Inter-ASIS distance1 | ASIS-ASIS distance is the distance between the left ASIS and right ASIS. This measurement is only needed when markers cannot be placed directly on the ASIS, for example, in obese patients. | _____ mm | |
| Leg Length | Full leg length, measured between the ASIS marker and the medial malleolus, via the knee joint. Measure with patient standing, if possible. If the patient is standing in the crouch position, this measurement is NOT the shortest distance between the ASIS and medial malleoli, but rather the measure of the skeletal leg length. | _____ mm | _____ mm |
| ASIS-Trochanter Distance | ASIS-greater trochanter distance is the vertical distance, in the sagittal plane, between the ASIS and greater trochanter when the patient is lying supine. Measure this distance with the femur rotated such that the greater trochanter is positioned as lateral as possible. | _____ mm | _____ mm |
| Knee Width | The medio-lateral width of the knee across the line of the knee axis. Measure with patient standing, if possible. | _____ mm | _____ mm |
| Ankle Width | The medio-lateral distance across the malleoli. Measure with patient standing, if possible. | _____ mm | _____ mm |
| Shoulder Offset2 | Vertical offset from the base of the acromion marker to shoulder joint center. | _____ mm | _____ mm |
| Elbow Width3 | Width of elbow along flexion axis (roughly between the medial and lateral epicondyles of the humerus). | _____ mm | _____ mm |
| Wrist Width4 | Anterior/Posterior thickness of wrist at position where wrist marker bar is attached. | _____ mm | _____ mm |
| Hand Thickness5 | Anterior/Posterior thickness between the dorsum and palmar surfaces of the hand. | _____ mm | _____ mm |

## A.2 Subject Anthropometric Data Collection

Shoulder Offset: This is the vertical distance from the center of the glenohumeral joint to the marker on the acromion clavicular joint (RSHO & LSHO). Some researchers have used the (anterior/posterior girth)/2 to establish a guideline for the parameter.

Elbow Width: This is the distance between the medial and lateral epicondyles of the humerus.

Wrist Width: This is the distance between the ulnar and radial styloids.

Hand Thickness: This is the distance between the dorsal and palmar surfaces of the hand.

If the InterAsis distance has not been entered in the subject measurements, this is calculated as the mean distance between the LASI and RASI markers, for each frame in the trial for which there is a valid position for each marker.

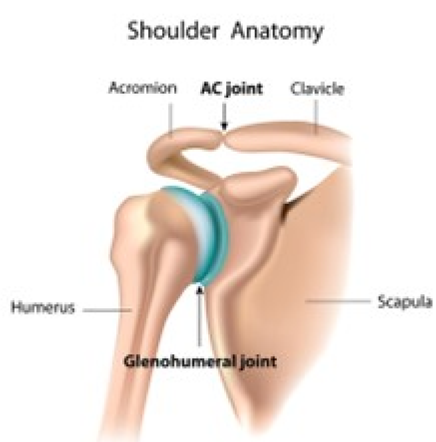



Figure 31: Shoulder Anatomy

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VITA

Md Arifuzzaman is currently a doctoral candidate in interdisciplinary Ph.D. program (Mechanical Engineering & Mathematics) at the University of Missouri-Kansas City. His research interests include experimental biomechanics and computational modeling of biomechanical systems, estimating joint mechanics using patient-specific computational models, developing surgical simulators and computational tools for surgical trainees to prevent surgical errors, and development of surgical pre-op planning tools. Topics of interest include surgical safety and orthopedic applications.

He has been working as a Graduate Research Assistant at the Musculoskeletal Biomechanics Research Laboratory under the direction of Dr. Antonis Stylianou since June, 2016. His doctoral study has been funded by the National Institute of Biomedical Imaging and Bioengineering and conducted through a multi-disciplinary collaboration between Surgical Innovation Lab, and Human Balance and Ambulation Research Laboratory, University of Missouri-Kansas City. Earlier, he obtained MS in Mechanical Engineering (Concentration: Biomechanics) from the University of Missouri-Kansas City in 2019 and BS in Mechanical Engineering from Khulna University of Engineering & Technology, Bangladesh in 2014.

## A.3 Publications

### A.3.1 Conference Publications

- Sutkin, G., Arif, M. A., Cheng, A. L., King, G. W., Bachar, A., Stylianou, A. P. Estimation of Ideal Retropubic Trocar Passage during Simulated Midurethral Sling Surgery, AUGS Pelvic Floor Disorders (PFD) Week 2023, Portland, OR, 2023 (Accepted)

- Arif, M. A., Bachar, A., King, G. W., Sutkin, G., Stylianou, A. P. Retropubic Trocar Temporal Characteristics Between Expert and Novice Surgeon, Summer Biomechanics, Bioengineering and Biotransport Conference (SB3C 2023), Vail, CO, USA, June 2023.

- Mueller, F., Arif, M. A., Stylianou, A. P., Cheng, A. L., King, G. W., Bachar, A., Sutkin, G. Cognitive Models for Mentally Visualizing a Sharp Instrument in a Blind procedure, Association for Surgical Education Annual Meeting, San Diego, CA, April 2023.

- Stylianou, A. P., Arif, M. A., Cheng, A. L., King, G. W., Bachar, A., Sutkin, G. Kinematic Differences between Novice and Expert Surgeons during Simulated Midurethral Sling Surgery, Surgeons and Engineers: A Dialogue on Surgical Simulation, Chicago, IL, March 2023.

- Sutkin, G., Mueller, F., Arif, M. A., Stylianou, A. P., Bachar, A., Cheng, A. L., King, G. W. Estimating Surgical Instrument Position in Blind 3D Space during

Simulated Retropubic Trocar Passage, Surgeons and Engineers: A Dialogue on Surgical Simulation, Chicago, IL, March 2023.

- Stylianou, A. P., Arif, M. A., Mahmud, F., King, G. W., Sutkin, G. Virtual pelvic model for study of surgeon kinematics during retropubic trocar passage, AUGS/ IUGA Scientific Meeting, Nashville, TN; Int Urogynecol J (2019) 30 (Suppl 1): 190-91. DOI: https://doi.org/10.1007/s00192-019-04125-2

- Arif, M. A., Mahmud, F., King, G.W., Sutkin, G., Stylianou, A. P., Development of a Pelvic Model for Study of Surgical Errors in the Midurethral Sling Procedure, 42nd Annual Meeting of the American Society of Biomechanics, Rochester, Minnesota, August 2018 (Poster).

### A.3.2 Journal Publications

- Arif, M. A., Stylianou, A. P., Bachar, A., King, G. W., & Sutkin, G. (2022). Retropubic trocar modified with a load cell to verify contact with pubic bone. Surgery. DOI: https://doi.org/10.1016/j.surg.2022.06.011.

- Mueller, F., Arif, M. A., Bachar, A., King, G. W., Stylianou, A. P., Sutkin, G. (2023). Surgeon Estimation of Retropubic Trocar Position in Blind 3D Space. International Urogynecology Journal. DOI: 10.1007/s00192-023-05541-1

- Mueller, F., Bachar, A., Arif, M. A., King, G. W., Stylianou, A. P., Sutkin, G. Cognitive Models for Mentally Visualizing a Sharp Instrument in a Blind Procedure, Global Surgical Education - Journal of the Association for Surgical Education.

### A.3.3 Student Conferences

- Arif, M. A., Stylianou, A. P., Bachar, A., King, G. W., & Sutkin, G. (2022). Retropubic trocar modified with a load cell to verify contact with pubic bone. UMKC Health Sciences District Student Research Summit 2022.

- Arif, M. A., Stylianou, A. P., Bachar, A., King, G. W., & Sutkin, G. (2021). Retropubic trocar modified with a load cell to verify contact with pubic bone. 8th Vijay Babu Quality and Patient Safety Day 2021 (Poster).

- Arif, M. A., Stylianou, A. P., Bachar, A., King, G. W., & Sutkin, G. (2019). Virtual Pelvic Model for Study of Surgical Errors in the Midurethral Sling Procedure. UMKC Health Sciences District Student Research Summit 2019 (Poster).