A Method of Measuring Force/Torque at the Tool/Tissue Interface in Endoscopy

by

Armen Bakirtzian

A thesis submitted in conformity with the requirements for the degree of Master of Health Science in Clinical Biomedical Engineering
Institute of Biomaterials and Biomedical Engineering
University of Toronto

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Abstract

The adoption of Minimally Invasive Surgery (MIS) and Robot-Assisted MIS has resulted in the distortion of haptic cues surgeons rely on. The application of excessive force during port creation has lead to increased surgical access trauma. This study aims to quantify the forces experienced during port creation with a blunt-ended Threaded Visual Cannula (TVC) in an effort to ameliorate patient safety, provide a quantitative platform for surgeon training, and offer a gateway for the eventual automation of this problematic aspect of MIS. A method of determining the torque encountered during port creation was established. It was found that the magnitude of torque required to cannulate different materials was unique and was dictated by the friction observed at the tool/tissue interface. Furthermore, the ability to detect instantaneous changes in torque arising from the transition between two different media was not found to be possible with the current design of the TVC.
Acknowledgments

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Armen Bakirtzian
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List of Abbreviations

ωz = angular speed about z-axis
vz = linear speed along z-axis
FRF = feed rate of trocarless visual cannula
Dof = degrees of freedom
tH = nominal thickness of Hard foam sample
tS = nominal thickness of Soft foam sample
tH/S = thickness of Hard→Soft foam medium
hH/S = z-axis position of Hard→Soft foam medium’s top surface in the SCARA robot’s Cartesian coordinate system
bH/S = z-axis position of Hard→Soft foam medium’s bottom surface in the SCARA robot’s Cartesian coordinate system
δH/S = deflection of Hard→Soft foam medium
σH/S = compression of Hard→Soft foam medium
ΔH/S = combined deflection and compression of Hard→Soft foam medium
zH/S,s = z-axis starting position of the TVC in Hard→Soft foam medium
zH/S,t = z-axis position of the TVC at the transition from Hard to Soft foam layer in Hard→Soft foam medium
zH/S,e = z-axis end position of the TVC in Hard→Soft foam medium
UH/S,s = Angular start position (about z-axis) of the TVC in Hard→Soft foam medium
UH/S,t = Angular position (about z-axis) of the TVC during the transition from Hard to Soft foam layer in Hard→Soft foam medium
υH/S,t = Percentage of total trajectory where the transition from Hard to Soft foam layer in Hard→Soft foam medium occurs
SH/S,t = Sample number where the transition from Hard to Soft foam layer in Hard→Soft foam medium occurs in the torque profile
TVC: Threaded Visual Cannula
MIS: Minimally Invasive Surgery
RMIS: Robot-Assisted Minimally Invasive Surgery
Chapter 1: Introduction

1.1 Background and Motivation

Minimally Invasive Surgery (MIS or Endoscopy) has transformed surgical care in all disciplines and is now the preferred method for many diagnostic and operative procedures. By replacing conventional open surgeries, that require large incisions to access the operative site, with techniques that require miniscule incisions (known as conduits or ports; 1-2cm), MIS significantly shortens patient recovery time by reducing surgical access trauma [1]. Laparoscopy is defined as MIS of the abdominal cavity. In order to access the body cavity of interest, ports are introduced into the body by access devices. A wide array of these devices are currently available, but can be classified into two main categories: Sharp and Blunt. As the name suggests, sharp access devices create ports into a body cavity by cutting through the tissues isolating the cavity from the outside environment. Due to the predominant use of sharp-ended access devices in MIS, the most severe complications associated with laparoscopic surgery arise during port creation [2,3]. Blunt access devices, such as a Threaded Visual Cannula (TVC), do not contain a cutting edge [4,5]. Access into a body cavity is achieved with a TVC similar to the way a wood screw is driven through a wooden board. Where the wood screw and TVC differ is how their first thread is engaged in the material. A wood screw requires a pointed tip which depresses the material and allows its thread to engage during rotation. The hollow TVC does not have a pointed tip. During port creation, the access site is prepared by incising the skin and teasing the subcutaneous fatty tissue. This allows easy engagement of the TVC’s external threads into the tissue. When the TVC is rotated into a body cavity, the tissues it encounters are separated radially, and not cut.

Most MIS procedures require a primary port (created first) and a varying number of ancillary ports which are dependent on the nature of the procedure taking place. MIS continues to evolve to further minimize surgical discomfort and improve patient safety by integrating interdisciplinary emerging engineering ideologies and surgical principals. MIS robotic surgery is one aspect of such collaboration where research in different disciplines can result in significant innovative progress. It is the objective of the project to improve on current port creation techniques by developing a reproducible method for evaluating the magnitude of entry torque required to gain access to the abdominal cavity. By quantifying one of the largest variables in
port creation, the project aims to improve patient safety, facilitate the training of future surgeons and provide a platform for the inevitable automation of the procedure.

1.1.1 Patient Safety

The shift from conventional open procedures to MIS has forced surgeons to be one step removed from the operative environment. By interacting with body tissues through slender endoscopic instruments instead of their gloved hands, the presence of haptic (force and tactile) cues available to the surgeon is altered. This effect is further compounded in Robot-Assisted MIS (RMIS) as the surgeon is two steps removed from the operative environment. Since the surgeon interacts with the tools inserted into the patient’s body via a console, haptic cues are eliminated. Experienced and talented cardiac surgeons performing RMIS of the heart with the da Vinci robotic surgical system often break the fine polypropylene sutures and tear delicate tissues due to the application of excessive force [6]. When the tension applied to the suture by the surgeon’s hand was measured and relayed back to them via a visual sensory substitution interface, the applied tension was significantly more consistent [6]. The notion of applying excessive force is also present during port creation and can result in serious patient harm. By quantifying the magnitude of force applied during port creation, an upper bound of allowable force can be determined for MIS and the basis for restoring haptic cues in RMIS can be established. In order to provide a true measure of the forces encountered by the surgical tools in an operative environment, they must be sensorized [6]. These data can then be used to limit the force applied during port creation in MIS and be combined with tactile information to restore the absent haptic cues in RMIS.

1.1.2 Surgeon Training

Traditionally, MIS surgeon training has taken place in the operating room (OR) [7]. This reduces OR efficiency and can potentially lead to patient harm [7]. The need to address the lack of advanced surgical simulators has always been an issue of priority for surgical educators [8,9]. Furthermore, the development of haptic feedback enabled virtual reality (VR) simulators for accurate simulation of surgical environments has been a long-term goal for numerous researchers [10,11,12]. Non-OR based training techniques include box trainers and VR simulators. Of these, the box trainer is the only method where any form of haptic feedback is available as the novice surgeons interact with tissues placed in a box via endoscopic instruments [13]. This
provides the same altered form of haptic feedback present in MIS. By integrating feedback enabled endoscopic instruments in virtual reality simulators, a more realistic training platform can be created for novice surgeons who can acquire operative skills that can readily translate into the operating room [14]. Studies have confirmed that force feedback (even if distorted) positively influences laparoscopic skills, especially when pushing and pulling forces are applied [14]. When surgeons are trained first on a platform capable of providing force feedback, then transition to one that is not (i.e. VR simulator), there was a positive effect on performance [14]. The reverse transition did not have a positive effect. This can suggest that advanced surgical tasks, such as body cavity entry, should be trained on a platform capable of providing force feedback.

1.1.3 Automation

Robotic surgery appears to be here to stay [15]. It facilitates procedures (i.e. prostatectomy) that would not normally be candidates for MIS [15]. Despite their high cost, the prevalence of robotic systems is on the rise across North America [16]. In current RMIS techniques, the robot controlled by the surgeon interacts with the operative environment. This condition is true for all steps of the procedure except for port creation, which remains manual [17]. By quantifying the forces required to safely enter a body cavity, framework for the integration of haptic feedback can be established and facilitate the transition to the eventual automation of this problematic aspect of RMIS.

1.2 Problem Statement

Port creation is an aspect of MIS that requires better understanding by health care professionals and the academic community. There are three main shortcomings associated with the current practice of port creation, namely:

1. Application of excessive force on the access device which can lead to unexpected patient trauma.
2. Subjective teaching methods used for surgeon training.

These factors lead to port creation being one of the most problematic aspects of MIS.
1.3 Objective and Hypothesis

The main objective of the research is to develop a reproducible method of determining the forces and torques encountered by a TVC during laparoscopic body cavity entry. Furthermore, to investigate the feasibility of detecting instantaneous changes in the material properties of the layers contained inside the abdominal wall.

Given that the magnitude of torque required to drill through a specific material is dictated by its specific properties [18,19,20], it is hypothesized that the torque experienced during cannulation will behave in the same way. In other words, the magnitude of torque required to cannulate specific materials will be dictated by their unique properties. Furthermore, as the TVC traverses materials with different properties, the generated torque profile is expected to exhibit an instantaneous shift in trend corresponding to the transition point.

1.4 Road Map

In this chapter, background information pertaining to Minimally Invasive Surgery and Robot-Assisted Minimally Invasive Surgery in the context of Patient Safety, Surgeon Training and Automation was presented. Furthermore, the problem posed to the surgical and academic communities was outlined and the objective of the project was stated. Lastly, the expected result of the research carried out in the project was highlighted.

A comprehensive literature review outlining the adoption of MIS and RMIS techniques is presented in Chapter 2. The inherent shortcomings associated with the aforementioned techniques and the current research to address these is also outlined.

The research method is then presented in Chapter 3. A description of the test apparatus as well as the test conditions investigated in the project is outlined. The issues encountered during the progression of the research as well as the limitations of the developed methods are also described.

The results observed in the outlined test conditions are presented in Chapter 4. A graphical representation of the torque profiles generated during cannulation of the specified materials is included in this Chapter. A discussion of the results and recommendations for future work are also presented in Chapter 4. The conclusions of the project are then presented in Chapter 5.
Chapter 2: Literature Review

Robotic systems are categorized into two groups, Offline and Online robots [21]. Offline robots, also referred to as fixed path robots, are devices that operate autonomously through pre-programmed movements based on integrated pre-operative data, e.g., images [21]. In other words, they are capable of operating without external intercession. Presently, there are numerous situations where offline robots are not suitable. In a surgical setting, these instances include procedures that require continuous manipulation of soft tissues that cannot be pre-programmed into the offline robot’s memory. As a result, continuous input from the operator is necessary to complete the surgical objectives safely. Online robots base their movements and actions on real-time input from an operator. In order for a system to be classified as a ‘real-time’ system, its output must be formulated at the same rate at which an input is received. Therefore, the research will focus on the role of online robots in safe port creation.

Laparoscopic surgery is ideal for online robotic operations. Continuous seamless manipulation of soft tissues relies on real-time surgeon input. However, laparoscopic surgery has several notorious and well-known shortcomings. They are listed below:

1. Given that most laparoscopic instruments traverse through a fixed port (in the patient’s abdominal wall), the long shaft of the instrument becomes anchored to that port’s location. This restricts surgeons from translating their instruments laterally (reducing dexterity), and forces them to articulate the handles of the instruments in one direction to reach the target in the opposite direction, reducing their hand-eye coordination. Collectively, this is known as the fulcrum effect [22].

2. The dependence of most laparoscopic techniques on two dimensional (2D) images leads to the distortion of a surgeon’s depth perception. [22]

3. Suboptimal ergonomic layout of several MIS rooms influences operative outcome and surgeon performance, discomfort and fatigue [23].

4. Alteration of real-time haptic feedback. In conventional open procedures, surgeons use their gloved hands to directly palpate tissues in order to assess its texture which will aid in intra-operative diagnoses [24]. In MIS procedures, surgeons indirectly “palpate” tissue via a long instrument that eliminates tactile cues and alters force cues [25].

By definition, haptic feedback refers collectively to tactile and force feedback. Tactile information is crucial in providing surgeons with a sensation of touch while force feedback
provides a sense of the forces and/or torques that is present between the interface of the surgical instrument (or robotic arm) and tissues of the human body [1]. The lack of haptic feedback in current laparoscopic techniques has lead to an increase in intra-operative injury [25]. Sensory substitution techniques have been employed in laparoscopic procedures to replace haptic information with visual and/or auditory information, but have not been accepted because of their distracting nature and the lack of an additive effect [6,26,27]. Haptic information is of such significant value that, when paired with visual information, non-surgeons equipped with a force feedback enabled laparoscopic grasper can distinguish soft tissue sensation with similar accuracy as surgeons [24,28]. Moreover, pointing devices which provide a user with tactile stimuli results in quicker motor responses, thus reducing time to target [26]. Previous studies investigating the benefits of haptic feedback in virtual-reality (VR) simulators have shown that human operators display shortened task completion times as well as improved perceptual motor aptitude [29]. This result can be extended to suggest that providing haptic feedback during laparoscopic procedures may improve the quality outcome of the operation, enhance patient safety, as well as provide a training platform for surgeons to efficiently acquire fundamental laparoscopic skills [13].

Robotic systems used in MIS successfully overcame difficulties of reduced dexterity by translating a surgeon’s hand motions to an endoscopic wrist placed within the body cavity, allowing for greater degrees of freedom than manually operated endoscopic instruments [6]. Furthermore, the digital interface between the surgeon’s hands and the endoscopic instruments allows for motion scaling (amplifying or dampening) while eliminating hand tremor using high-frequency filtering [6]. In addition, robotic systems replace conventional 2D with stable 3D images that restore the surgeon’s depth perception while improving the efficiency and accuracy of their manipulation of tissues in the operative environment [22].

Moreover, the ergonomics of the operating environment is also improved where the robotic system modulates to optimize the surgeon’s hand and body positions and orientations [22]. All of these advantages create an enhanced surgical milieu, minimizing surgeon fatigue and improving patient operative safety. Despite the aforementioned advantages, the haptic cues which were only altered in conventional laparoscopic procedures are completely eliminated in RMIS because the surgeon no longer manipulates the surgical instruments directly [25]. Integrating haptic feedback in RMIS is lacking in a clinical setting and is in its infancy in academic realms.
Contemporary robotic surgery research has demonstrated that one of the two aspects of haptic feedback can be successfully integrated into the robotic system’s controls [1]. Pneumatically controlled balloon actuator arrays have been developed to provide surgeons with tactile feedback. They are designed to relay the sensation of touch from the robotic end-effector to the thumb and index fingers of the surgeon operating the system. During the validation of this technology, using simulated tactile stimuli (not real-time information from the operative environment), surgeons found that it did not hinder nor help with basic RMIS tasks [1]. Although tactile feedback lost in traditional laparoscopic procedures can be restored with robotic systems, force feedback remains unaddressed.

One real shortcoming of robotic systems arises during the initial setup stage when considerable time and effort is required before any laparoscopic surgery can begin. Prior to laparoscopic surgery, primary and ancillary ports must be established in the patient’s abdominal wall to access the peritoneal cavity, thus allowing insertion of the laparoscope and various laparoscopic operative instruments.

Traditionally, access devices consist of a sharp-ended pointed trocar (or “push-through trocar”, Figure 2-1) with a sheathed cannula. These devices are used to blindly transect the abdominal wall. In other words, visual feedback is not present during port creation as the laparoscope is introduced into the cannula only after the trocar has created the port and is withdrawn. As a result, most severe complications during laparoscopic procedures are associated with primary port creation [2,3]. Once inserted, the central sharp trocar is retracted and the valved hollow cannula remains in place, as an operating conduit (or port). The surgical and human factors literature describes several reasons why a sharp, blind ended trajectory is not an ideal instrument and method for creating conduits in the human body. Most importantly, uncontrolled application of linear force usually results in trajectory overshoot (caused by excessive unmonitored entry force, applied in a direction normal to the surface of the patient’s abdominal tissue layers) during laparoscopic port creation; causing inadvertent serious injury to vital intra-abdominal organs [4,5,30]. The use of a sharp ended trocar is also linked to excessive patient bleeding, scarring and prolonged recovery time [31]. Given that conventional port creation instruments (Trocar and Cannula) and abdominal entry methods are blind, most primary trocar injuries remain undetected. Delayed recognition of these serious injuries (severe internal bleeding or bowel perforation and ensuing infection) delays reparative efforts and may allow progression of the
modified entry techniques with a sharp trocar in which port creation can be performed under visual guidance (open laparoscopy) has been associated with less surgical complications than the predominant blind entry method (closed laparoscopy) [33,34]. Reports from the US Food and Drug Administration (FDA) describe 1,353 serious injuries and 31 deaths over 5.5 years as a result of sharp-ended blind trocar use in MIS [32]. More importantly, the inability to document and analyze primary port insertion mishaps prevents surgeons from learning from inadvertent errors. In effect, visual port creation raises operating room staff risk-awareness and improves error recording and reporting compliance.

In an attempt to improve patient safety during laparoscopic procedures, Dr. Artin Ternamian (supervising the project) deconstructed conventional port creation, identified Trocar and Cannula performance shaping factors and engineered a laparoscopic port creation system and instrument that renders body cavity entry and exit less dangerous and traumatic.

Five aspects of conventional port creation were identified as rendering the process accident prone irrespective of a surgeon’s dexterity or training.

1. Application of excessive Penetration Force.
2. Linear direction of the Penetration Force towards the very organs surgeons have to avert.
3. Absence of a system to mitigate overshoot.
4. Use of a blind instrument.
5. Use of a sharp instrument.

By eliminating these five accident prone aspects of laparoscopic primary port insertion, a new and innovative body cavity entry system and instrument was developed that by design is less dangerous than conventional systems. A threaded visual cannula was designed that is used to create and maintain the required ports. The threaded visual cannula, named the Ternamian EndoTIP (Figure 2-2), is a blunt ended instrument whose threads advance the tool into the patient’s abdominal cavity under direct visual guidance of a zero degrees laparoscope that is sheathed inside the hollow shaft. By changing the direction of the required entry force from axial to radial, no component of the applied force is in the normal direction, thus reducing the probability of overshoot and ultimately, inadvertent injury [4,5]. It is this primary design difference between the two access devices that makes the TVC an intuitive and logical choice for creating access ports in the abdominal wall.
‘Access device’ and ‘Robotic surgery’ are two terms that are rarely mentioned in the same phrase. In fact, the only FDA approved robotic surgical system, the da Vinci Surgical System [36], requires supporting operating room staff members to manually “prepare the 1-2 cm port” during the set-up phase before the laparoscopic robotic surgery can be performed [17]. It is clear that in an effort to improve patient safety and enhance traditional laparoscopic surgery, engineers have integrated robotic-assisted operations. However, one of the most critical and litigious preliminary steps, primary port placement, has remained manual and accident prone [30].

A single study investigating the force profile generated during body cavity entry using a traditional sharp-ended push through trocar has been performed [2]. In this study, a reproducible method of determining the linear force required to penetrate a swine’s abdominal wall was established.

The engineering academic community has investigated torque measurement during drilling [18,19,20,37,38,39]. Although this operation is not identical to the threading operation observed during body cavity entry using a TVC, the method of accomplishing torque measurement is comparable. The predominant objective of monitoring torque in the engineering literature is to predict tool wear and to maximize tool performance. The most relevant study investigates the thrust force and torque observed during drilling through a graphite/bismaleimide composite material [19]. The results of this study showed the magnitude of torque increased as the tool traversed the medium, and then approached a steady-state value before returning to zero after
penetration. The torque and thrust force profiles generated during six different drilling operations is shown in Figure 2-3.

Figure 2-3: Thrust and Torque Profiles Generated during Drilling of a Graphite/Bismaleimide Composite Material using a Hardened Stainless Steel Bit [19]
Chapter 3: Research Method

The TVC was tested on 51 samples of foam. The foam samples consisted of two types with different material properties (Table 3-1). The foam medium was used as a substitute for biological tissue to improve the repeatability of the system, while remaining consistent with the inanimate media used in current laparoscopic training methods [40]. Furthermore, the TVC was tested on 5 samples of ex vivo animal tissue, namely bovine muscle tissue. Approval from the Office of Research Ethics at the University of Toronto was not required as the tissue was store-bought. The bovine muscle tissue sample was cut into 5in² pieces at a thickness of 0.75in (19.1mm). The density of lean bovine muscle tissue is estimated at 1.10lb/ft³ [41].

Table 3-1: Foam Properties

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<tr>
<td>Grade</td>
<td>22135RBR</td>
<td>1585RBR-AM</td>
</tr>
<tr>
<td>Density</td>
<td>2.12 lb/ft³</td>
<td>1.37 lb/ft³</td>
</tr>
<tr>
<td>IFD (25%)*</td>
<td>105.02 lb/in²</td>
<td>83.29 lb/in²</td>
</tr>
<tr>
<td>Surface Area</td>
<td>1 ft²</td>
<td>1 ft²</td>
</tr>
<tr>
<td>Thickness (nominal)</td>
<td>t_H = 1/2” (12.7mm)</td>
<td>t_S = 0.354” (9.0mm)</td>
</tr>
</tbody>
</table>

*IFD measures the force (in pounds-force) required to make a dent 1” into a 15” x 15” x 4” foam sample by an 8” diameter (50in²) disc

3.1 Test Apparatus

Designed specifically for the project, a test apparatus was constructed to insert the TVC into the medium at constant linear and angular speeds while measuring the forces in all three Cartesian axes and the torque about those axes (F_x, F_y, F_z, T_x, T_y, T_z) (Figure 3-1). In a surgical setting, no linear force is applied to the TVC during entry, only radial force. As the device is rotated, the tissue climbs up along its threads. To simulate this behaviour while simplifying the apparatus, the medium remained fixed while the TVC translated linearly by a magnitude equal to its feed rate during rotation. To ensure a constant rate of entry, an Epson E2L853S-UL SCARA robot was used to drive the TVC at an angular speed of \( \omega_z = 8 \text{RPM} \) and a linear speed of \( v_z = 59.68 \text{mm/rev} \). This was achieved by controlling the position (in the z-direction) and orientation (about the z-axis) of the TVC by describing a point to point path of the desired tool trajectory with respect to time. To measure the forces and torques as a function of time, an ATI Mini45 force/torque transducer (Figure A-1) coupled with an ATI Data Acquisition (DAQ) interface was used. The transducer was calibrated to SI-145-5 specification which gives an operating range of 0-5N-m and a resolution of 1/1504N-m in the z-direction. To ensure accurate torque data, the force/torque transducer, and the TVC were mounted uniaxially with the
robot end-effector in the vertical, z-, direction. To accommodate the varying thicknesses of the media used, the device height could be varied.

**Figure 3-1: Test Apparatus**

The inanimate media, i.e. foam samples, were secured to the test apparatus by Velcro strips. To ensure consistency of recorded torque values, the foam samples were not tensioned when secured to the platform. In a surgical setting, an incision is made at the entry site and the subcutaneous fatty tissue is teased to facilitate threading the TVC through the abdominal wall. This detail was not replicated in the laboratory setting as the TVC is able to thread through the foam samples unaided. Furthermore, by omitting a variable depth incision, the procedure is more reproducible. The bovine muscle tissue sample was secured to the platform by a clamped wooden board (Figure 3-2). After the sample is placed at the entry site, the hinged board is secured in place with a c-clamp. A single entry site was performed on each sample.
A Logitech Webcam Pro 9000 was mounted underneath the test apparatus facing the positive z-direction (i.e. up towards the test medium). By mounting the camera underneath the apparatus, the instant when the visual trocarless cannula penetrates the medium is known. An algorithm was created to capture still images at a rate of 5Hz. These images were attached with a time stamp in order to synchronize them with the force/torque data captured by the transducer. As the image capture algorithm and the force/torque measurements were made on separate computers, their system clocks were synchronized prior to any data collection. With this experimental setup, the TVC was driven through various media and the resulting torque profiles were generated.

### 3.2 Test Conditions

To quantify the amount of torque required to penetrate the media used, while ensuring accuracy of the recorded data, several test conditions were investigated. They are outlined in the following sections. In all test conditions, the TVC completed two full rotations (720°) into the test media. It should be noted that the Hard and Soft foam samples are very similar in density. They are nearly indistinguishable by manual palpation.

#### 3.2.1 Single Layer Foam

The first test condition was used to determine the torque profile generated when the TVC traversed and penetrated a single layer of foam. Both the Soft (n = 9) and Hard (n = 9) foam samples were tested and their respective observed means and 95% confidence intervals were calculated.
3.2.2 Thick Single Layer Foam

In this test condition, the torque profile resulting from entry into thick single layer Soft (n = 2) and Hard (n = 2) foam samples was investigated. The thickness of the Soft and Hard foam samples was 19mm. This condition was used to determine if the steady-state value observed in the single layer collections was accurate.

3.2.3 Double Layer Foam

Once the profile of the individual layers was determined, the single layer foams were joined using SAR 505 Super Strength All Purpose Aerosol Adhesive to investigate the resulting torque profiles observed during the transition from one layer to the next. In the second test condition, the following combinations were investigated:

1. Soft → Soft (n = 2)
2. Hard → Hard (n = 2)
3. Hard → Soft (n = 14)*
4. Soft → Hard (n = 7)*

* Two additional samples were tested with the outer sheath of the TVC lubricated by a uniform layer of Jig-A-Loo dry silicon based lubricant.

3.2.4 Bovine Muscle Tissue

In the fourth test condition, a bovine muscle tissue sample was used as a test medium (n = 5). This allowed for a more accurate measure of the torque required to penetrate a biological tissue specimen.

3.2.5 Foam and Bovine Muscle Tissue

In the final condition, a Soft sample of foam and a bovine muscle tissue sample (n = 1) were clamped together. In this test condition, a more pronounced transition from one medium to the next was investigated.

3.3 Issues and System Limitations

3.3.1 End Effector Rotation about Z-axis

The Epson SCARA robot has one major limitation which confines the total thickness of the medium tested. The end-effector of the robot is able to complete only two full rotations about the z-axis (720°). This is inherent in the design of the robot itself. As a result, the TVC is limited to two rotations as well during torque data collection. Given that the rate of descent of
the TVC is dictated by its feed rate, \( FR_E = 7.46 \text{mm/rev} \), the maximum thickness the cannula can traverse without causing compression and deflection in the medium is twice the feed rate, i.e. 14.92mm.

In the double layer foam test conditions outlined above, the combined thickness of the sample exceeded the upper bound of 14.92mm. Therefore, to observe the behaviour of the torque profile during penetration of the foam medium by the TVC’s tip, the start position of the tool was lowered. This caused a predictable amount of compression and deflection in the double layered foam sample by the bottom face of the TVC.

### 3.3.2 Offset of End-Effectors Z-axis Orientation from Vertical

During data collection, it was observed that the rotating TVC translated in the x and y directions. This effect is undesirable as the magnitude of friction between the TVC and the foam samples is distorted by these translations. This bi-directional translation was due to the slight deviation in the end-effector’s longitudinal orientation with respect to absolute vertical. To determine the magnitude of this deviation, a pen was attached to the geometric centre of the robot’s cylindrical end-effector and placed over a sheet of paper. The end-effector was then rotated 360°.

The pen drew a small (3mm diameter) circle on the paper (Figure 3-3) instead of a dot which would have been seen if there was no deviation from absolute vertical. This deviation could not be corrected and should be checked prior to any future work performed on the setup.

![Figure 3-3: End-Effector Deviation from Vertical](image-url)
3.3.3 Robot End Effector Rate of Descent

One of the unique aspects of the TVC’s design is the threads on the outside of the cannula’s shaft. This threading allows tissue to ‘climb’ along its length during port creation. In the experimental setup, the simulated tissue remains fixed to a table top, as a result, it cannot ‘climb’ up the trocarless visual cannula’s shaft during port creation.

To address this problem, the end-effector of the robot complete with the TVC must be driven into the simulated tissue at a specific rate. This rate is dictated by the feed rate of the TVC’s thread. Feed rate defines the amount of linear displacement per rotation. For example, with a feed rate of 7.46mm/rev, a single rotation will result in a linear translation of 7.46mm (7.46mm/360°).

Therefore, to mimic the characteristics of the TVC, the end-effector of the robot must descend 7.46mm for every full rotation (360°). This will prevent the medium from being compressed between the threads of the TVC during entry and allows for proper cannulation.

To ensure that the end-effector with the attached TVC descends at 7.46mm/360°, a position point file describing its motion was created. Given that prior to port creation, the tip of the TVC was located at (-132.333mm, 656.909mm, -27.181mm, 413.724°) in the SCARA robot’s global (x, y, z, U) co-ordinate system, the next point in the robot’s path was calculated by (for a file with 180 points describing the entire motion – rate of descent multiplied by a factor of 4):

\[
x = \text{unchanged} \quad y = \text{unchanged} \quad z = -27.181 - 4 \cdot \left(\frac{7.46}{360}\right) = -27.264mm \quad U = 413.724° - 4 = 409.724°
\]

A profile describing the entire path of the tip of the TVC was calculated in the same fashion.

3.3.4 Simultaneous Movement and Torque Collection

The EPSON SCARA robot is controlled by proprietary software called EPSON RC+ and uses the SPEL+ programming language. The ATI Mini45 sensor can be used in conjunction with the robot and has software which is compatible with EPSON RC+. Forces and torques (in 3 axes) can be determined by executing the Force_GetForce() command in SPEL+.

For the project, the torque about the z-axis must be collected. In SPEL+ as in all other programming languages, only a single line of code can be executed at a time. As a result, at a
given moment in time, the robot is limited to either threading the TVC through the various layers of foam or to collecting the torque values about the z-axis. This posed a problem as the torque must be collected in real-time while the TVC is threaded through the foam. This is necessary to capture the differential in torque as the tool tip traverses the different foam layers.

This issue was resolved by using independent software to achieve both motion and data collection simultaneously. ATI data acquisition (DAQ) software was used to collect and log torque data while EPSON RC+ software was used to thread the TVC through the foam.

### 3.3.5 Suitable Foam Types

The material properties of the two types of foam used in the project were extremely similar. Foam types with a higher density than that of the Hard foam medium used experienced coring during cannulation. In other words, when the TVC was retracted from the dense medium, a hole remained at the entry site (Figure 3-4). This behaviour was undesirable because it did not simulate reality. Foam types that were less dense (memory type) than the Soft foam medium used could not be cannulated because the local material surrounding the TVC could not retain its shape and thus rotated with it. This caused a significant increase in the torque required to traverse the material.

![Figure 3-4: Coring at the Entry Site of the TVC](image)

### 3.3.6 Rigid Base for Foam Samples

Given the objective of the research is to determine the magnitude of torque required to traverse each layer of the abdominal wall, all factors which may lead to a corruption of the data must be properly addressed. In order to ensure the reliability of the torque values collected, the simulated
tissue (foam sample) must be securely fastened to the table top to prevent any rotational motion during port creation. Any rotational motion will result in a smaller torque value than expected.

Originally, a plastic base with a foam sample was secured to the table top with Velcro (Figure 3-5). On numerous occasions, the plastic base would rotate slightly during port creation. This could lead to unreliable data.

To address this problem, a wooden base was fabricated with four locations for foam samples and secured to the table top with C-clamps (Figure 3-6). This improved setup does not allow for any rotation, thus improving the reliability of the torque values recorded.

The locations of the feet of the table were also marked on the floor in order to ensure consistent positioning of the TVC with respect to the foam from day to day collections.

3.3.7 Penetration of TVC through Medium

In addition to determining the difference in torque required to traverse materials with different properties, determining the point at which the TVC penetrates the medium and enters the peritoneal cavity is of utmost importance for patient safety. Given the setup shown in Figure 3-6, the ability to visually establish when the TVC has penetrated the medium is not possible. By elevating the setup and placing a camera underneath a single entry point (Figure 3-7), i.e. one foam sample in the setup, (facing in the positive z-direction) the instant the tip of the TVC penetrates the medium is known and can be synchronized with the force/torque data to establish a condition describing that penetration.
3.3.8 Force/Torque Sensor Wire Tension

The ATI Mini45 Force/Torque transducer has a wired connection with its DAQ. Because the threading procedure inherently requires rotation, the wire can wrap around the length of the TVC. This may result in data inaccuracies if the junction between the wire and the sensor is loaded at any point during data collection. Any tension in the wire can be translated to this junction and distort the readings from the sensor.

To avoid this, the junction between the wire and the sensor must be isolated from the remaining wire. This is achieved by fixing a point of the wire (a few centimetres from the junction) to the rotating robot end-effector. As a result, the tension along the cable is absorbed at that fixed point and will not be translated to the junction site, thus preventing any distortion of the collected data.
Chapter 4: Results and Discussion

The TVC was driven through two foam media with different densities. First independently then combined, to observe the change in torque as the tool passed from one layer to the next. Furthermore, ex-vivo animal tissue (bovine muscle) was used as a medium to estimate the real magnitude of torque required to penetrate the muscle layer of the peritoneal cavity.

4.1 Results

The resulting torque profiles from each test condition outlined in Section 3.2 are presented below. Note that due to the design of the trocarless visual cannula, the direction of rotation required to traverse the media resulted in a negative value of torque. It should also be noted that due to the small magnitude of torque recorded during cannulation, the noise in the system caused a cyclical variation in the recorded data. To observe the trend in the generated torque profiles, a 5th order polynomial regression was fitted to the data recorded across all trials.

4.1.1 Single Layer Foam

In order to identify the layer that the TVC traversed in a multilayered medium, the torque profile of each layer must first be determined independently. Examples of the torque profiles generated in the Soft and Hard foam media are shown in Figure 4-1a and Figure 4-2a, respectively. A 5th order polynomial regression was fitted to the torque profile of each sample. The individual regressions from all trials, as well as an average regression were also generated for the Soft (Figure 4-1b and Figure 4-1c) and Hard (Figure 4-2b and Figure 4-2c) media. The torque profiles generated in all trials of the single layer foam are shown in Appendix B.

The resulting steady-state value achieved in the single layer foam media was determined by taking the first derivative of the 5th order polynomial regression, establishing the sample number where the extrema occurs (when derivative equals zero), and then substituting that sample number into the original expression. A sample calculation for the single layer Hard foam (Trial 4) is shown below.

Given: \[ y = -3E - 11x^5 + 8E - 09x^4 - 6E - 07x^3 + 3E - 05x^2 - 0.0029x + 0.0062 \] \[ 4V1 \]

1st Derivative: \[ \frac{dy}{dx} = 0 = -1.5E - 10x^4 + 3.2E - 08x^3 - 1.8E - 06x^2 + 6E - 05x - 0.0029 \] [4-2]
Extrema occurs at sample: \( x = \{71.98, 141.84\} \); 71.98 is chosen as it falls within the range of the collection. Therefore, by substituting this value back into equation 4-1, the maximum magnitude of output torque is calculated as:

\[
y_{\text{max}} = -3E -11 \cdot (71.98)^3 + 8E -09 \cdot (71.98)^4 - 6E -07 \cdot (71.98)^3 + 3E -05 \cdot (71.98)^2 - 0.0029 \cdot (71.98) + 0.0062
\]

\[
y'_{\text{max}} = -0.1141 N \cdot m
\]

Table 4-1 describes the observed mean steady-state output torque and the bounds of the 95% confidence interval. Penetration through the medium by the tip of the TVC (exit point) was observed by the under mounted camera. The time stamp attached to the image allowed synchronization with the recorded force/torque data. A sample image of the exit point is shown in Appendix C.

Table 4-1: Single Layer Foam Torque Profile Steady-State Values

<table>
<thead>
<tr>
<th>Foam Type</th>
<th>SOFT</th>
<th>HARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Mean Steady-State</td>
<td>-0.08191 N-m</td>
<td>-0.1038 N-m</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.363E-03 N-m</td>
<td>9.726E-03 N-m</td>
</tr>
<tr>
<td>Upper Bound (95% confidence)</td>
<td>-0.08803 N-m</td>
<td>-0.1102 N-m</td>
</tr>
<tr>
<td>Lower Bound (95% confidence)</td>
<td>-0.07580 N-m</td>
<td>-0.09747 N-m</td>
</tr>
</tbody>
</table>

Figure 4-1a: Single Layer SOFT Foam Torque Profile (Trial 06)
Figure 4-1b: Single Layer SOFT Foam Torque Profile 5th Order Polynomial Regressions

Figure 4-1c: Single Layer SOFT Foam Torque Profile Average 5th order Polynomial Regression
Figure 4-2a: Single Layer HARD Foam Torque Profile (Trial 04)

Figure 4-2b: Single Layer HARD Foam Torque Profile 5th Order Polynomial Regressions
4.1.2 Thick Single Layer Foam

The thickness of the single layer foam media presented in Section 4.1.1 was equal to those in the double layer media, i.e. \( t_S \) and \( t_H \). The ensure that the steady-state output torque value was reached in each foam type, thick (19mm) samples of both Soft and Hard foam types were tested and the respective steady-state values of their 5\(^{th}\) order polynomial regressions were determined. The torque profile generated in the thick Soft foam medium (Figure 4-3) showed a steady-state value of -0.0942N-m, while that shown in the Hard foam medium (Figure 4-4) was -0.1201N-m.
Figure 4-3: Thick Single Layer SOFT Foam Torque Profile (Trial 01)

Figure 4-4: Thick Single Layer HARD Foam Torque Profile (Trial 01)
4.1.3 Double Layer Foam

Prior to investigating the transition from one foam type to the next, two identical foam samples were joined to determine if the glue resulted in any deviation from the trends observed in the single layer thick foam media. The transition point between the layers of the double layer foam media was estimated using the position and orientation data of the TVC tip trajectory and was then overlaid on the resulting torque profiles. A sample calculation for the Hard→Soft foam medium is shown below. A side view depicting the starting geometry of the test apparatus for this test condition is shown in Figure 4-5. As outlined in Section 3.3.1, the start position of the trocarless visual cannula’s tip caused compression in the foam sample. It was assumed that compression only occurs in the first layer of the combined sample.

Given: \( t_{H/S} = 21.7 \text{mm}, \ t_H = 12.7 \text{mm}, \ h_{H/S} = -16.888 \text{mm}, \ z_{H/S,s} = -27.181 \text{mm}, \ z_{H/S,e} = -42.098 \text{mm}, \ U_{H/S,s} = 413.724^\circ; \) then,

\[
\begin{align*}
    b_{H/S} & = h_{H/S} - t_{H/S} \\
    b_{H/S} & = -16.888 - 21.7 \\
    b_{H/S} & = -38.588 \text{mm}
\end{align*}
\]

However, the images captured by the under mounted camera shows that penetration occurs at \( z_{H/S,e} \). Therefore, the deflection of the foam sample (into the centre opening of the test apparatus base) is:

![Figure 4-5: Side-View of Test Apparatus Depicting Starting Geometry of HARD→SOFT Test Condition](image-url)
\[ \delta_{H/S} = |z_{H/S,e} - b_{H/S}| \]  
\[ \delta_{H/S} = |-42.098 - (-38.588)| \]
\[ \delta_{H/S} = 3.51\text{mm} \]

Furthermore, the magnitude of compression observed in the foam medium can be calculated as:
\[ \sigma_{H/S} = t_{H/S} - (z_{H/S,s} - z_{H/S,e}) \]
\[ \sigma_{H/S} = 21.7 - [-27.181 - (-42.098)] \]
\[ \sigma_{H/S} = 21.7 - 14.917 = 6.783\text{mm} \]

Therefore:
\[ \Delta_{H/S} = \delta_{H/S} + \sigma_{H/S} \]
\[ \Delta_{H/S} = 3.51 + 6.783 \]
\[ \Delta_{H/S} = 10.293\text{mm} \]

It was assumed that all compression occurs in the first layer of foam (in all double layer foam media), therefore, the transition location from Hard to Soft foam can be calculated as:
\[ z_{H/S,t} = V[|h_{H/S}| + t_H + (\Delta_{H/S} - \sigma_{H/S})] \]
\[ z_{H/S,t} = -16.888 + 12.7 + (10.293 - 6.783) \]
\[ z_{H/S,t} = -33.098\text{mm} \]

From the position data describing the trocarless visual cannula’s trajectory, it can be seen that \( z = z_{H/S,t} = -33.098\text{mm} \) occurs when \( U = U_{H/S,t} = 129.724^\circ \). Over its entire trajectory, the TVC rotates 720°, therefore, the percentage completed at the transition point from the Hard to Soft foam layer is:
\[ \vartheta_{H/S,t} = \left[ \frac{U_{H/S,t} - U_{H/S,\ell}}{720^\circ} \right] \cdot 100\% \]
\[ \vartheta_{H/S,t} = \left[ \frac{413.724 - 129.724}{720} \right] \cdot 100 \]
\[ \vartheta_{H/S,t} = 39.4\% \]

With this percentage, the sample number in the torque profile which corresponds with the transition from Hard to Soft foam can be determined. Given that the total number of samples in the torque profile is 120, then:
\[ S_{H/S,t} = 120 \cdot \vartheta_{H/S,t} \]
Therefore, the transition from the Hard to the Soft foam layer occurs at Sample 47 on the torque profile. A similar calculation was performed to determine the transition point for all other double layered foam conditions (Table 4-2). The exit point from the double layer foam media was determined by the under mounted camera.

<table>
<thead>
<tr>
<th>Foam Medium</th>
<th>Transition Point (Sample No.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARD→SOFT</td>
<td>47</td>
</tr>
<tr>
<td>SOFT→HARD</td>
<td>18</td>
</tr>
<tr>
<td>SOFT→SOFT</td>
<td>47</td>
</tr>
<tr>
<td>HARD→HARD</td>
<td>18</td>
</tr>
<tr>
<td>SOFT→BOVINE</td>
<td>31</td>
</tr>
</tbody>
</table>

Examples of the torque profiles generated in the Soft→Soft and Hard→Hard media are shown in Figure 4-6a and Figure 4-7a, respectively. A 5\(^{th}\) order polynomial regression was fitted to the torque profile of each sample. The individual regressions from all trials, as well as an average regression were also generated for the Soft→Soft (Figure 4-6b and Figure 4-6c) and Hard→Hard (Figure 4-7b and Figure 4-7c) media. The torque profiles generated in all trials of the double layer foam are shown in Appendix D. The average steady-state value observed in the double layer Soft→Soft foam medium was -0.1075N-m, while that observed in the Hard→Hard medium was -0.1453N-m.
Figure 4-6a: Double Layer SOFT→SOFT Foam Torque Profile (Trial 01)

Figure 4-6b: Double Layer SOFT→SOFT Foam Torque Profile 5th order Polynomial Regressions
Figure 4-6c: Double Layer SOFT→SOFT Foam Torque Profile Average 5th order Polynomial Regression

Figure 4-7a: Double Layer HARD→HARD Foam Torque Profile (Trial 01)
Figure 4-7b: Double Layer HARD→HARD Foam Torque Profile 5th order Polynomial Regressions

Figure 4-7c: Double Layer HARD→HARD Foam Torque Profile Average 5th order Polynomial Regression
Double layered foam collections containing a transition from one foam type to another were then performed. Examples of the torque profiles generated in the Hard→Soft and Soft→Hard media are shown in Figure 4-8a and Figure 4-9a, respectively. A 5th order polynomial regression was fitted to the torque profile of each sample. The individual regressions from all trials, as well as an average regression were also generated for the Hard→Soft (Figure 4-8b and Figure 4-8c) and Soft→Hard (Figure 4-9b and Figure 4-9c) media.

Figure 4-8a: Double Layer HARD→SOFT Foam Torque Profile (Trial 12)
Figure 4-8b: Double Layer HARD $\rightarrow$ SOFT Foam Torque Profile 5th order Polynomial Regressions

Figure 4-8c: Double Layer HARD $\rightarrow$ SOFT Foam Torque Profile Average 5th order Polynomial Regression
Figure 4-9a: Double Layer SOFT→HARD Foam Torque Profile (Trial 01)

Figure 4-9b: Double Layer SOFT→HARD Foam Torque Profile 5th order Polynomial Regressions
It should be noted that during cannulation of the double layer foam media, a non-constant audible squeaking sound was present. This suggested a stick/slip condition between the threads of the TVC and the foam medium. In other words, the foam medium would stick to the threads of the TVC during its rotation causing the material to rotate with it. Once released from the threads, the material would slip back to its original position. This would cause an increase in the output torque during the stick condition and a drop during the slip. To investigate if this phenomenon contributed to the deviation from steady-state once it was achieved in the second layer of the medium, the outer sheath of the TVC was lubricated and two samples each of the Hard→Soft (Figure 4-10a) and Soft→Hard (Figure 4-11a) foam media were tested. A 5th order polynomial regression was fitted to the torque profile of each sample. The individual regressions from all trials, as well as an average regression were also generated for the Hard→Soft (Figure 4-10b and Figure 4-10c) and Soft→Hard (Figure 4-11b and Figure 4-11c) media.
Figure 4-10a: Double Layer HARD→SOFT Foam Torque Profile - TVC Lubricated (Trial 01)

Figure 4-10b: Double Layer HARD→SOFT Foam Torque Profile 5th order Polynomial Regressions - TVC Lubricated
Figure 4-10c: Double Layer HARD→SOFT Foam Torque Profile Average 5th order Polynomial Regression - TVC Lubricated

Figure 4-11a: Double Layer SOFT→HARD Foam Torque Profile - TVC Lubricated (Trial 01)
Figure 4-11b: Double Layer SOFT→HARD Foam Torque Profile 5th order Polynomial Regressions - TVC Lubricated

Figure 4-11c: Double Layer SOFT→HARD Foam Torque Profile Average 5th order Polynomial Regression - TVC Lubricated
4.1.4 Bovine Muscle Tissue

Bovine muscle tissue was used as a medium in order to estimate the magnitude of torque required to cannulate biological tissue. An example of the torque profiles generated in this test condition is shown in Figure 4-12a. A 5th order polynomial regression was fitted to the torque profile of each sample. The individual regressions from all trials, as well as an average regression were generated and are shown in Figure 4-12b and Figure 4-12c, respectively. The torque profiles generated in all trials of the bovine muscle tissue condition are shown in Appendix E. An average steady-state value of -0.06232N-m was observed.

Figure 4-12a: Bovine Muscle Tissue Torque Profile (Trial 05)
Figure 4-12b: Bovine Muscle Tissue Torque Profile 5th order Polynomial Regressions

Figure 4-12c: Bovine Muscle Tissue Torque Profile Average 5th order Polynomial Regression
4.1.5 Foam and Bovine Muscle Tissue

In this test condition, the transition between two materials with a pronounced difference in properties was investigated. The transition point was calculated in the same fashion as in Section 4.1.3. The resulting torque profile is shown in Figure 4-13.

![Graph showing torque profile](image)

**Figure 4-13: Double Layer SOFT→BOVINE Torque Profile (Trial 01)**

4.2 Discussion

There exists a wide variety of access devices currently used in MIS procedures which can be classified into two basic categories: sharp and blunt. The application of linear force in the direction of internal structures and the blind nature of port creation with a sharp trocar has lead it to become one of the most severe complications associated with laparoscopic surgery [2,3]. By using a blunt ended access device that is driven by a radial force under direct visual guidance, the incidence of complication during port creation can be reduced [4,5].

The transition from conventional open techniques to MIS has yielded shortened patient recovery times due to the reduction in surgical access trauma [1]. However, this transition has resulted in a disconnection between the surgeon and the operative environment as they must interact with body tissues via long endoscopic instruments, not with their gloved hands. This disconnection
has been further emphasized with the adoption of RMIS as surgeons no longer directly interact with the endoscopic instruments. To repair this disconnection between surgeons and the operative environment, the distorted haptic cues in MIS and the absent haptic cues in RMIS must be restored. A true measure of the haptic feedback can be provided to surgeons intra-operatively if and only if, their endoscopic tools are sensorized [6]. The project aimed to address the force component of haptic feedback, and focused on the torque observed at the tool/tissue interface during body cavity entry using a TVC.

In order to provide intra-operative force feedback, the forces observed at the tool/tissue interface must be measured and then relayed to the surgeon. In the project, a method of determining the torque observed at the tool/tissue interface during port creation was developed to investigate the feasibility of detecting minute changes in the material properties of the various layers encountered during entry into a body cavity using a TVC.

In the first test condition, single layer foam media were tested. In this, and all subsequent test conditions, the TVC completed its first rotation into the medium by Sample 60. Due to the varying thickness of the media tested (and in some cases, the deflection of the medium) penetration by the tip of the TVC was observed at different samples. The exit point observed in each sample of the different conditions was confirmed by the under mounted camera. The torque profiles observed in the single layer foam conditions showed that the magnitude of torque increased during the first rotation of the TVC and reached a steady-state value by the end of that rotation (Figure 4-1a and Figure 4-2a). Furthermore, after penetration of the medium, the torque profile shifted away from the steady-state value and approached zero. The rate at which torque increased during the first rotation was non-constant. It showed that the magnitude of torque decayed over time until it settled upon a steady-state value which was specific to the medium tested. This result suggested that by the end of the first rotation, equilibrium between torque growth and torque decay was achieved. The only force contributing to the change in torque observed at the tool/foam interface was friction. Therefore, the torque profiles generated during the single layer foam collections suggested that the magnitude of friction between the threads of the TVC and the foam decayed over time and settled to a steady-state value by the end of the TVC’s first rotation. This observation was further reinforced by examining the portion of the torque profile generated after the exit point. After this point, the thread distal to the tip of the TVC remained engaged in the foam sample, yet the magnitude of torque decreased over time.
This suggested that as the thread of the TVC continually passed over the same portion of the foam sample, the magnitude of friction decreased over time. This finding implied that the final steady-state value achieved during cannulation of a specific material was the factor which defined its properties, as each material will exhibit a unique equilibrium between torque growth and decay dictated by its coefficient of friction.

To ensure steady-state was reached in the single layer foam conditions, thick single layer foam media were investigated (Figure 4-3 and Figure 4-4). The average steady-state values observed in this test condition were -0.0942N-m and -0.1201N-m for the Soft and Hard media, respectively. These values lay outside the 95% confidence interval determined for the single layer foam condition. This may be a result of the compression present between the bottom face of the TVC and the foam medium. As a result of the compression, the foam encountered at the entry site was denser than in the single layer nominal thickness conditions, causing a greater magnitude of torque required to traverse the layer. The significant result from the thick single layer condition was that steady-state was observed in both the Soft and Hard foam media by the end of the TVC’s first rotation (i.e. by Sample 60).

In the following test condition, double layer Soft→Soft and Hard→Hard media were tested to investigate the effect the glue joining the two layers has on the torque profiles generated (Figure 4-6a and Figure 4-7a). The combined thickness of the samples was comparable to the thick single layer foam media. The average steady-state values observed in this double layer test condition were -0.1075N-m and -0.1453N-m for the Soft→Soft and Hard→Hard media, respectively. Again, an increase from the previous condition was observed and steady-state was reached by the end of the first rotation. This suggested that the glue joining the two foam layers added rigidity to the medium, inhibiting separation and resulted in a greater magnitude of torque required to separate the material during cannulation. The significance of this test condition was to investigate if a local spike in torque was observed at the interface between the two foam layers. Despite the increase in steady-state torque, the glue did not cause a distortion in the overall trend in the generated torque profiles.

Before analyzing the torque profiles generated in the double layer Hard→Soft and Soft→Hard media, the result of the trials performed with the TVC lubricated should be mentioned (Figure 4-10 and Figure 4-11). It was noted that during the collection of the double layer foam conditions, an audible squeaking sound was heard as a result of the stick/slip between the TVC...
thread and the foam medium. Applying lubricant to the outer sheath of the TVC did appear to inhibit deviation from steady-state once it was achieved. It should be mentioned, however, that the lubricant did not eliminate the squeaking sound, but did cause it to be more consistent (i.e. it was heard throughout the entire collection, not at random), hence the increased signal amplitude from the non-lubricated condition.

In the double layer foam media exhibiting a transition from one foam type to the next, two different results were observed. In the Hard→Soft medium (Figure 4-8a), the generated torque profile showed the magnitude of torque first settled upon the steady-state value dictated by the Hard foam layer, then shifted towards and settled upon the steady-state value dictated by the Soft foam layer. The magnitude of the steady-state value achieved during penetration of the Hard foam layer, however, laid outside the bounds of the 95% confidence interval determined by the single layer Hard foam condition. This may be a result of the compression of the top (Hard) foam layer by the bottom face of the TVC or the glue joining the two foam layers. After the tip of the TVC traversed into the Soft foam layer, the torque profile shifted and approached the steady-state value of the Soft foam. This result was promising as it indicated a predictable trend in the torque profile as the TVC traversed from one foam type to the next. Studying the torque profile generated throughout the entire collection clearly shows a transition point. On the other hand, the value of the torque data captured between the TVC and the medium is only valuable during body cavity entry if it can provide an instantaneous indication that the tool tip has traversed into a different layer. If the torque profile in Figure 4-8a was investigated in real-time during the collection, no clear indication would be present that the transition occurred at Sample 47. In other words, a transition in trend is difficult to observe unless the entire signal is available. This finding was a direct result of the inherent design of the TVC. Because the entire length of the cannula is threaded, the output torque recorded by the force/torque transducer represents the total magnitude of torque experienced along the entire tool, not only at the tip. This design feature of the TVC also contributed to the different result observed in the Soft→Hard foam condition (Figure 4-9a). Due to the compression of the top (Soft) layer of the medium by the bottom face of the TVC, the transition to the Hard foam layer occurred before any steady-state condition was achieved. As mentioned above, the magnitude of output torque settled to a constant value near the end of the first rotation of the TVC. Therefore, if the thickness of the medium was less than FR_E, steady-state would not be achieved. After the transition into the Hard foam layer, the torque profile settled to a magnitude of -0.098N-m,
which was included in the bounds of the 95% confidence interval. A similar result was observed in only two of the seven trials. Furthermore, none of the fourteen trials of the Hard→Soft medium settled to a steady-state value bounded by the 95% confidence interval for the Soft foam.

This change in the steady-state value achieved in the second layer of the double layer foam media may have resulted from the difference in torque decay observed in the two foam types. In the double layer foam conditions, the rate of torque growth and decay will differ as the threads of the TVC are engaged in two different materials. Consider the Hard→Soft foam medium. As the tip of the TVC traversed from the Hard to Soft foam, the rate of torque growth was dictated by the Soft foam while the rate of torque decay was dictated by the Hard foam. Therefore, the torque values recorded after the transition point by the force/torque transducer should be modified to include the rate of torque decay in the Hard foam sample. Using the 5th order polynomials fitted to the torque profile of the single layer Hard foam media, an average rate of torque decay after the exit point was established (Figure 4-14). This signal was then subtracted from the torque profile (starting at the transition point) of the Hard→Soft foam media. The modified torque profile (in red) is shown in Figure 4-15.
Figure 4-14: Average Torque Decay after Exit in Single Layer HARD Foam Media

Figure 4-15: Double Layer HARD→SOFT Foam Torque Profile Modified to Include Average Rate of Torque Decay in HARD Foam (Trial 12)
By subtracting the average torque decay observed after penetration of the single layer Hard foam sample, torque growth was observed as the TVC traversed the Soft foam layer. Furthermore, the final steady-state output torque value was reduced from -0.1342N-m to -0.110N-m, which remained outside the bounds of the 95% confidence interval for the single layer Soft foam. Even though steady-state output torque was achieved after a single rotation of the TVC in a foam medium, the magnitude of output torque observed in the single layer foam conditions did not return to zero during the second rotation (i.e. first rotation after penetration). Just after the transition into the Soft foam, the magnitude of torque in the modified profile was -0.02751N-m. Shifting the modified torque profile towards zero by this amount would result in a steady-state torque value in the Soft layer of -0.110N-m + 0.02751N-m = -0.08249N-m, which lies within the bounds of the 95% confidence interval for the single layer Soft foam medium.

The torque profiles generated in the Bovine Muscle Tissue condition yielded interesting results. Firstly, the overall trend observed remained consistent with that observed in the inanimate foam samples. In other words, an average steady-state value of -0.06232N-m was achieved by the end of the TVC’s first rotation. It should be noted, however, that due to the inconsistent nature of the medium, deviation from steady-state was observed. This may have resulted from a transition from muscle tissue to a harder medium (i.e. fat at room temperature). Secondly, the sudden spike in the magnitude of torque observed near the end of the torque profile in Figure 4-12 could indicate that the tip of the TVC interacted briefly with a material that differed significantly from the surrounding tissue, i.e. a ligament or tendon. A spike of this nature was observed in three of the five trials.

Although the notion of steady-state torque has justified the results observed during the project, the secondary objective of instantaneous detection of the change in torque experienced by the TVC during port creation was unsuccessful. The results of the example trials included in Section 4.1 showed that given an entire torque profile, fitting a 5th order polynomial regression could suggest when the transition between different layers of material occurred. However, this was not apparent in all trials collected as can be seen in the averaged 5th order polynomial regressions. Due to the similarity in material properties between the Hard and Soft foam media, noise in the system may have caused distortion of the results. It should be mentioned that the torque profile trend observed in the double layer HARD→SOFT foam medium with lubrication applied to the TVC (Figure 4-10) consistently showed a more predictable transition between the steady-state
values achieved in the different layers. In other words, both trials of this condition showed that the torque profile first settled upon the steady-state value dictated by the Hard foam layer, then after the transition into the next layer, the torque profile settled upon the steady-state value of the Soft foam. Despite the similarities in the material properties of the two foam types, the transition was more consistently observed when the outer sheath of the TVC was lubricated. In a preliminary investigation, the transition between two dissimilar materials, i.e. from the Soft foam to Bovine Muscle Tissue, was investigated (Figure 4-13). The transitional behaviour of the torque generated between these two dissimilar materials was much more clearly depicted. Although the transition from Soft foam to Bovine muscle tissue was clearly shown, the inability to determine the transition point in real-time remained. If a 5th order polynomial regression was fitted to the torque profile in real-time with every additional sample collected, it would not show the transition occurring at Sample 31 until Sample 82 was collected (Figure 4-16). Given that the force/torque transducer recorded data at 8Hz, the transition would not be apparent until collection continued for approximately 6 seconds.

Figure 4-16: Duration of Data Collection Required to Determine Transition from SOFT→BOVINE Occurred at Sample 31
4.3 Recommendations and Future Work

The results showed that the ability to determine a transition point with the torque profile alone could not be achieved with the current design of the TVC. The threads located along the entire length of the TVC are continually engaged in a material during body cavity entry. As a result, a force/torque transducer mounted at the interface between the robot’s end-effector and the TVC will record the total torque experienced along the length of the tool, not only at its tip.

To investigate the behaviour of the torque profile generated if only the tip of the TVC was threaded, a preliminary test was conducted. In the test, the start position of the TVC was elevated such that the torque profile observed during entry into a medium by the first portion of thread was apparent. Using video data captured during the test, the sample number in the torque profile corresponding to contact between the tool’s bottom face and the foam sample, as well as the engagement of the tool thread with the foam sample was determined. Contact occurs at Sample 21 in both the Soft and Hard media, while engagement of the thread occurs at Sample 35 for the Soft medium and at Sample 42 for the Hard. The resulting torque profiles are shown in Figure 4-17 and Figure 4-18 below.

![S-thick_T2 - Tz](image)

Figure 4-17: Thick Single Layer SOFT Foam Torque Profile (Trial 02)
These results show that the output torque starts to build as soon as the bottom face of the TVC contacts the top surface of the sample. Furthermore, the rate at which the torque builds changes dramatically once the thread has engaged the material. This preliminary test suggests when the threads of the cannula distal to its tip are not engaged in a solid material (or are not present), the change in the torque profile is very pronounced at the transition point and could be used to indicate transitions instantaneously as the recorded data is indicative of the torque experienced at the tool tip. As a result, it is recommended to limit the number of threads located along the TVC’s shaft. If only a half-rotation of thread extended from the tool tip, the torque recorded by the force/torque transducer would more accurately represent the magnitude of torque present at the tool tip. In this situation, the thread would only be engaged in 3.73mm of material (FR_E/2). Furthermore, the transition from one medium to the next would be more apparent and could be determined instantaneously by a change in slope in the generated torque profile. Future work to investigate this behaviour is warranted.
Chapter 5: Conclusion

The necessity of sensorizing endoscopic instruments to provide an accurate form of feedback in both traditional and robotic MIS is a driving force in the academic community. Without restoring the lost form of feedback, surgeons will continue to be disconnected from the operative environment. The rising prevalence of MIS procedures and the adoption of robotic systems across the continent and the globe suggest that these surgical techniques are here to stay. In an effort to quantify the tool/tissue interaction during body cavity entry using a TVC, a platform for restoring the force component of haptic feedback was established.

In conclusion, the torque profile generated during cannulation of individual media is unique and is dictated by the characteristics of the specific material. The unique profile is generated due to the magnitude of friction present between the threads of the TVC and the medium it is traversing. Furthermore, a steady-state magnitude of torque is achieved after one complete rotation of the TVC into the medium.

It is also concluded that given the presence of threads along the entire length of the TVC, instantaneous detection of a change in torque arising from the transition between two different media (or penetration in the peritoneal cavity) is not possible. It is therefore recommended to modify the design of the TVC such that only a half rotation of thread is present at the tip of the instrument.
Chapter 6: Bibliography


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Figure A-1: ATI Mini45 Force/Torque Transducer
Appendix B: Torque Profiles of Single Layer Foam Media

Figure B-1: Single Layer SOFT Foam Torque Profile (Trial 04)

Figure B-2: Single Layer SOFT Foam Torque Profile (Trial 05)
Figure B-3: Single Layer SOFT Foam Torque Profile (Trial 06)

Figure B-4: Single Layer SOFT Foam Torque Profile (Trial 07)
Figure B-5: Single Layer SOFT Foam Torque Profile (Trial 08)

Figure B-6: Single Layer SOFT Foam Torque Profile (Trial 09)
Figure B-7: Single Layer SOFT Foam Torque Profile (Trial 10)

Figure B-8: Single Layer SOFT Foam Torque Profile (Trial 11)
Figure B-9: Single Layer SOFT Foam Torque Profile (Trial 12)

Figure B-10: Single Layer HARD Foam Torque Profile (Trial 01)
Figure B-11: Single Layer HARD Foam Torque Profile (Trial 02)

Figure B-12: Single Layer HARD Foam Torque Profile (Trial 03)
Figure B-13: Single Layer HARD Foam Torque Profile (Trial 04)

Figure B-14: Single Layer HARD Foam Torque Profile (Trial 05)
Figure B-15: Single Layer HARD Foam Torque Profile (Trial 06)

Figure B-16: Single Layer HARD Foam Torque Profile (Trial 07)
Figure B-17: Single Layer HARD Foam Torque Profile (Trial 08)

Figure B-18: Single Layer HARD Foam Torque Profile (Trial 09)
Appendix C: Penetration through Foam Medium

* Time Stamp is included in the file name of the image, i.e. Frame_212_TS_17-43-6-421.bmp – corresponding to 5:43:06.421pm

** Images included for completeness
Appendix D: Torque Profiles of Double Layer Foam Media

Figure D-1: Double Layer SOFT→SOFT Foam Torque Profile (Trial 01)

Figure D-2: Double Layer SOFT→SOFT Foam Torque Profile (Trial 02)
Figure D-3: Double Layer HARD→HARD Foam Torque Profile (Trial 01)

Figure D-4: Double Layer HARD→HARD Foam Torque Profile (Trial 02)
Figure D-5: Double Layer HARD ➔ SOFT Foam Torque Profile (Trial 02)

Figure D-6: Double Layer HARD ➔ SOFT Foam Torque Profile (Trial 03)
Figure D-7: Double Layer HARD→SOFT Foam Torque Profile (Trial 04)

Figure D-8: Double Layer HARD→SOFT Foam Torque Profile (Trial 05)
Figure D-9: Double Layer HARD→SOFT Foam Torque Profile (Trial 06)

Figure D-10: Double Layer HARD→SOFT Foam Torque Profile (Trial 07)
Figure D-11: Double Layer HARD$\rightarrow$SOFT Foam Torque Profile (Trial 08)

Figure D-12: Double Layer HARD$\rightarrow$SOFT Foam Torque Profile (Trial 09)
Figure D-13: Double Layer HARD→SOFT Foam Torque Profile (Trial 10)

Figure D-14: Double Layer HARD→SOFT Foam Torque Profile (Trial 11)
Figure D-15: Double Layer HARD→SOFT Foam Torque Profile (Trial 12)

Figure D-16: Double Layer HARD→SOFT Foam Torque Profile (Trial 13)
Figure D-17: Double Layer HARD→SOFT Foam Torque Profile (Trial 14)

Figure D-18: Double Layer HARD→SOFT Foam Torque Profile (Trial 15)
Figure D-19: Double Layer SOFT→HARD Foam Torque Profile (Trial 01)

Figure D-20: Double Layer SOFT→HARD Foam Torque Profile (Trial 02)
Figure D-21: Double Layer SOFT→HARD Foam Torque Profile (Trial 03)

Figure D-22: Double Layer SOFT→HARD Foam Torque Profile (Trial 04)
Figure D-23: Double Layer SOFT→HARD Foam Torque Profile (Trial 05)

Figure D-24: Double Layer SOFT→HARD Foam Torque Profile (Trial 06)
Figure D-25: Double Layer SOFT→HARD Foam Torque Profile (Trial 07)

Figure D-26: Double Layer HARD→SOFT Foam Torque Profile - TVC Lubricated (Trial 01)
Figure D-27: Double Layer HARD→SOFT Foam Torque Profile - TVC Lubricated (Trial 02)

Figure D-28: Double Layer SOFT→HARD Foam Torque Profile - TVC Lubricated (Trial 01)
Figure D-29: Double Layer SOFT→HARD Foam Torque Profile - TVC Lubricated (Trial 02)
Appendix E: Torque Profiles of Bovine Muscle Tissue Media

Figure E-1: Bovine Muscle Tissue Torque Profile (Trial 01)

Figure E-2: Bovine Muscle Tissue Torque Profile (Trial 02)
Figure E-3: Bovine Muscle Tissue Torque Profile (Trial 03)

Figure E-4: Bovine Muscle Tissue Torque Profile (Trial 04)
Figure E-5: Bovine Muscle Tissue Torque Profile (Trial 05)