TORQUE MEASUREMENT DURING BODY CAVITY ENTRY USING A THREADED VISUAL CANNULA

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Abstract- Port creation is one of the most common complications associated in endoscopic procedures. The focus of our study was to establish a reproducible method of determining the torque profile generated during body cavity entry using a Threaded Visual Cannula (TVC). A TVC was evaluated on 32 samples of foam media. A torque profile was generated by measuring the torque required to cannulate the foam media. Penetration of the media was captured by a digital imaging system. The magnitude of torque to required cannulate the foam media was dictated by the amount of friction present between the foam and the external threads of the TVC. Furthermore, the magnitude of friction was dictated by the material properties of the individual media. A reproducible method of measuring entry torque during body cavity entry was established.

Index terms: Torque measurement, laparoscopic surgery, port creation
I. INTRODUCTION

Minimally Invasive Surgery (MIS) has transformed surgical care in all disciplines and is now the preferred method for many diagnostic and operative procedures. By replacing conventional open surgery with methods that require minuscule incisions to operate (known as conduits or ports; 10-20 mm in diameter), MIS has diminished postoperative discomfort, significantly shortened patient recovery time by reducing surgical access trauma, and decreased surgical costs [1].

Endoscopy has become one of the most widespread operative approaches in North America. More than 2 million laparoscopies (endoscopy of the abdomen) are performed annually and as a result, more than 6 million ports are created every year in the United States alone [2]. It is anticipated that with the advent of robotic surgery and Natural Orifice Transluminal Endoscopic Surgery (NOTES), these numbers are set to increase further in the near future. According to Medical Data International, volume is estimated to rise at a compounded annual growth rate of 4.8% [3].

In order to access body cavities, operators require knowledge of anatomy, an access method, and an entry instrument to navigate towards the desired body area. Surgeons have used conventional push-through body cavity entry instruments that contain a central pointed or sharp obturator (trocar), sheathed inside a hollow conduit (cannula).

Despite significant advances in endoscopy and patient safety, major operative complications with serious consequences continue to occur at about 1 per 1000 procedures [4,5]. Large multi-centre studies and meta-analyses have shown that over 50% of bowel (0.4 per 1000) and major vessel (0.2 per 1000) injuries occur at primary peritoneal entry where 80% are attributed directly to primary trocar and cannula use [6]. Indeed, of all devices used in laparoscopic surgeries, trocars account for a largest number of injuries. Furthermore, more than two thirds of these injuries are not detected until the operation has ended [7].

In a recent report on laparoscopic surgery, the US Food and Drug Administration stated that in order to address patients’ expectations and societal safety requirements surgeons must be well versed in different laparoscopic access methods and instruments [8]. The US Institute of Medicine Committee report on Patient safety indicated more than 90% of unintended medical accidents are related to human error [9]. Accordingly, surgeons and the associated industry appreciate the need for less hazardous endoscopic access options with significant redundancies to
avert mishaps, especially in high-risk situations. Additionally, systems that can anticipate, avoid, or at least recognize inadvertent injury are preferred, where error recovery is possible, before permanent patient harm occurs [10].

Due to the predominant use of sharp-ended and non-visual trocars in MIS, the most severe complications associated with laparoscopic surgery arise during primary port creation [11,12]. Several port-creation Performance Shaping Factors (PSFs) are known to predispose inadvertent entry injury during primary peritoneal port creation when using the push-through conventional trocar and cannula system. Elimination of these accident-prone PSFs, can render port creation less hazardous, if not safer.

Removal of the central trocar; application of radial, as opposed to linear, penetration force; conversion of this blind step to visual; rendering the process incremental as opposed to sudden; and, diminishing the overall amount of force recruited to create ports, result in a more redundant and less hazardous process [13,14].

Blunt access devices, such as a Threaded Visual Cannula (TVC, i.e., EndoTIP) do not contain a cutting edge [15,16]. Port creation with a TVC is achieved by incising the skin at the access site and loosening the subcutaneous fatty tissue. This allows easy engagement of the TVC’s external threads into the anterior abdominal wall fascia. As the TVC is rotated into a body cavity, the tissues it encounters are separated radially, and not transected/cut. This process is performed under direct visual guidance as the hollow sheathe of the TVC can house a laparoscope and camera during port creation.

Employing a TVC to achieve peritoneal port creation addresses the aforementioned PSFs, but an explicit process to monitor force recruitment remains. To date, there exist limited studies measuring the magnitude of force and torque applied to an access device during body cavity entry. As a result, teaching safe application of laparoscopic ports in general remains arbitrary and application of excessive force during port creation leads to a significant number of trocar-related injuries. Reports from the US FDA describe 1353 serious injuries and 31 deaths over 5.5 years as a result of sharp-ended trocar use in MIS [17]. In an attempt to better understand this relationship, Passeroti et al. [11] describe an apparatus capable of measuring linear force during body cavity entry using a sharp-ended access device.
II. METHODOLOGY

This paper aims to expand on the current force-measurement methodologies to include torque measurement during body cavity entry using a Threaded Visual Cannula (TVC). By establishing a reproducible apparatus and algorithm to quantify entry force and torque in port creation, an upper bound of allowable force/torque can be established to improve patient safety, and would aid in determining the magnitude of torque required to cannulate the different layers of an anterior abdominal wall [18, 19]. Furthermore, this data can be used to provide an objective teaching platform for novice surgeons and provide the framework for advanced just-in-time training capabilities in remote expert-guided critical body cavity access in under-supported or hostile environments [20].

a. Experimental set-up

As noted above, real-time sensory feedback is crucial during robotic surgery and rehabilitation [21, 22, 23]. A reproducible apparatus and algorithm for capturing the magnitude of forces and torques experienced by a TVC during cannulation of foam media was established in our lab. A custom test apparatus was constructed for this study to insert the TVC into the foam media at constant linear and angular speeds while measuring the forces in all three Cartesian axes and the torques about those axes \( (F_x, F_y, F_z, T_x, T_y, T_z) \), Figure 1. The foam medium was used as a substitute for biological tissue to insure reproducibility of the system, while remaining consistent with the inanimate media used in current laparoscopic training methods [24]. The TVC was tested on 32 samples of foam media. The foam samples consisted of two types with different material properties (Table 1).

When accessing the peritoneal cavity during endoscopic surgery, a zero degree laparoscope is sheathed into the TVC and locked 10 mm short of the cannula’s distal end. It is held perpendicular to the patient’s supine abdomen with the surgeon’s non-dominant hand. The TVC is rotated clockwise with the dominant hand while keeping the cannula fixed in the horizontal plane to avoid linear force. As the device is rotated, radial force is created and a cascade of anterior abdominal wall tissue layers are engaged by the TVC’s distal tip, which climb up along the cannula’s outer thread until the desired body cavity is reached. In order to simulate this
behaviour while simplifying the apparatus, in our experiments the foam media was kept fixed while the TVC translated linearly by a magnitude equal to its feed rate during rotation.

![Experimental test apparatus](image)

**Figure 1.** Experimental test apparatus

<table>
<thead>
<tr>
<th>Classification</th>
<th>Hard</th>
<th>Soft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grade</strong></td>
<td>22135RBR</td>
<td>1585RBR-AM</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>2.12 lb/ft³ (333.02 N/m³)</td>
<td>1.37 lb/ft³ (215.21 N/m³)</td>
</tr>
<tr>
<td><strong>IFD (25%)</strong></td>
<td>105.02 lb/in² (0.7241 N/mm²)</td>
<td>83.29 lb/in² (0.5743 N/mm²)</td>
</tr>
<tr>
<td><strong>Surface Area</strong></td>
<td>1 ft² (0.0929 m²)</td>
<td>1 ft² (0.0929 m²)</td>
</tr>
<tr>
<td><strong>Thickness (nominal)</strong></td>
<td>t₁ = 0.5” (12.7 mm)</td>
<td>t₂ = 0.354” (9.0 mm)</td>
</tr>
</tbody>
</table>

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

An Epson E2L853S-UL SCARA robot was used to drive the TVC at an angular speed of \( \omega_z = 8 \) rpm and a linear speed of \( v_z = 59.68 \) mm/min (feedrate, \( FR_z = 7.46 \) mm/rev) to ensure a constant rate of entry. 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.

An ATI Mini45 force/torque transducer coupled with an ATI Data Acquisition (DAQ) interface was used to measure forces and torques as a function of time. The transducer was calibrated to SI-145-5 specification, which gives an operating range of 0 to 5 N-m and a resolution of 1/1504 N-m in the z-direction. The force/torque transducer and the TVC were mounted uniaxially with the robot end-effector in the vertical –z direction to ensure accurate torque data. In order to accommodate the varying thicknesses of the media used, the device height could be varied. Penetration through the foam media by the tip of the TVC was observed by a camera mounted underneath the base of the apparatus.

b. Procedure

To quantify the amount of torque required to penetrate the media, while maintaining accuracy of the recorded data, several test conditions were investigated. In all test conditions, the TVC completed two full rotations (720°) into the test media.

In the first test condition, single layer hard \((n = 9)\) and soft \((n = 9)\) foam samples were tested. The torque generated during cannulation of the media was captured by the ATI force/torque transducer and relayed to an adjacent PC for recording. The observed means and 95% confidence intervals for the magnitude of torque required to cannulate the hard and soft foam samples were then calculated.

Once the torque profile of the individual foam types was determined, the two types of single layer foam were joined using SAR 505 super strength all purpose aerosol Adhesive to investigate the resulting torque profiles observed during the transition from hard to soft foam \((\text{hard} \rightarrow \text{soft}, n = 14)\) in a double-layer foam medium. More specifically, if an instantaneous shift in the magnitude of torque could be observed at the transition point between the different foam types.

III. EXPERIMENTAL RESULTS

Both aforementioned foam types (hard and soft) were cannulated by the TVC to determine their respective torque profiles. Furthermore, a double-layer foam medium (transition from hard \(\rightarrow\) soft
foam) was tested to determine whether an instantaneous change in torque could be detected during the transition from hard to soft foam. One can note that due to the TVCs inherent design requirement of only radial force to cannulate tissue, only torque profiles are shown in the figures below (linear force profiles are omitted). Additionally, due to the design of the TVC, the direction of rotation required to traverse the media resulted in a negative value of torque. In order to observe the trend in the generated torque profiles, a 5th order polynomial regression was fitted to the data recorded across all trials.

a. Single-Layer Foam

In order to identify the instant the TVC traverses each layer in a multi-layer medium, the torque profiles of the individual layer types were first determined independently. The individual torque profiles for all trials, as well as average regressions were generated for both the soft and hard media, as shown in Figures 2 and 3, respectively.

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 curve, establishing the sample number where the extremum occurs (when the 1st 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 given below.

Given:
\[ y = -3 \times 10^{-11} x^5 + 8 \times 10^{-9} x^4 - 6 \times 10^{-7} x^3 + 3 \times 10^{-5} x^2 - 2.9 \times 10^{-3} x + 6.2 \times 10^{-3}, \quad (1) \]

the 1st Derivative:
\[ dy/dx = -1.5 \times 10^{-10} x^4 + 3.2 \times 10^{-8} x^3 - 1.8 \times 10^{-6} x^2 + 6 \times 10^{-4} x - 2.9 \times 10^{-3}, \quad (2) \]

the extremum occurs at sample: \( x = \{71.98, 141.84\} \). 71.98 was chosen, as it falls within the range of the collection. Therefore, by substituting this value back into Equation (1), the maximum magnitude of output torque is calculated as: \( y_{max} = -0.1141 \text{N-m} \).

Table 2 summarizes 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.
b. Double-Layer Foam

For the double-layer (hard→soft) foam media the individual regressions from all trials, as well as an average regression were also generated (Figure 4).

Table 2. Single-layer-foam torque profile steady-state values

<table>
<thead>
<tr>
<th>Foam Type</th>
<th>Soft</th>
<th>Hard</th>
</tr>
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<tbody>
<tr>
<td>Observed Mean Steady-State</td>
<td>-0.0819 N-m</td>
<td>-0.1038 N-m</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.0094 N-m</td>
<td>0.0097 N-m</td>
</tr>
<tr>
<td>Upper Bound (95% confidence)</td>
<td>-0.0880 N-m</td>
<td>-0.1102 N-m</td>
</tr>
<tr>
<td>Lower Bound (95% confidence)</td>
<td>-0.0758 N-m</td>
<td>-0.0975 N-m</td>
</tr>
</tbody>
</table>

Figure 2. Single-layer soft-foam torque profiles
Figure 3. Single-layer hard-foam torque profiles

Figure 4. Double-layer hard→soft foam torque profiles
IV. DISCUSSION

In order to better understand the amount of force and torque applied to an access device during port creation, a reproducible method and algorithm to capture these variables was established. By doing so, the probability of applying excess force and overshoot (torque in case of the TVC) can be mitigated, improving patient safety and reducing human error. Furthermore, by quantifying these variables, an objective teaching platform can be established for novice surgeons while providing the framework for eventual automated body cavity entry and remote port creation in endoscopy.

Port creation can be achieved through the use of a wide variety of access devices. In this study, a TVC was used to cannulate two different single-layer foam media (hard and soft) as well as a double-layer medium containing the two foam types (transition from hard→soft). The torque experienced by the TVC during cannulation was recorded and a torque profile was generated for each experimental trial. The single-layer test condition was used to determine the average torque required to cannulate the different foam types, while the double-layer medium was used to investigate whether an instantaneous change in torque can be observed as the tip of the TVC transitions from the hard to the soft foam. Establishing a functional platform for force/torque measurement at the interface between a tool (i.e., a TVC) and tissue can provide a basis for intraoperative force-feedback.

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 Number 60. 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 2 and Figure 3). Furthermore, after penetration through the medium, the torque profile shifted away from the steady-state value and approached, but did not reach, zero.

The rate at which torque increased during the first rotation of cannulation was non-constant. The magnitude of torque decayed over time until it settled upon a steady-state value specific to the medium tested. This result suggests that by the end of the first rotation equilibrium between torque growth and torque decay is achieved. The only force contributing to the change in torque observed at the tool/foam interface is friction. Therefore, the torque profiles generated during the single-layer foam collections suggest that the magnitude of friction between the threads of the
TVC and the foam decay over time and settle to a steady-state value by the end of the TVC’s first rotation.

The above 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 suggests that as the thread of the TVC continually passes over the same portion of the foam sample, the magnitude of friction decreases over time. This finding implies that the final steady-state value achieved during cannulation of a specific material is the factor that defines its properties, as each material will exhibit a unique equilibrium between torque growth and decay dictated by its coefficient of friction. In the second test condition, double-layer foam media exhibiting a transition from hard→soft foam were tested. The generated torque profile (Figure 4) showed that the magnitude of torque first settled upon the steady-state value dictated by the hard foam layer, then shifted towards and settled upon another steady-state value. 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 a new steady-state value. This result was promising as it indicates a predictable trend in the torque profile as the TVC traverses 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 particularly valuable during body cavity entry if it can provide instantaneous indication that the tool tip has traversed into a different body layer, to reinforce the visual feedback off the monitor.

If the torque profiles in Figure 4 were to be investigated in real-time during the collection, no clear indication would be present that the transition between foam types occurred at Sample Number 47. Namely, a transition in trend is difficult to observe unless the entire signal is available. This finding can be attributed to the inherent cannula design as the entire length of the cannula is threaded, and 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. 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 condition, the rate of torque growth and decay would differ as the threads of the TVC are engaged in two different In our experiments, 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 average torque profile of the single layer hard foam media, an average rate of torque decay after the exit point was established (Figure 5). The average torque decay signal was subtracted from the torque profile (starting at the transition point) of the hard→soft foam media. The modified (upper) torque profile (in red) is shown in Figure 5. 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 −0.1342 N-m to −0.110 N-m, which more accurately depicts the characteristics of the soft foam, yet 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 (i.e., by Sample 60), the magnitude of output torque observed in the single-layer foam conditions did not return to zero during the second rotation (first rotation after penetration). Just after the transition into the soft foam, the magnitude of torque in the modified profile was −0.0275 N-m. Shifting the modified torque profile towards zero by this amount would result in a steady-state torque value in the soft layer of (−0.110 N-m + 0.0275 N-m =) −0.0825 N-m, which lies within the bounds of the 95% confidence interval for the single layer soft foam medium.

The notion of steady-state torque has justified the results observed during this study: the secondary objective of instantaneous detection of the change in torque experienced by the TVC during port creation was unsuccessful. The results of the hard→soft foam media showed that given an entire torque profile, fitting a 5th order polynomial regression could suggest when the
transition between different layers of material occurs. However, this was not apparent in all trials collected as can be seen in the averaged 5\textsuperscript{th} 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, Figure 6.

![Average Decay (H)](image)

**Figure 5.** Average torque decay after exit in single-layer hard-foam media materials

![Torque Profile](image)

**Figure 6.** Double-layer hard→soft foam torque profile modified to include average rate of torque decay in hard foam (Trial 12)
V. CONCLUSIONS

The primary objective of this study was to create a reproducible method of capturing the force and torque experienced by a TVC during body cavity entry. Additionally, this study aimed to investigate the feasibility of detecting instantaneous changes in torque as the TVC traversed between materials of different properties.

The primary objective of this study was achieved, as a reproducible method for force/torque measurement is established. The results of this study show that 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 external thread of the TVC (and to a lesser effect, the outer surface of the cannula) 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.

Additionally, it appears that presence of a continuous/running thread along the entire length of the TVC, renders instantaneous detection of a change in torque arising from the transition between two different media difficult to capture, as 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.

REFERENCES


