

# Force Measurement Methods for Intelligent Box-Trainer System – Artificial Bowel Suturing Procedure

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*Abstract: During laparoscopic surgery, surgeons carry out surgical procedures with the assistance of a video camera and several surgical instruments. A critical skill for a successful operation is to develop a sense of the applied forces on the tissue using laparoscopic tools. A novel technique to measure the forces applied by the needle driver during artificial bowel suturing tests is proposed in this paper using strain gauges (SGs). A method to aggregate the responses of the SGs on a cylindrical shaft is also proposed. Another innovation involved in this study is a force feedback display system that utilizes Augmented Reality (AR) glasses that provide a real-time visual representation of the force to the surgeon without obscuring the field of view. An electromechanical calibration system to calibrate the force measurements for the needle driver and acquire force data using LabVIEW is also presented. This study is part of a collaborative research partnership between the Department of Electrical and Computer Engineering and the Department of Surgery of the Homer Stryker M.D. School of Medicine, at WMU.*

*Keywords: Laparoscopic Surgery Skill Test; Bowel Suturing Force Measurement; Needle Driver Force Measurements Using Strain Gauges; AR Glasses for Real Time Feedback*

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# 1 Introduction

In laparoscopic surgery, which is also referred to as minimally invasive surgery (MIS), surgeons carry out surgical procedures with the assistance of a video camera and several surgical instruments. Laparoscopic surgeons should possess excellent eye-hand coordination capabilities, strong cognitive knowledge, case and problem management, and manual dexterity skills. Such skills can be acquired through simulation using a basic, low-fidelity setup, such as the surgical box-trainer. General surgeons must pass a set of tests on a Fundamentals of Laparoscopic Surgery (FLS) Trainer device [1], [2], [3].

Pivotal skill for a successful operation is to develop a sense of the applied forces on the tissue using the long, mostly metal laparoscopic tools, with the goal being to prevent tissue damage. A novel technique to measure the forces applied by the needle driver during artificial bowel suturing tests is proposed in this paper by using strain gauges (SGs). A method to aggregate the responses of the SGs on a cylindrical shaft is also proposed. Another innovation involved in this study is a force feedback display system that utilizes Augmented Reality (AR) glasses that provide a real-time visual representation of the force to the surgeon without distracting the field of view. An electromechanical calibration system to calibrate the force measurements for the needle driver and acquire force data using LabVIEW is also presented.

Simulation results presented in this paper indicate that accurate force measurement can be achieved. The implemented prototype of the proposed enhancements to the Intelligent Box-Trainer System (IBTS) [16] has also demonstrated that the force measurements are precise, the transfer function is primarily linear, and the measurements can be replicated consistently. In addition, the implementation of the AR glasses has shown that the approach is responsive and capable of handling image frame rates high enough to create a smooth display for the surgeon's eye.

The objectives of this study include proposing an applied force measurement and real-time feedback system for surgeons during suturing exercises and taking steps towards an objective skill assessment system using the IBTS. This paper reports on the results of a new collaborative research projects between the Department of Electrical and Computer Engineering and the Department of Surgery of the Homer Stryker M.D. School of Medicine, at WMU.

The paper is organized as follows: Section 2 reviews related work in this research area. Section 3 presents the proposed force measurement methods. Implementation and experimental results are discussed in Section 4. Finally, conclusions and plans for further research are outlined in Section 5.

## 2 Related Work

A number of research papers have been published on measuring forces in a laparoscopic or robotic surgery environment.

Wang et al. [4] reviewed force sensing techniques in robotic-assisted Laparoscopic Surgery (LS). The advantages and disadvantages of placing a force sensor on four different locations of a surgical instrument were discussed as follows: on the tip, on the shaft, on the abdominal wall, and the driving unit of the surgical instrument. In addition, the paper presented various force-sensing methodologies, including capacitor-based force detection, resistor-based force detection, current-based force detection, pressure-based force detection, and optics-based force detection. However, no new force-sensing techniques were proposed.

Witte et al. [5] suggested an E-type buckle strain gauge transducer for measuring dynamic forces applied on surgical sutures. The intention was to evaluate a force transducer to be used for MILS systems. However, the study was limited to evaluating the transducer model's linearity and error quantifications during cyclic loading, *in vitro*, and *ex vivo* conditions.

In the paper by Ebin et al. [6], strain gauges were attached to the gripper of a forceps to measure the grasping forces. A windowed type forceps was used (where there is a hole in the grasping surface); therefore, the grasping point location was assumed to be at the geometric average of the gripper surface. A cable was needed to connect the strain gauges to the electrical components of a grasping force-sensing unit that sent the force data to a PC through a wireless connectivity module. Different loads in the range of 0 g to 500 g were applied to the grasping point to calibrate the proposed force sensor. The proposed sensor showed a good linear relation between the estimated force and the applied force in the specified load range.

Yu et al. [7] proposed an empirical model based on Artificial Neural Network (ANN) methodology to develop a model that estimated tensile forces during renal suturing. The idea was to reduce the risk of damaging the soft tissue during suturing by estimating tensile force limits beyond which the soft tissue starts tearing. However, the model was developed using empirical data under specific conditions. Therefore, the model estimations could be applicable only under the same suturing conditions.

Horeman et al. [8] proposed a six degree of freedom (6D) force platform for laparoscopic training purposes. An artificial skin was placed on the force sensor platform inside a laparoscopic box trainer to provide a training tool for soft tissue handling during laparoscopic procedures. A monitor was used to provide feedback on the forces and torques applied to the artificial skin tissue during the training session. However, the approach required the trainee's attention to be split between the actions inside the box trainer and the force monitor. It could be challenging to

do that for complex tasks. It should also be noted that the proposed technique was limited for training purposes when the workpiece (the artificial skin) could be placed on the surface of the force sensor.

Kitagawa *et al.* [9] proposed using auditory feedback or visual feedback to substitute for direct or haptic force feedback during suture manipulation in robotic surgery. This provided a quantitative representation of the suture tying force, which could be critical for soft tissue manipulation. The objective was to avoid tissue damage due to excessive force or applying inadequate (too weak) force in suture tying.

Takayasu *et al.* [10] conducted an investigation study based on experiments to observe force patterns during laparoscopic knot tying. A 6D force platform was used to measure forces and torques in three dimensions as a function of time. At the same time, the knot tying procedure was conducted by surgeons divided into three groups according to their skill level as novices, intermediates, and experts. The study focused on force direction and the time required for knot tying and the force magnitude. The study showed that the force direction, magnitude and the execution time of knot tying were functions of surgeons' skill level. The study could be helpful to understand the elements of force patterns applied by an expert surgeon.

Horeman *et al.* [11] presented the design of two force sensors to measure the tension force in the thread inside a closed incision and another one for measuring the pulling force to close the incision. These two sensors could be used for both training and practical surgery purposes. The two sensors were designed to be easily applied on the surgical thread. A third force sensor was present with a LED to indicate if the tension force exceeded a predefined force threshold. However, the paper did not show how to define a safe force threshold for different soft tissues or how a surgeon could monitor the force variations during a practical surgery.

Stephan *et al.* [12] proposed a prototype design of a gripper for minimally invasive surgery (MIS) systems. The gripper is equipped with strain gauges to provide force measurement in XYZ directions, in addition to the gripping forces by the jaws. The sensor could measure forces up to 10N with a 0.1N resolution. The gripper mechanical and electronic design details were also presented, along with a finite element (FE) analysis of the gripper force. However, the paper focused solely on the gripper design and did not address how the force feedback would improve the outcome of a surgical procedure.

Jackson *et al.* [13] developed a lumped mathematical equation that modeled needle interaction forces with soft tissue during automated suturing by assuming a rigid suturing needle with a planner motion. An experimental suture apparatus was used to gather the required data to evaluate the model parameters. The model simulation results showed a good agreement with experimental data. However, it should be noted that the model estimation can be valid just for the specified needle type, tissue properties, and motion geometry.

Choi et al. [14] proposed using an ANN model to estimate the pinch force as a function of surface electromyography (SEMG) signals. The required input data for the ANN model were gathered from three electrodes located at specified locations based on anatomical considerations. In contrast, the output data were collected from a force sensor utilized to measure pinch forces.

The available literature covers various approaches to sense applied forces during suturing exercises and provides some feedback. However, the methods and implementations using strain gauges, as presented in this paper, seem more accurate than others. A real-time, non-obstructive, visual feedback using AR glasses is also proposed to help surgeons in developing consistent suturing skills.

### **3 Proposed Force Measurement Methods**

One of the main objectives in this study, while researching advanced methods for force skill assessment using the IBTS, is to preserve the original design of the laparoscopic hand tools (LHTs), namely the needle driver. Altering the laparoscopic hand tools' look and feel may create different training experiences from real-world clinical experiences, leading to less effective training and deviations from the main objectives of the IBTS.

The second objective is to keep the cost as low as possible by using the same laparoscopic hand tools available in the Western Michigan University School of Medicine Surgery Simulation Center (Sim Center) and in other medical training centers, by using cost-effective sensors, off-the-shelf ones whenever possible, and by designing simple, modular components to simplify the installation and reduce downtime during maintenance.

The third objective is to provide direct high-fidelity feedback and help in self-assessment for the surgeon.

The final objective is that the force measurement system needs to accommodate as many different types of tissues as possible.

#### **3.1 Measuring the Tension Forces Applied on an Artificial Bowel Model**

Having investigated different approaches and closely monitored the bowel suturing process, a new approach to measure the forces applied by the suture thread during a laparoscopic operation is proposed in this study.

The laparoscopic needle driver hand tool of interest comprises a stainless-steel cylindrical shaft of 300 mm in length and 5 mm in diameter, as shown in Fig. 1.

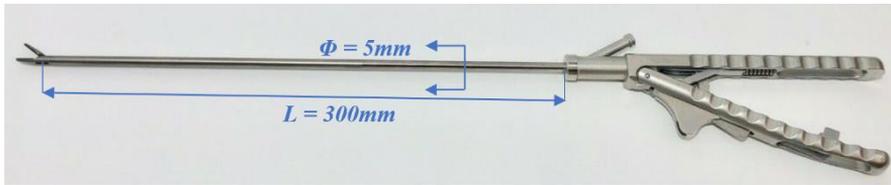


Figure 1  
Typical LS Needle Driver

As the surgeon performs the suturing task, the needle driver shaft slightly bends in different directions. However, this laparoscopic tool always regains its original shape after the surgeon has released the suture or removed the tension from the thread.

The needle driver's behavior was simulated using Matlab and Simulink. Two Matlab Toolboxes were used, namely Simscape and Simscape Multibody, to model the mechanics, the material, and the dynamics of the needle driver. Some of the steps of the development and the simulation execution via Matlab Simulink environment are illustrated in Figs. 2 and 3 (they were created by using Matlab Simscape).

Studying the behavior of the needle driver during the suturing task has led to the proposed method to design the force measurement system by using strain gauges (SGs) as force transducers.

As the needle driver shaft bends under the effect of the suture tension force, the shaft surface will experience two different types of strains: tension strain on the bent convex side and compression strain on the opposite concave side, as illustrated in Fig. 4 (it was created by using MS Visio). The convex surface will experience a tension strain, i.e., the change in length  $\Delta L$  will be positive. On the other side, the concave surface will experience a negative change in length.

The SG transducers can be bonded to the surface of the needle driver shaft to detect the strain on the stainless-steel surface and convert the strain, i.e., change in length, to change in the SG resistance. That resistance change will eventually be turned into a voltage change when the SG is placed into a Wheatstone Bridge circuit. The best location to attach the SG is where the maximum strain happens on the needle driver shaft. The needle driver can be modeled as a cantilever beam with a point load.

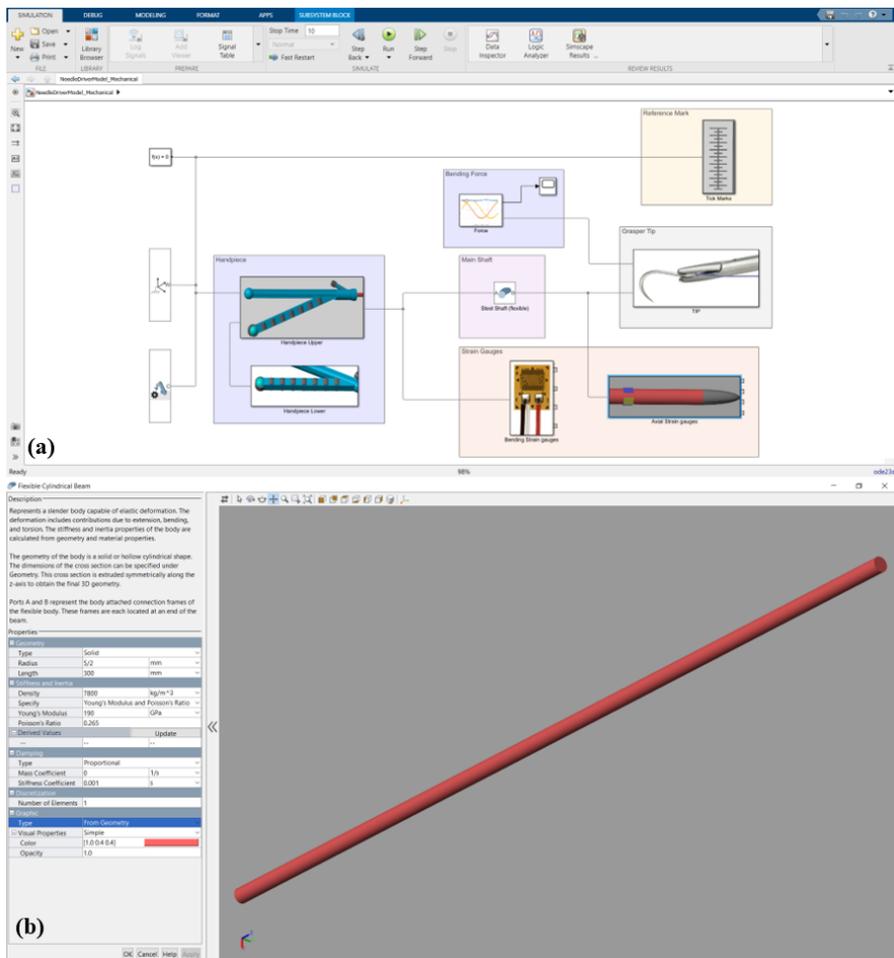


Figure 2

(a) Needle driver main components in Matlab Simscape Multibody. (b) Simscape Multibody model for the needle driver shaft showing the mechanical parameters, stiffness, and inertia with the shaft dimensions

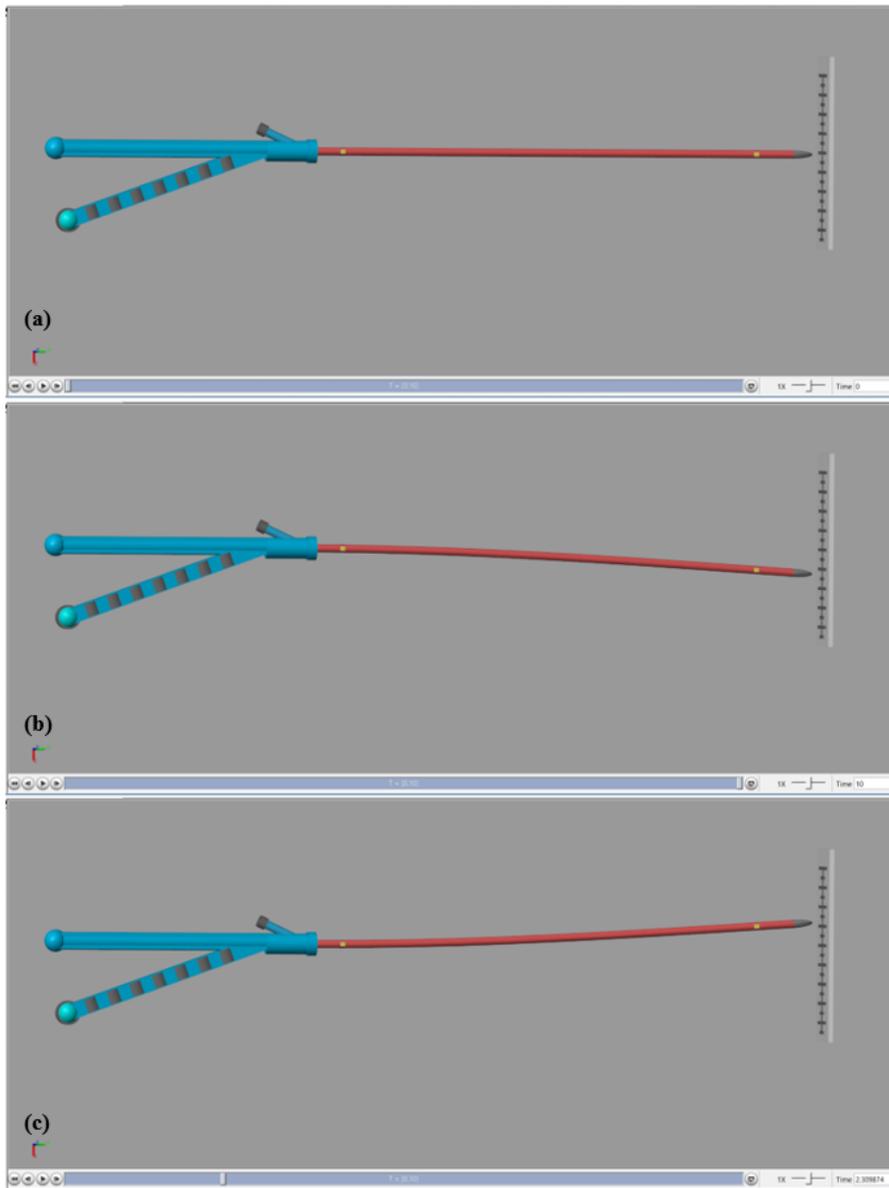


Figure 3

(a-c) Three screenshots from Simscape Multibody simulation showing the needle driver bending when a simulated tension force is applied on the tool tip

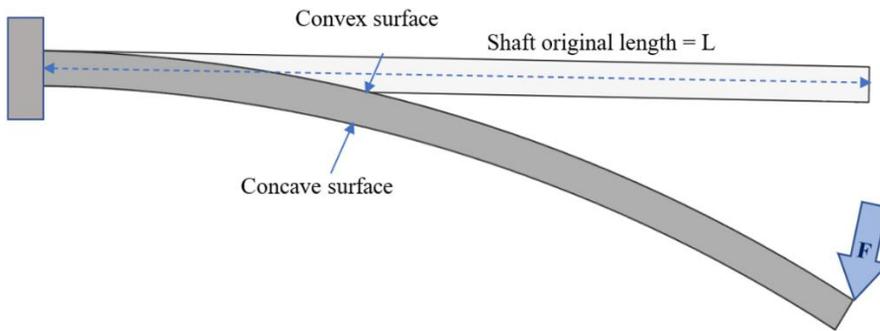


Figure 4  
Simulation of the needle driver shaft under suture force

The analysis of a cantilever beam shows that the maximum moment is present at the fixed side, i.e., where the beam meets the handle, as shown in Fig. 5 (it was created by using MS Visio). The maximum moment is given by Eq. (1) [15]:

$$M = F \cdot L ; [N \cdot m] \quad (1)$$

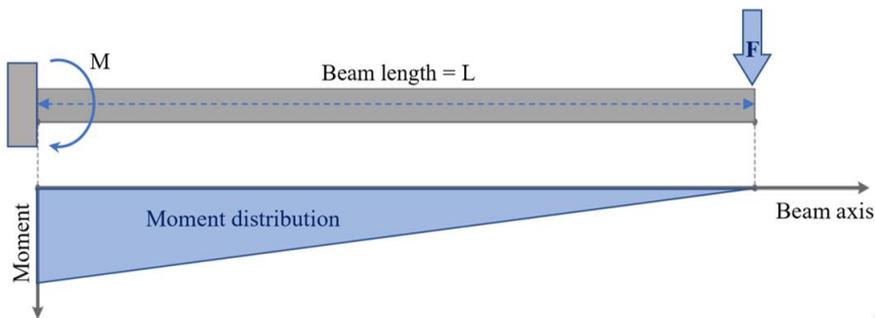


Figure 5  
At the tip of the beam the Moment = zero. The Maximum Moment caused by the force F is at the point where the beam is fixed,  $M = - F \cdot L$

### 3.2 Wheatstone Bridge Arithmetic SG

SGs of  $350\Omega$  resistance were chosen over the typical  $120\Omega$  ones for two reasons: first, to reduce the resistance impact of the length of the wires on the overall SG resistance. This way, the impact of the lead wires' resistance will be insignificant on the accuracy of the force measurements. The second reason is to reduce power consumption and therefore minimize the thermal effects on the SG measurements.

Using one SG in the Wheatstone Bridge circuit in various position results in a desired low current passing through the SG. However, the output voltage is given by Eq. (2) (as it is also illustrated in Figs. 6 and 7) is too low and might be susceptible to noise interference. Figs. 6 and 7 were created by using LTSpice).

$$E_o = V_1 - V_2 = V_s \cdot \frac{R_2 R_4 - R_1 R_3}{R_1 R_3 + R_1 R_4 + R_2 R_3 + R_2 R_4} ; [V] \tag{2}$$

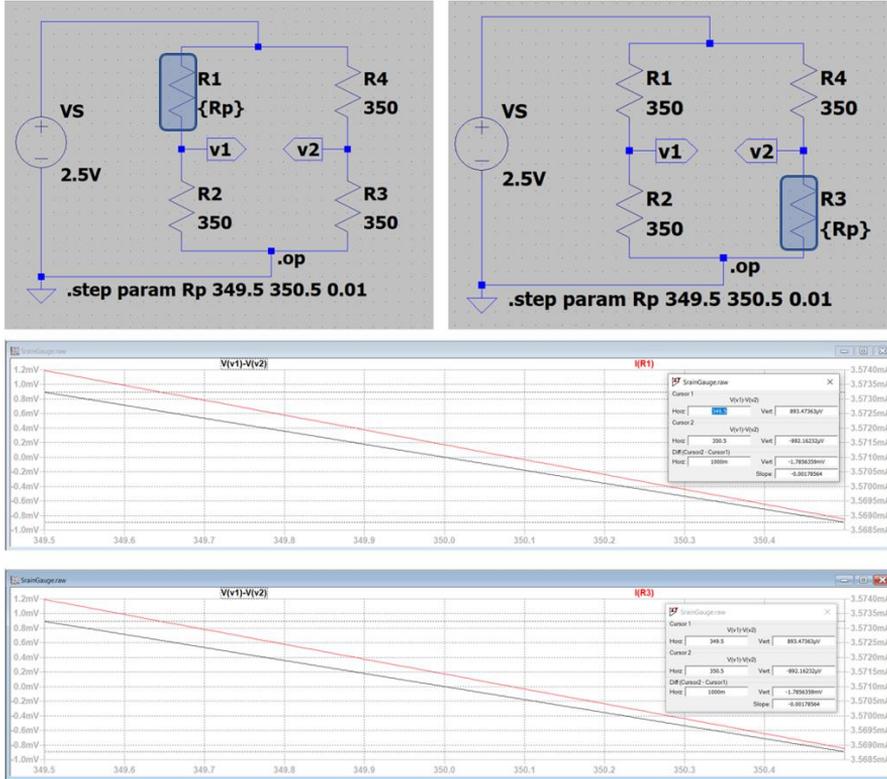


Figure 6

One SG is in location R<sub>1</sub> and the other in location R<sub>3</sub> in Wheatstone Bridge. In the plot, both SGs generate the same response, around ± 893 µV

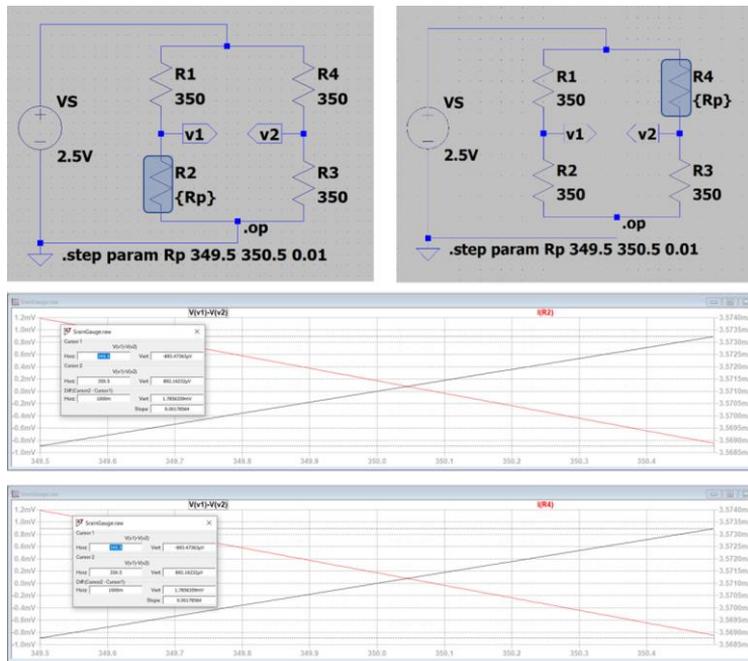


Figure 7

One SG is in location  $R_2$  and the other in location  $R_4$  in Wheatstone Bridge. Both SGs generate the same response, around  $\pm 893 \mu\text{V}$ , in opposite polarity to SGs in  $R_1$  and  $R_3$

### 3.3 Bonding Locations on the Needle Driver with Cylindrical Shaft

#### 3.3.1 Sensing of Bending Force Using the Quadrature Sum (QS)

The maximum moment occurs where the shaft meets the handle. Therefore, the logical place to install the SGs is as close as possible to the handle. For maximum sensitivity, they should be where the cylindrical shaft is attached to the handle, as illustrated in Fig. 8 (it was created by using MS Visio). In addition, to increase the sensitivity and double the output voltage, employing two SGs is proposed.

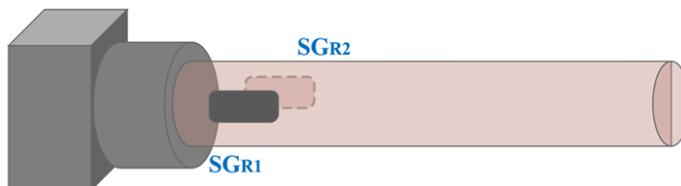


Figure 8

Section of the needle driver's shaft with two SGs bonded near the handle

As depicted in Fig. 9, forces on the needle driver are not confined to a single direction. They may be asserted from any direction depending on how the surgeon pulls the thread during suturing task. Fig. 9 was created by using Matlab SimScape).



Figure 9

Forces on the needle driver can be asserted in different directions

By applying a constant force  $F$  and rotating the needle driver 360 degrees, the response of SGR1R2 is sinusoidal, instead of a constant response, as depicted in Fig. 10 (it was created by using MS Visio).

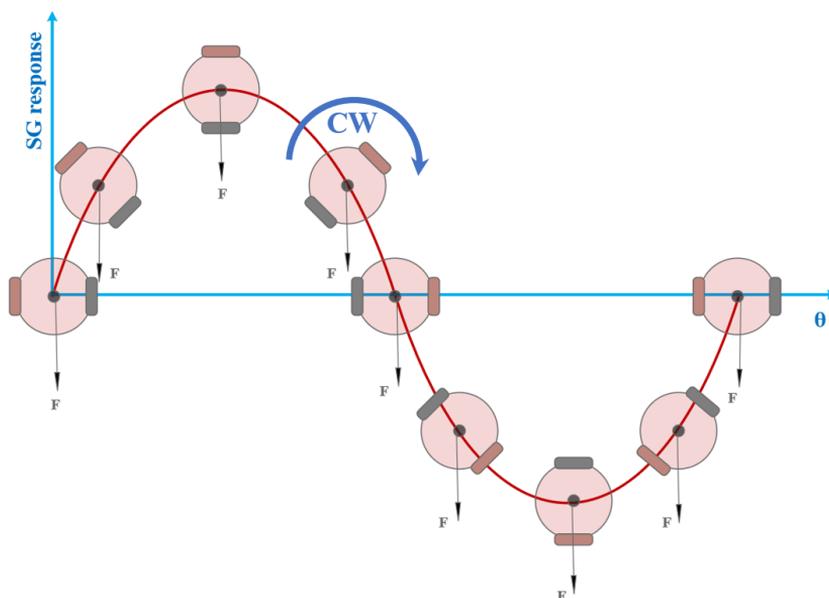


Figure 10

The two SGs' voltage response to a constant force  $F$  while it is rotating 360 degrees

To sense the suture force acting in different directions and overcome the challenge this scenario imposes, adding two more SGs to the configuration is proposed, as shown in Fig. 11 (it was created by using MS Visio).

The two SGs in the x-axis must be independent electrically from the two SGs on the y-axis. Therefore, the two SGs in the same axis must be in one Wheatstone Bridge. When the laparoscopic tool is bent due to the suture tension, one surface will be subjected to tensile strain, and the opposite side of the shaft will be in compressive strain.

The measured strain on the shaft is in the order of  $\mu\epsilon$  (micro strain), and the corresponding SG response is in the  $\mu\text{V}$  ( $10^{-6}$  V) range. Therefore, to obtain the maximum response and, hence, maximum sensitivity, the two SGs must be placed in two adjacent arms of the Wheatstone Bridge.

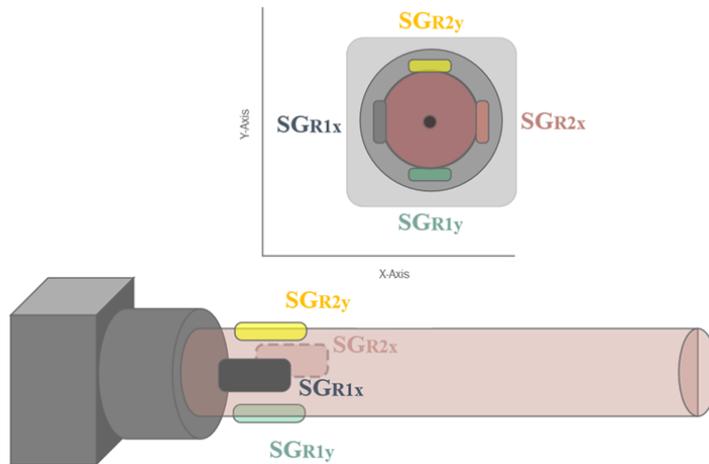


Figure 11

Front and isometric view of the proposed four strain gauges to sense the bending forces in all 360 degrees

The quadrature responses can be summarized by separating the two Wheatstone Bridge responses, as given in Eq. (3):

$$\overline{F_{xy}} = \overline{F_x} + \overline{F_y} \quad (3)$$

where  $F_x$  stands for the vector representation of the SGs in the Wheatstone Bridge's response in the x-direction and  $F_y$  stands for the vector representation in the y-direction.

By applying a perpendicular, 360-degree rotating force vector to the tip of the needle driver, the two quadrature SGs will have the response given by Eqs. (4) and (5).

$$F_x = A_x \cos \theta \quad (4)$$

$$F_y = A_y \sin \theta \quad (5)$$

The net response, which can be calculated by the quadrature sum, is given in Eq. (6):

$$F_{bending} = \sqrt{(A_x \cdot \cos \theta)^2 + (A_y \cdot \sin \theta)^2} \quad (6)$$

The magnitudes of  $A_x$  and  $A_y$  for a constant force are equal, therefore, the bending force  $F_{\text{bending}}$  is given by Eq. 7):

$$F_{\text{bending } 2\text{Pairs}} = A \cdot \sqrt{(\cos \theta)^2 + (\sin \theta)^2} = A \quad (7)$$

MATLAB Simscape Electrical simulations, as shown in Fig. 11, show the resulting bending forces. The resulting Quadrature Sum (QS) is a constant value.

By generalizing the mathematical approach to  $N$  SG pairs, the voltage response will be increased by a factor of  $\sqrt{\frac{N}{2}}$ , as given by Eq (8):

$$F_{Np} = \left\{ \begin{aligned} &(A_1 \sin(\theta))^2 + \left(A_2 \sin\left(\theta - \frac{\pi}{N}\right)\right)^2 + \left(A_3 \sin\left(\theta - \frac{2\pi}{N}\right)\right)^2 + \\ &\dots + \left(A_N \sin\left(\theta - \frac{(N-1)\pi}{N}\right)\right)^2 \end{aligned} \right\}^{1/2} \quad (8)$$

$$= \sqrt{\frac{N}{2}} \cdot A \quad \text{As}$$

As a numerical example: ten pairs of SGs will result in  $\sqrt{5} A$ , i.e., 2.236 times the amplitude of two pairs of SGs.

Increasing the number of SG pairs has benefits. For one, the magnitude of the output voltage will be increased. For two, the misalignment distortion effect on the output voltage will be reduced. The overall response will be smoother. However, the overall circuit complexity and cost will also increase.

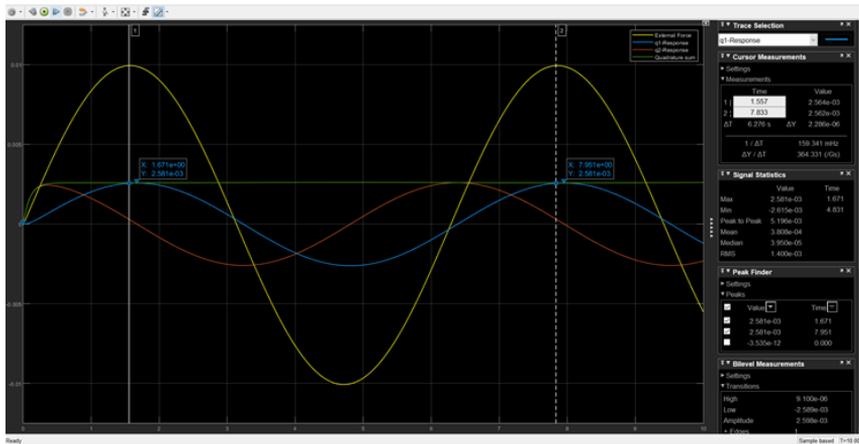


Figure 12

The yellow line represents a constant rotating force, the red line represents the x-quadrant response of the SGs and the blue line represents the y-quadrant response. The resulting Quadrature Sum is represented by the green line

### 3.3.2 Axial Force Sensing

In addition to the bending forces perpendicular to the needle driver, the suture force may be asserted in an arbitrary angle  $\beta$ , hence, there will be two force components in effect, an axial component along the cylindrical shaft and another normal force component perpendicular to the cylindrical shaft, as depicted in Fig. 12 (it was created by using Matlab Simscape).

The axial component of the force will either cause the cylindrical shaft to be in tension or compression, depending on whether the surgeon is pulling up or down the thread on the suture. The normal component of the force will cause a bending moment on the hand tool, which will be sensed by the four SGs mounted near the handle of the laparoscopic tool.

To implement the sensing of the axial forces, tension or compression, adding extra SGs near the needle driver tip is proposed, as shown in Fig. 13 (it was created by using Matlab Simscape). The reason for this location can be justified because the moment of the bending force is zero at the point where the force is acting. The near tip location will guarantee the decoupling of the bending and axial force measurements.

The axial forces are two orders of magnitude (100 times) smaller than the normal forces caused by bending moments. The Poisson ratio  $\nu$ , is the negative of the ratio of the transverse strain to the axial strain, as illustrated in Fig. 14 (it was created by using MS Visio).

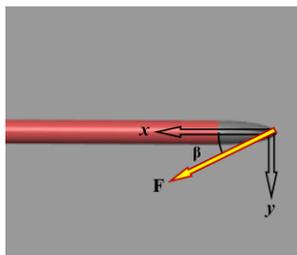


Figure 13

The suture force can be asserted in an angle  $\beta$  angle and  $F$  will have  $x$  and  $y$  components

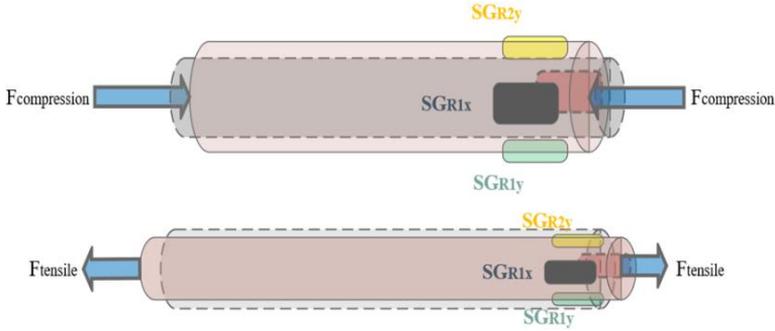


Figure 14

Two axial forces acting on the cylindrical shaft showing the Poisson effect

In summary, four SGs in two independent Wheatstone Bridges are deployed near the handle of the needle driver. These SGs will be sensitive to bending moments and insensitive to the axial forces. In addition, an extra four SGs near the tip of the hand tool are deployed in a configuration that is different from the SGs near the handle. These SGs will be sensitive to only axial forces and insensitive to bending forces. Four SGs, rather than two, are used to increase the output voltage due to the relatively small axial response. The total response is given by Eq. (9):

$$\overline{F_{total}} = \overline{F_{Bend}} + \overline{F_{Axial}} ; [N] \quad (9)$$

### 3.4 Augmented Reality (AR) Glasses as a Force Visualization Feedback Approach

Since the proposed system is capable of measuring the forces applied by the needle driver on the artificial bowel tissue, this vital information should be passed on to the surgeon in an easy way to provide feedback. A visual representation of the suture force is proposed both in graphical and textual forms.

The visual feedback must not obstruct the surgeon's view who is focusing on the main task, i.e., executing the suturing task in the best possible way. In addition, the surgeon should have the force feedback in front of his eye no matter of their head's orientation.

Considering the above factors, the use of an Augmented Reality (AR) approach is proposed. AR can be defined as an interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information.

The key component of the proposed AR feedback device is a transparent LCD that can be mounted on protective glasses or face shield.

The transparent LCD allows the surgeon to see through it, like in the case of normal glasses, and it can provide graphical information without blocking the view. The information about the applied force by the needle driver must be made available as it happens, i.e., in real-time. Presentation of the information should be made simple to interpret and be meaningful.

The visualization of the applied forces as a dynamic bar graph is proposed, as shown in Fig. 15. The force is displayed as a percentage of the maximum allowable tension (or threshold) the suturing action may apply on the bowel tissue. A numeric textual percentage is also made available to the surgeon.

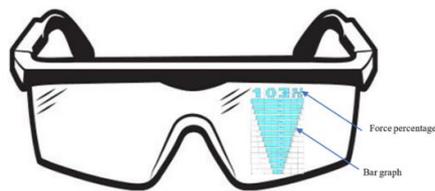


Figure 15  
Proposed AR glasses

## 4 Implementation and Experimental Results

### 4.1 Mounting the SGs on the Needle Driver

To properly bond the SG on the stainless-steel shaft of the needle driver, a precise and strict process must be followed. The process can be carried out in three major stages: surface preparation (it involves eleven steps), bonding the SGs to the shaft of the needle driver (it involves seven steps), and application of coating for environmental protection. Discussion of these steps is out of the scope of this paper.

### 4.2 Force Calibration Test Bench Design

Having built the needle driver force measurement system prototype, calibration is required to relate the suture tension forces applied on the tissue to the SG responses.

The proposed force calibration test bench (FCTB) includes an electromechanical system controlled by an MCU and a data acquisition (DAQ) system connected to the LabVIEW software tool to collect the data at the rate of 80 samples per second (80 S/s) for analysis.

Pictures from different angles of the completed FCTB are given in Fig. 16.

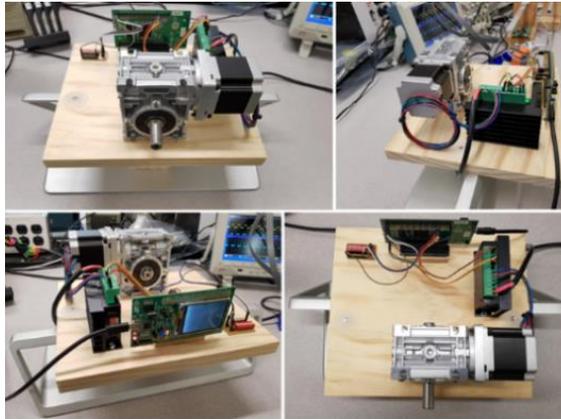


Figure 16

Experimental setup shows the FCTB at the ECE department Fuzzy Logic research laboratory

The use of several calibration weights is proposed to calibrate the force by the needle driver.

To calibrate the SG axial force responses, the FCTB is designed to rotate the needle driver in the clockwise direction (CW) one full  $360^\circ$  revolution and then another  $360^\circ$  revolution in the counterclockwise direction (CCW). Similarly, to calibrate the SG bending force responses, the FCTB is designed to rotate the needle driver in the clockwise direction (CW) one full  $360^\circ$  revolution and then another  $360^\circ$  revolution in the counterclockwise direction (CCW).

The calibration data have been collected by using four, 24-bit DAQ model MM01\_DAQ devices with a gain amplifier of 50, at a rate of 80 S/s, controlled by LabVIEW.

The calibration data of the axial tension response for the four SGs near the needle driver (ND) tip is listed in Table 1 and the calibration data for bending forces is tabulated in Table 2, respectively.

Table 1  
Axial tension calibration data

Weight [g]	Force [N]	TIP_SG <sub>RX</sub>	TIP_SG <sub>RY</sub>
<b>70</b>	0.6864655	0.001082	0.001112
<b>90</b>	0.8825985	0.001205	0.0013
<b>110</b>	1.0787315	0.001458	0.001471
<b>130</b>	1.2748645	0.001606	0.001554
<b>150</b>	1.4709975	0.001761	0.001667
<b>170</b>	1.6671305	0.001849	0.001773

Table 2  
Bending calibration data

Weight [g]	Force [N]	SGs Bending at $\theta = 0^\circ$	SGs Bending at $\theta = 90^\circ$	SGs Bending at $\theta = 180^\circ$	SGs Bending at $\theta = 270^\circ$
0	0	-	0.028837817	0.039190272	0.027679554
5	0.04903325	0.007173837	0.034819514	0.046441547	0.033410429
10	0.0980665	0.014143687	0.041305977	0.0535365	0.039756039
15	0.14709975	0.021264409	0.048018549	0.060783493	0.046357865
20	0.196133	0.028372896	0.054892624	0.067836332	0.053243841
50	0.4903325	0.070789039	0.098413676	0.110890909	0.097236286
70	0.6864655	0.099320082	0.127879869	0.13987889	0.127406229
90	0.8825985	0.127950665	0.157877938	0.168529636	0.157856934
110	1.0787315	0.15669681	0.187804839	0.197303087	0.188273674
130	1.2748645	0.184844439	0.21778668	0.226205801	0.218548512
150	1.4709975	0.213468891	0.247926475	0.255044319	0.248878287
170	1.6671305	0.242058425	0.277859245	0.284287643	0.279268707

### 4.3 Errors Due to SG Misalignment and Thermal Effects

There are two types of SG misalignment errors. One is an offset with a slight angle in the longitudinal direction, and the other one is that the SGs are not evenly spaced around the cylindrical shaft. In other words, the two SGs pairs are not exactly in a quadrature position to each other.

To analyze and characterize the errors due to SGs misalignment, a simulation case study was created to replicate the inspected ND installation under a digital microscope. The SGs misalignment simulation results closely matched the actual needle driver responses. The development of methods for proper installation and alignment of SGs for the needle driver is a topic for future work.

SGs are designed to bond to a specimen and respond properly to the applied strain only at room temperature. However, the responses of the SGs are affected by temperature variations. The SGs on the needle driver may indicate an erroneous force value if they are operated at high or low temperatures outside of the normal, indoor environment. To compensate for temperature variations, a temperature compensation algorithm was implemented by software. The details of that program are out of the scope of this paper.

#### 4.4 Experimental Results by Expert Surgeon

An expert surgeon working with the needle driver force measurement system to perform a suturing task on an artificial double-layer bowel tissue from SynDaver Labs, as shown in Fig. 17.

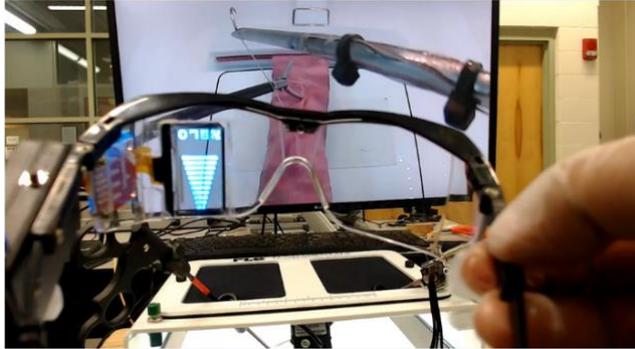


Figure 17  
AR glasses with the IBTS

The surgeon's qualitative assessments regarding the applied forces during the bowel suturing test are tabulated in Table 3.

Table 3  
The expert surgeon's qualitative assessment

Linguistic variable	ND Output Range (mV/V)	Calibrated Force Range (N)
<b>excessive</b>	greater than 0.360	greater than 2.659
<b>adequate</b>	0.150 – 0.250	1.188 – 1.888
<b>inadequate</b>	less than 0.015	less than 0.242

Excessive suture tension may cause complications and traumatic wounds after the surgery. On the other hand, inadequate tension leads to leaking colon and severe complications after the bowel surgery.

#### Conclusions and Future Research

In this paper, we proposed a strain gauge-based measurement system for forces applied during suturing tests using artificial bowel tissues. Mathematical and Matlab simulation models were developed to create the scientific foundation for the proposed methods. A sophisticated calibration and verification test bench system was also proposed and implemented. Simulation models were developed to treat errors due to misalignments of the bonded strain gauges. The corrections in the measurement results due to thermal effects were carried out by software. AR glasses were proposed to provide real-time feedback to the surgeon. It is believed that this

study will make significant contributions to the development of objective skill assessment systems.

In future research, we plan to develop an automated force assessment system by fusing the measured force data with expert surgeon opinion in a fuzzy logic-based intelligent decision support system framework. We also plan to extend this current research to measure forces applied during robotic surgery. Lastly, since the proposed system is capable of measuring the applied forces, images taken on the deformation of tissues during bowel suturing can be investigated using AI methods to estimate those forces.

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