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A Modular, Automated Laparoscopic Grasper with Three-Dimensional Force Measurement Capability

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***Abstract*— The introduction of robot-assisted surgery into the operating room has led to significant improvements in surgical procedures. However, the lack of haptic feedback in these robotic systems using long teleoperated instruments has negatively affected the surgeon's ability to palpate tissue and diagnose it as healthy or unhealthy. This paper describes our design of a modular, automated laparoscopic grasper with tri-directional force measurement capability. The grasper can measure normal grasping forces, as well as, sideways manipulation forces during grasping and palpation tasks. Additionally, a modular design allows for easy conversion between surgical modalities (e.g., grasping, cutting, and dissecting). Calibration of the force sensors and initial testing of the prototype has shown its ability to accurately measure tool-tissue interaction forces.**

I. Introduction

THE introduction of robot-assisted surgery into the operating room has led to significant improvements in surgical procedures. These robotic surgical systems, such as the Da Vinci Surgical System (Intuitive Surgical Inc.), incorporate advantages from minimally invasive surgery that include reduced patient trauma, shorter recovery time, and lower overall health care costs. Additionally, these robotic systems also improve dexterity, eliminate surgeon tremor, and reduce surgeon fatigue. However, these robotic surgical systems also have disadvantages, such as their initial high cost, inability to use qualitative information, and the lack of accurate haptic feedback to the surgeon. This lack of haptic feedback has led several researchers to develop new surgical tools and haptic devices to measure and reflect surgical tool-tissue interaction forces to the surgeon; thus restoring haptic feedback to the surgeon as they are accustomed to in conventional open surgical procedures.

Several researchers have developed novel surgical tools to accurately measure the tool-tissue interaction forces during surgical procedures. One area of research involves solutions that incorporate sensors into current laparoscopic tools using strain gages, force/torque sensors, or custom designed sensors on the shaft or jaws of the tool to measure tool-tissue interaction forces. Morimoto et al [1] and Bicchi et al [2] implemented strain gage sensors on the tool shaft that allow for measurement of indirect grasping forces and surgical manipulation forces, respectively. Dargahi et al [3] utilize a MEMS-based approach to measure normal forces at the jaws, however, cost and sterilizability issues were not discussed. Researchers have also focused on the development of new laparoscopic tools and systems with sensors located on the jaws or tool shaft to measure the surgical manipulation forces in one or more directions [4-9]. Rosen et al [6, 8] developed the FREG and BlueDRAGON systems for indirect measurement of the surgical forces. Prasad et al [7] developed a 2-DOF force sensing sleeve to measure bending forces in 5mm laparoscopic instruments. While these various designs can accurately measure the surgical forces, they have disadvantages towards incorporating them into an actual surgical setting. The retrofitting of existing laparoscopic tools with sensors would prove difficult, costly, and non-adaptable to current robotic surgical systems due to their non-modular, disposable design. The development of new modular laparoscopic tools with incorporated sensors would therefore offer an improvement over existing designs. However, previously developed surgical instruments with force measurement capabilities, such as [4-9], have the disadvantage of costly, non-disposable sensors, large jaw designs, and low degrees-of-freedom for force measurement. In addition, most of the previous research lacks modularity for easy conversion between tool types (e.g. grasper, cutter, and dissector) without removing the entire surgical tool.

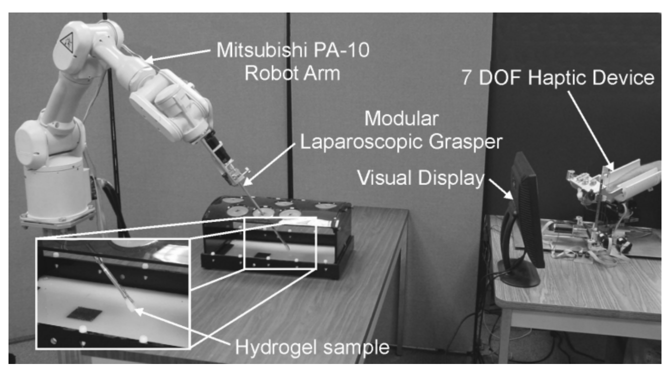

Fig. 1. Telemanipulation setup for characterizing tissue using a haptic device to control the robot arm with attached laparoscopic grasper.

Based on this motivation, we have developed a modular and automated laparoscopic grasper with tri-directional force measurement capability and a modular, disposable tool

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shaft for quick conversion between surgical modalities, such as grasping, cutting, and dissection. The current prototype has incorporated the advantages of previous graspers in a compact design for use in a clinical setting. Our overall research goal is the development of a haptic feedback surgical system that uses a robotic arm with an attached laparoscopic tool to perform surgical procedures and have the capabilities of measuring the tool-tissue interaction forces, thereby enabling the diagnosis of a particular tissue as healthy or unhealthy (see Fig. 1). This robotic arm with laparoscopic tool would be controlled by the surgeon using a haptic device that would reflect the surgical tool-tissue interaction forces.

II. Design and Development

A. Design

The design of the laparoscopic grasper was guided by our previously designed automated laparoscopic graspers and the advantages they incorporated, such as low backlash, compact design, and tri-directional force measurement capability [9]. In addition to these characteristics, the current prototype was significantly improved by using smaller sensors, a significantly smaller shaft diameter (~8mm), a linear actuation mechanism requiring no tensioning, and a disposable, modular instrument for easy conversion between surgical modalities.

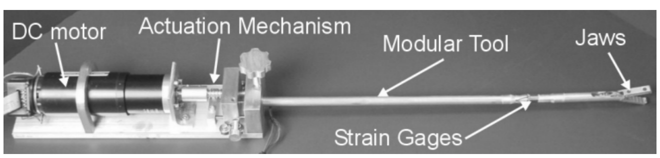

Fig. 2. Prototype of the modular laparoscopic grasper.

Our design consists of two components; namely, the actuation mechanism and the modular tool (see Fig. 2). The actuation mechanism uses a DC motor with gearbox and encoder that drives a leadscrew and linear positioning assembly. This linear positioning assembly connects to a push-rod that is part of the modular tool. The push-rod is contained within and translates along the shaft of the tool and actuates the two jaws of the tool using a linkage. The design uses 4 strain gages mounted on the shaft of the tool near the end of the shaft closest to the jaws to measure the horizontal and vertical forces exerted on the tool end-effector. Additionally, a small resistive force sensor is mounted in one of the jaws to measure the normal force during grasping and palpation tasks.

B. Actuation Mechanism

The actuation mechanism of the automated laparoscopic grasper consists of a DC motor (model RE36, manufactured by Maxon), linear positioning assembly, and quick-connect mechanism for the modular tool (see Fig. 3). The DC motor assembly that was used for our prototype includes an 18:1 ratio gearbox and incremental encoder. The motor with gearbox allows for an increase in torque using a smaller motor, thereby reducing the necessary weight of the tool. A low weight laparoscopic tool is important as it will be mounted on the end of a robotic arm for telemanipulation. An 18:1 ratio gearbox was used for the prototype due to its availability from a previous automated laparoscopic tool design, however, a smaller gearbox could be used to achieve the necessary torques required for grasping and palpation tasks. Researchers have found that in a typical palpation task, the average magnitude of grasping forces is 12.5N [10]. Therefore, we used these results as a constraint for the magnitude of grasping force necessary at the jaws. The prototype laparoscopic grasper is theoretically capable of producing up to 375N of grasping force, however, this does not account for frictional and spring losses. The incremental encoder used with the DC motor had 500 counts per quadrature for a total of 2000 counts per revolution. The addition of the 18:1 gearbox, linear positioning assembly, and push-rod linkage yields an effective resolution of the jaw angle of 0.001°.

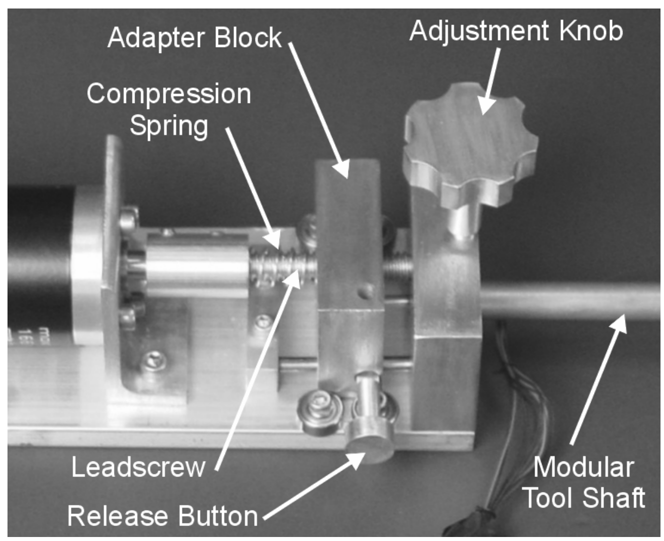

Fig. 3. Actuation mechanism of the modular laparoscopic grasper.

The DC motor assembly actuates a linear positioning assembly which uses a leadscrew and adapter block to convert the rotational movement of the motor to a translational movement necessary to actuate the push-rod and opening/closing of the jaws. The motor's output shaft is coupled to the end of a 6.35 mm diameter leadscrew that has a pitch of 0.787mm. The opposite end of the leadscrew passes through a threaded hole in the adapter block. This allows the rotation of the leadscrew to translate the adapter block along the axis of the tool. The adapter block uses two stainless steel dowel pins as supports and four ball bearings as guides along its translational axis. These pins and bearings prevent any rotation of the block along the leadscrew axis. In addition, a preloaded compression spring was placed between the motor shaft/leadscrew coupler and the adapter block to prevent backlash in the linear positioning mechanism.

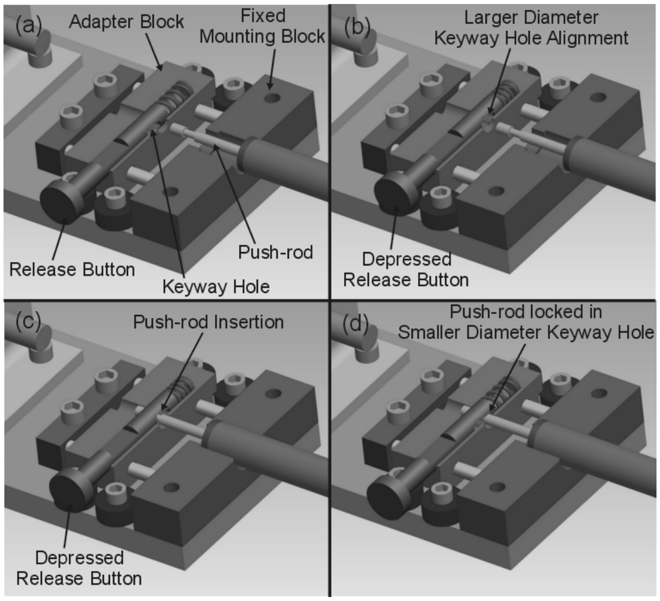

Fig. 4. Push-rod locking mechanism

The quick-connect mechanism used to attach the modular tool to the actuation mechanism consists two locking mechanisms, one for the push-rod and one for the modular tool shaft (see Fig. 3 and 4). The locking mechanism for the push-rod is located inside the adaptor block and consists of a spring-loaded release button with a keyway hole used to couple the push-rod to the adapter block. Fig. 4 shows a cutaway diagram of the actuation mechanism to demonstrate the steps to insert and lock the push-rod to the adapter block. The first step involves partially inserting the push rod at the end of the tool shaft into the fixed mounting block (see Fig. 4(a)). Next, the release button is depressed to align the larger diameter keyway hole with the push-rod (see Fig. 4(b)). The push-rod is inserted into the keyway hole while the release button has remained depressed (see Fig. 4(c)). Releasing the button allows the smaller keyway hole to engage a 4mm long recess (1.6mm diameter) at the end of the push-rod shaft, thus, locking the push-rod to the adapter block and allowing actuation of the jaws (see Fig. 4(d)). The steps are performed in reverse order to unlock the push-rod and remove it from the adapter block. The locking mechanism for the tool shaft consists of a fixed mounting block with keyway hole and adjustment knob that enables the tool shaft to be fixed to the actuation mechanism assembly. The tool shaft uses an alignment slot for correct orientation and insertion of the modular tool into fixed mounting block. The alignment slot is necessary to enable correct orientation of the jaws and sensors with the actuation mechanism. Finally, the adjustment knob acts as a set screw to lock the tool shaft in position with respect to the actuation mechanism.

C. Modular Tool

The modular tool of the laparoscopic grasper has a diameter of approximately 8mm, a length of 330mm, and consists of the tool shaft, flex shaft, and jaw assembly (see Fig. 5). The jaw assembly contains the two grasping jaws with the overall size of each jaw being 31mm long by 5.5mm wide by 8mm high and having a rectangular grasping surface of 121mm^2, which is comparable to conventional laparoscopic graspers. The three components of the tool (tool shaft, flex shaft, and jaw assembly) are attached in series using threaded couplers internally. A steel push-rod that couples the adapter block and jaw assembly is located inside the tool and extends the length of the tool protruding from the tool shaft at the end opposite the jaws for attachment to the adapter block. The opposite end of the push-rod attaches to a linkage adapter that drives two jaw links, each attached to an individual jaw to provide the opening/closing motion of the jaws in equal and opposite directions. This linkage mechanism in the modular tool is similar to mechanisms in conventional laparoscopic graspers that actuate the jaws. The push-rod will open the jaws as it translates towards the jaws and will close the jaws as it translates towards the adapter block to prevent buckling of the push-rod during high force grasping and palpation tasks.

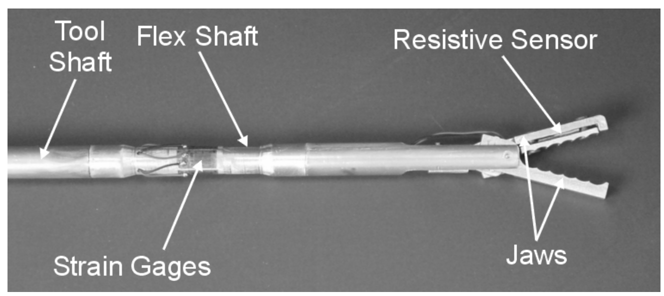

Fig. 5. Sensor locations on the modular tool.

The modular tool contains five sensors, one resistive and four strain gages, to measure the normal grasping force and sideways tissue manipulation forces (see Fig. 5). The resistive sensor (SF-4 model, manufactured by CUI, Inc.) has an overall size of 5mm long by 5mm wide with a height of 1mm. Some of the characteristics of this sensor are a response time of less than 6μsec, a maximum load of approximately 29N, and a resistance range from 10,000MΩ at zero load to approximately 15Ω at full load. The sensor was attached to one of the jaws between the grasping surface and body of the jaw using an adhesive and protected from the surgical environment using a thin film. The grasping surface of the jaw was then attached to the jaw using two PVC rivets to secure the grasping surface against the resistive sensor and preload the resistive sensor with approximately 1N force. The preload on the sensor is used to improve its sensitivity of forces below 0.5N while maintaining the capability to measure high grasping forces (15N). The four strain gages (model 125UN, manufactured by Vishay Intertechnology, Inc.) have overall dimensions of

3.05mm wide by 6.99mm long with a strain range of ±3%. The gages were placed on the flex shaft section of the modular tool at 90° intervals (top, bottom, left, and right sides) with each one of them having the same orientation with respect to the modular tool. The flex shaft component of the modular tool is a 30mm long section where the thickness of the shaft has been decreased to increase the strain at this location in the shaft. This design amplifies the measurements of the four strain gages while providing a recess along the tool shaft for the gages and protective covering without increasing the diameter of the tool. Finally, two 30 AWG wires were attached to each strain gage and the resistive sensor and travel within the tool shaft to a cable connector at the actuation mechanism.

D. Control and Data Acquisition

The control of the laparoscopic grasper is achieved using the QNX real-time operating system, data acquisition card, and motor amplifier in conjunction with our previously developed haptic device [11] to control the position of the jaws while measuring the forces from the sensors on the laparoscopic tool. This program operates at 500Hz and implements a PD controller to control the position of the jaws, which is given by:

$$T = K_p\left(q_d - q\right) + K_d\left(\dot{q}_d - \dot{q}\right) \tag{1}$$

where T is the motor torque, K_p and K_d are the proportional and derivative gains, q_d and q are the desired and actual positions of the jaws, and $\dot{q}_d$ and $\dot{q}$ are the desired and actual velocities of the jaws. The acquisition of the measured forces is achieved using amplification circuits and the data acquisition card to record the data from the sensors. The resistive sensor uses a voltage divider and operational amplifying circuit in conjunction with a 14-bit ADC channel to record the normal force from the tool-tissue interaction at the jaws. The strain gages use a Wheatstone bridge with differential amplifier circuit in conjunction with a 14-bit ADC channel for each of the gages to record the manipulation forces. The calibration method for these sensors is presented below in section III.

III. Calibration

The calibration of the sensors on the prototype laparoscopic tool is required for accurate measurement of the tool-tissue interaction forces. Specifically, the preload in the normal force sensor and the manufacturing tolerances of the prototype make it necessary to calibrate each sensor once it has been placed on the tool. To perform this calibration, an electro-mechanical device that is capable of generating a linear force and recording the values was used (see Fig. 6). This device consists of two linear slide rails mounted on a base on either side of an aluminum fixture. A one degree-of-freedom linear actuation mechanism with a load cell mounted at the end-effector was attached to the linear slide rail. This allowed the linear actuator to travel parallel to the aluminum fixture for proper alignment while producing a force and displacement perpendicular to the rail. The aluminum fixture was used for mounting the prototype tool and sensors for calibration.

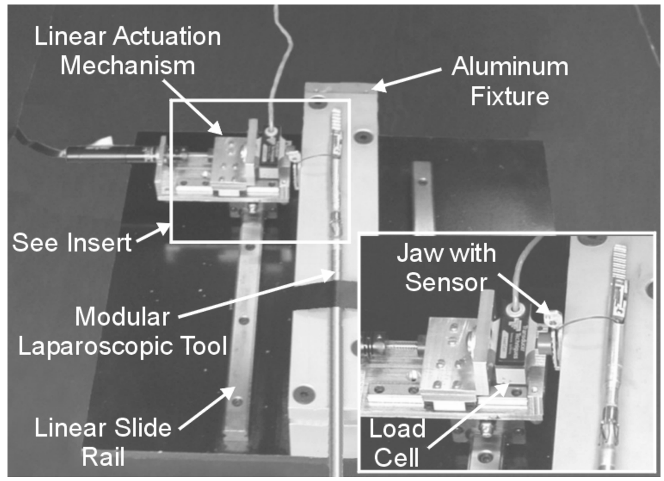

Fig. 6. Electro-mechanical device for calibration of force sensors

A. Normal Force Sensor Calibration

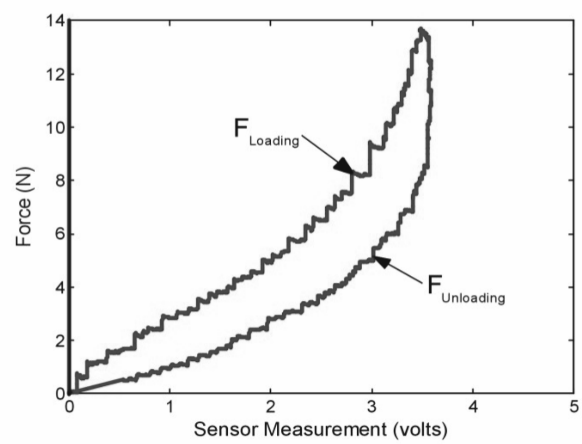

Fig. 7. Calibration curve for the resistive sensor.

Calibration of the resistive sensor for normal force was performed by removing the jaw with the resistive sensor from the modular tool and attaching it to the side of the aluminum fixture using a cyanoacrylate adhesive (see Fig. 6). This was necessary to accurately apply a force against the grasping surface of the jaw and measure the output of the resistive force sensor located inside the jaw. A control program was developed for the linear actuation mechanism to increase its applied force on the jaw from 0N to 13N and then from 13N to 0N at a rate of 0.13N/sec while recording the measured values from the load cell and resistive sensor. Therefore, a comparison of the load cell measurements, which are the actual forces applied, to the measurements of the resistive sensor will yield the calibration curve for the resistive sensor. Fig. 7 shows the results of this calibration procedure. The resistive sensor measurements have been filtered using a 5th order Butterworth filter to eliminate the high frequency noise. Additionally, a least squares linear regression was used to derive a best-fit mathematical model for the loading and unloading of the calibration curve, given by:

$$\mathrm{F}_{loading} = 0.60x^3 - 2.4x^2 + 4.9x - 0.13 \tag{2}$$

$$\mathrm{F}_{unloading} = 0.43x^5 - 3.4x^4 + 10x^3 - 13x^2 + 7.6x - 1.2 \tag{3}$$

where $F_{loading}$ and $F_{unloading}$ is the normal force in Newtons for loading and unloading curves respectively. As shown in Fig. 7, the calibration curve for the normal force resistive sensor is non-linear and shows significant hysteresis, which is characteristic of this sensor as per the manufacturer specifications. Therefore, separate models for the loading and unloading of the sensor were necessary.

B. Strain Gages Calibration

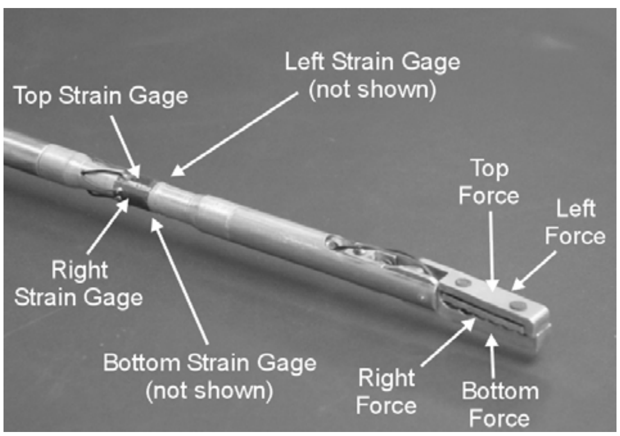

Fig. 8. Location of the strain gages on the flex shaft and loading positions for the strain gage calibration.

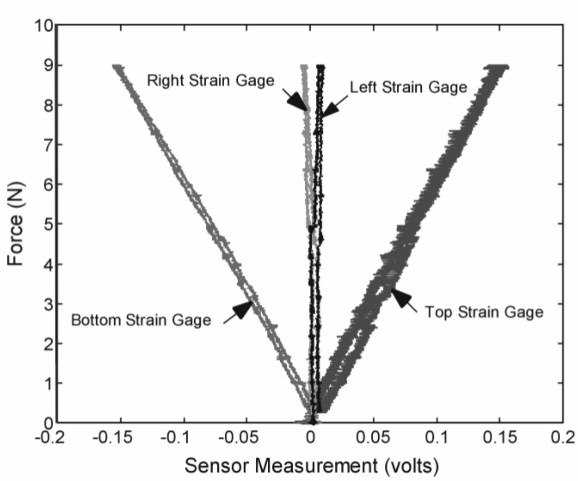

Fig. 9. Strain gage calibration curve for application of a force to the top of the jaws.

Calibration of the strain gages was performed by mounting the entire prototype to the aluminum fixture on the mechanical calibration device. The prototype was clamped at the actuation mechanism base with sufficient force to prevent any movement; thus mimicking the constraint in surgery where the tool would be attached to the end-effector of a robot arm. Another control program, similar to the program for the resistive sensor calibration, was developed for the linear actuation mechanism to increase its applied force on the jaw from 0N to 10N and then from 10N to 0N while recording the measured the values from the load cell and strain gages. The loading was performed at a rate of 0.1N/sec at 90° intervals (top, bottom, left, and right) on the jaw (see Fig. 8). The measurements from the load cell and all four strain gages were recorded and plotted to obtain the calibration curve. Fig. 9 shows an example calibration curve for the top loading point with similar plots for each loading point that are shown in Fig. 8. As shown by Fig. 9, a linear relationship exists between the strain gage output and the actual force measured by the load cell. In addition, the calibration curve shows a positive curve for the loading point strain gage and a negative curve for the strain gage opposite to the loading point which was present for each loading point calibration curve. As expected, the remaining two gages, which are transverse to the applied force direction, show minimal measurements compared to the loading point strain gages. A least squares linear regression was used to derive the best-fit mathematical model of the calibration curve for each strain gage. The models for each of the calibration curves for the top, bottom, left, and right loading points are given by:

$$F_{top} = 59x_{top} + 0.092 \tag{4}$$

$$F_{bottom} = 61x_{bottom} - 0.11 \tag{5}$$

$$F_{left} = 59x_{left} - 0.23 \tag{6}$$

$$F_{right} = 62x_{right} - 0.27 \tag{7}$$

where F is the magnitude of force in Newtons exerted at the specified loading point and x is the strain gage output in volts at the specified loading point.

IV. Tissue Characterization Experiment

As a demonstration of the capabilities of our modular laparoscopic tool, we have conducted a tissue characterization experiment to evaluate the force measured by the tool when grasping simulated tissue samples of varying stiffness. The simulated tissue samples were made up of Hydrogel material [12]. For this experiment, we selected three Hydrogel samples (corresponding to soft,

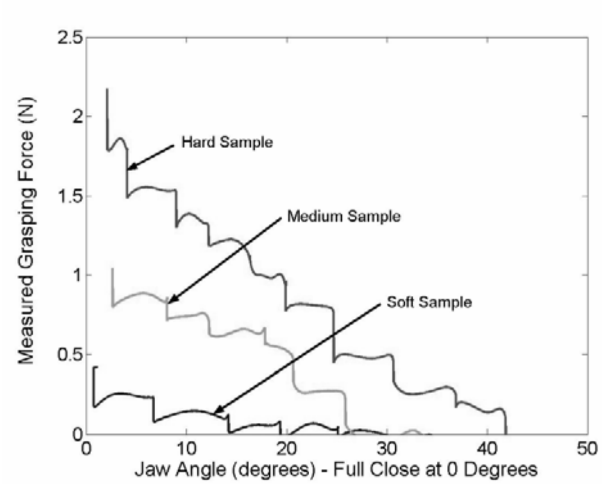

Fig. 10. Characterization of the Hydrogel samples using the modular laparoscopic grasper.

medium, and hard tissue) that had a significant variation in stiffness and would be easily differentiated with one's fingers. The samples were identical in size and thickness, therefore, the only variable would be the required force to deform the samples by the same magnitude. The experimental setup consisted of using a haptic device [11] to control the laparoscopic tool's jaws and grasp each of the simulated tissue samples. As each sample was grasped, the normal force measurement at the jaws and the angle of the jaws were recorded. As shown in Fig. 10, the results show that the laparoscopic grasper can differentiate between samples of different stiffness. All three samples shown were grasped to a jaw angle of approximately 1°, therefore, all incurring the same deformation but a significantly different normal force for each sample. The soft Hydrogel sample showed a maximum force of 0.4N while the medium Hydrogel sample showed a maximum force of 1N and the hard Hydrogel sample showed a maximum force of 2.2N for the same angular displacement of the jaw. Additional tissue grasping trials were performed with similar results for validation. Therefore, the grasper's capability of distinguishing between tissues of different stiffness has been demonstrated.

V. Conclusion

This paper presents the design and development of a modular, automated laparoscopic grasper with tri-directional force measurement capability. The mechanism consists of a DC motor driven linear positioning assembly and modular tool with incorporated force sensors. The modular tool incorporates a resistive sensor in one of the grasping jaws and four strain gages along the tool shaft for measurement of the normal force and manipulation forces respectively. Calibration of the resistive sensor and strain gages, along with a tissue characterization experiment was presented. Future work includes telemanipulation experiments that use a previously developed haptic device to control a robotic arm with the prototype laparoscopic tool mounted on its end-effector for performing tissue suturing experiments and evaluating the overall system capability.

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