

# Mobile *In Vivo* Biopsy Robot

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**Abstract** – A mobile *in vivo* camera robot was developed to provide the ability for a single port biopsy procedure. Such a robot can be inserted into the abdominal cavity through a standard trocar. The surgeon controls the robot using visual feedback from the on-board camera. Measurements were made to identify the forces required to successfully biopsy *in vivo* tissue, including clamping and tearing forces. The robot design was developed around these parameters and the need to traverse the abdominal environment using specially designed wheels. This mobility allows the biopsy robot to move to the area of interest to sample specific tissues. The lead-screw linkage system that actuated the graspers allows for large force production through careful mechanical design. *In vivo* testing of this system in a porcine (pig) model has been successful. The robot is capable of traversing the entire *in vivo* abdominal environment and has successfully been used to biopsy hepatic tissue. In addition, experimental analysis of the biopsy mechanism shows good results towards more elaborate tissue manipulation in the future.

**Index Terms** – Biopsy, surgical robots, cutting force, *in vivo*, laparoscopy.

## I. INTRODUCTION

While minimally invasive surgery reduces patient trauma, it also reduces surgical access since tools are constrained by the entry incision. Several robot systems exist to help increase the surgeon's dexterity by precisely manipulating laparoscopic tools. Such systems generally consist of a multi-arm robot that is external to the patient [1, 2]. Each arm manipulates a tool (or camera) that is tele-operated by a surgeon. The robots can filter the natural tremor present in the human hand, correct for the effects of motion reversal, and/or perform motion scaling to provide greater instrument control. Such systems are generally large, expensive and have limited motion because they are still constrained by the insertion points.

A new approach to laparoscopy involves inserting miniature robotic assistants entirely into the patient. Such *in vivo* robots will provide vision and task assistance without being constrained by the entry incision.

The robot being analyzed in this paper, shown in Fig. 1, is cylindrical and is 20 mm in diameter and 100 mm long. It has two wheels that are independently driven and a small appendage is attached to prevent the body from spinning. This appendage is spring loaded to retract and provide easy entry through the entry port. At the distal end of this appendage is biopsy forceps used for sampling tissue. In between the wheels is a small lens used for the adjustable-focus camera mechanism housed inside the robot. Entry into the abdominal

cavity is gained through a traditional trocar port. The robot can currently be removed with laparoscopic tools using only one port (entry port).

These types of *in vivo* robots need to traverse the abdominal organs without causing damage. Mobility is difficult because the environment is slick, hilly, and deformable. Previous work has led to wheel designs that provide sufficient traction without causing tissue damage [3].



Fig. 1 Mobile *in vivo* camera biopsy robot.

Traditionally, a biopsy is performed with two ports; one for the camera and one for the tool. By inserting such a mobile biopsy camera robot into the abdominal cavity through one standard laparoscopic port, the additional port could be eliminated. This would reduce patient trauma, and has the potential to improve laparoscopy compared to current systems. The long term goal of this work is to create a team of *in vivo* robots that could serve as surgical assistants and/or replace traditional laparoscopic tools.

This paper presents experimental analysis of the forces required to biopsy tissue as well as the forces capable of being generated with the biopsy robot design. Drawbar forces are also analyzed. Finally, the results of *in vivo* experiments are presented.

## II. BACKGROUND

### A. Robot Assisted Endoscopy

The use of robotics is currently recognized as the major driving force for the future technological advance of minimally invasive surgery [1, 2, 4]. The first application of robotics to laparoscopic surgery was the Automated

Endoscopic System for Optimal Positioning (AESOP), which allowed the surgeon to position and stabilize a laparoscopic camera using voice control [5]. This was the first robotic device to receive approval from the Food and Drug Administration (FDA) for clinical use in abdominal surgery [2], and it successfully launched the era of robot-assisted surgery [1]. The da Vinci Surgical System (Intuitive Surgical) is a current, commercially available telerobotic device. Da Vinci, and similar robots, serve in a master-slave relationship with the surgeon, and use separate arms to hold a camera and the surgical instruments. Computerized control systems are used to filter the natural tremor present in the human hand, correct for the effects of motion reversal, and perform motion scaling to provide greater control of instrument movements in the surgical field. Such systems have been available for only a few years, and their efficacy and value are currently being evaluated in randomized clinical trials [1]. Other master/slave robots similar to da Vinci have been developed (e.g. ARTEMIS, ZEUS) but none has yet seen da Vinci's widespread application. Other research has focused on tool designs and end-effectors that restore some of the lost dexterity by including a wrist-like joint [6].

Hirose and Breedveld have developed a steerable endoscope that can rotate left to right 60° and up 180° [7], while the commercially available Olympus endoscope can rotate left to right 100°, down 90° and up 120°. These systems have not been widely accepted for abdominal laparoscopic surgery as surgeons have found them disorienting and difficult to use. These scopes, while increasing the available visual field, remain limited by range of actuation. Providing *in vivo* robotic visual feedback allows the surgeon to see the entire visual field, including looking back at the entry port to assist trocar and tool insertion. Further, *in vivo* robotic camera feedback eliminates the need for the laparoscope incision.

All of the above systems that are implemented from outside the body are still fundamentally constrained by the limited access to the abdominal cavity provided by small access incisions. Moreover, each of the robotic arms is necessarily long and bulky to accommodate the range of motion required to maneuver the long instruments attached to each arm. Large excursion arcs of the arms lead to collisions outside the patient, and improper placement of the access ports leads to collisions inside the patient [2]. Each arm requires a separate access port; hence the number of incisions is not reduced compared to traditional non-robotic laparoscopy. These incisions are made as part of the set-up procedure for the robot, so the problems associated with injuries caused by access port insertion remain unaddressed. Similarly, a limited range of motion for the robotic camera can still result in obstructed or incomplete visual feedback. Tool changes still require the removal of the existing tool and the reinsertion of the new one, adding to the overall surgical time and adversely affecting the efficiency of the operation [6, 8].

### B. *In vivo* Medical Robotics

Several *in vivo* devices have been developed to assist during surgical procedures. Locomotion devices have been designed to assist with gastrointestinal procedures [9] while still others are designed to provide a stabilized platform for heart manipulation [10]. These devices address fundamentally different problems than those of the abdominal cavity. Robots designed to navigate the gastrointestinal tract are confined to a tube, which is used to assist motion.

Initial work has begun to address *in vivo* robotic visual feedback during porcine (swine) cholecystectomies [11, 12]. These successful clinical trials demonstrated that *in vivo* robotic cameras can provide useful and improved visual feedback. Although to the author's knowledge successful *in vivo* robotic tissue manipulation has yet to be achieved in a manner considered useful to the surgeon.

### C. Tissue Manipulation

Simulation and modeling of tissues has been addressed aggressively in the research community as surgical simulation packages have been developed. However, little research has been done concerning the forces and pressures required to biopsy or cut tissue. One group has measured the force required to cut pig liver at various speeds using a scalpel blade [13]. Results show that a force of approximately 4 N is required to cut the tissue over a range of speeds.

## III. BIOPSY FORCES

A tool was designed to measure the forces produced during the *in vivo* biopsy of several sets of porcine tissue. The force measurements were needed to design a robot and mechanism to produce sufficient force to biopsy tissue.

### A. Cutting Force

A biopsy forceps device that is commonly used for tissue sampling during esophagogastroduodenoscopy (EGD) and colonoscopies was modified to measure cutting forces during tissue biopsy. These forceps, shown schematically in Fig. 2, consists of a grasper on the distal end with a handle/lever system on the proximal end. A flexible tube is affixed to one side of the handle and the other end is attached to the fulcrum point of the biopsy grasper. A wire enclosed in Teflon inside the tube is used to actuate the grasper. This wire is affixed to the free end of the handle lever and at the other end to the end of the grasper lever arm. Actuation of the handle lever causes the wire to translate relative to the tube and actuate the biopsy graspers. The tip of the forceps is equipped with a small spike that penetrates the tissue during sampling.

The diameter of the forceps ( $h$ ) is 2.4 mm. The dimensions of  $c$ ,  $g$  and  $f$  are 2.1 mm, 2.0 mm and 6.7 mm respectively. The force at the tip of the grasper when the forceps are nearly closed is a function of the geometric design of the forceps.

$$F_{tip} = F_{cable} \left( \frac{d}{a+b} \right) \quad (1)$$

For a cable force of 10 N, the force at the tip is approximately 1.4 N for this design where  $a$  is 2.9 mm,  $b$  is 1.7 mm, and  $d$  is 0.65 mm. The maximum area of the forceps in contact with tissue during a biopsy is  $0.3756 \text{ mm}^2$ .

$$P_{\text{contact}} = \frac{F_{\text{tip}}}{A_{\text{contact}}} \quad (2)$$

Assuming an even distribution of force, the applied pressure is approximately 3.75 MPa. However, by taking a smaller “bite”, the contact area is reduced and the pressure can be drastically increased and the required force is decreased.

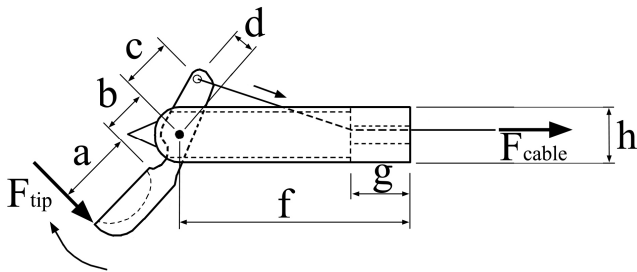
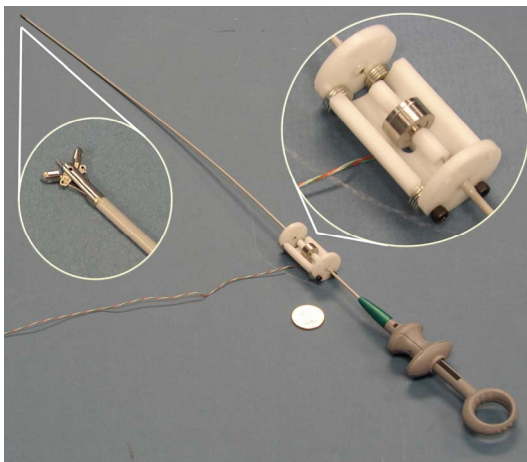
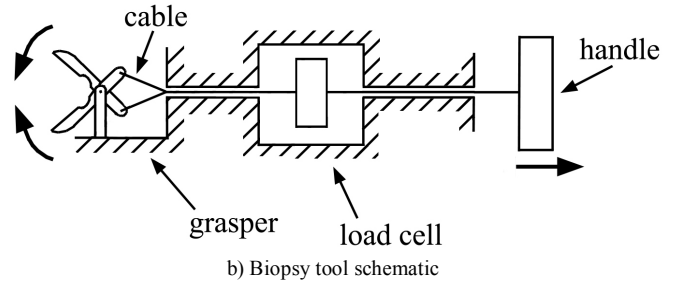


Fig. 2 Schematic of the biopsy forces.

This normal biopsy device was modified to contain a load cell to measure clamping forces indirectly, as shown in Fig. 3. The modifications made to this tool include cutting the tube and wires to place a load cell in series with the wires to measure tensile force when the wires are actuated as shown in Fig. 3b. A plastic case was built to connect the two free ends of the tube to retain the structure of the system, while the wires were affixed to the free ends of the load cell. Using this design, the force in the cable was measured. Along with the above model the force at the tip of the grasper was estimated while sampling sets of *in vivo* tissue using a porcine model.



a) Biopsy tool to measure clamping forces



b) Biopsy tool schematic

Fig. 3 Biopsy tool used to measure *in vivo* biopsy clamping forces.

Measurements of cable force were made while sampling liver, omentum, small bowel and the abdominal wall of an anesthetized pig. Representative results for a liver biopsy are shown in Fig. 4. The initial negative offset is due to the slight compression in the cable to push the grasper jaws open before biopsy. The average maximum measured force to biopsy porcine liver for three samples was  $12.0 \pm 0.4 \text{ N}$ . These results are consistent in magnitude with other published results [13] concerning forces sufficient to cut porcine liver.

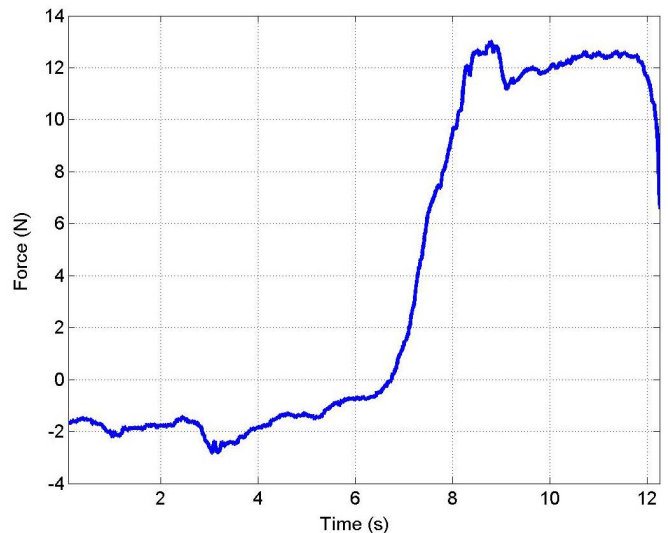


Fig. 4 Measured cable force during the *in vivo* biopsy of porcine liver.

### B. Sample Extraction Force

Generally, the biopsy forceps do not completely sever the tissue. When this is the case, the forceps are gently pulled to free the sample. This extraction force also needs to be produced by a successful biopsy robot. The magnitude of the extraction force needed to be determined so that a robot could be designed to provide sufficient drawbar force to free the sample.

A laboratory test jig was built to measure the force needed to free a biopsy sample of bovine liver. After clamping the sample with the biopsy forceps a load cell attached to the handle of the device was gently pulled to free the sample while the tensile force was recorded.

Representative results shown in Fig. 5 indicate that approximately 0.6 N of force is needed to extract bovine liver tissue with the use of the biopsy forceps.

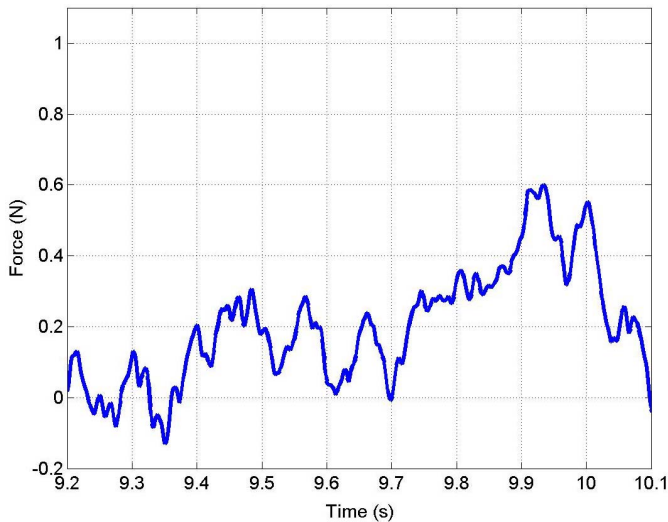


Fig. 5 Force required to extract a full bite of bovine liver in the laboratory.

#### IV. BIOPSY ROBOT

Based on the *in vivo* biopsy force measurement results, the design objectives for the biopsy robot were determined. The biopsy robot will need to produce approximately 0.6 N of drawbar force to free the tissue. The wheel design will also need to traverse the *in vivo* environment without causing tissue damage. Cable forces near 14 N will be needed to successfully biopsy porcine tissue. Also, a camera system is needed to provide visual feedback to the surgeon for abdominal exploration and assistance during tissue biopsy. Finally, the design will need to be contained in a small robot that can fit through the small entry port.

##### A. Robot Design

This robot has two aluminum wheels that are attached to two 6 mm diameter permanent magnet direct current motors through a set of bearings and spur gears. The motors are housed in a cylindrical body that also contains the CMOS camera imager, camera lens, motor and video control boards, and actuation motor and mechanisms for camera adjustable-focus and biopsy capabilities. The camera is capable of focusing at 2mm to infinity. The inner and outer diameters of the wheel are 17 mm and 20 mm, respectively. The helical profile of the wheels has a pitch of 30° and a grouser depth of 1 mm based on experimental study of wheel performance [14]. The robot has a top speed of approximately 2 cm/s. The current model is tethered for power.

##### B. Drawbar Force

As stated earlier a complete cut of the tissue is rarely achieved and some tearing of the sample is needed to extract the sample. To be successful the *in vivo* robot will need to produce enough drawbar force to pull the sample free. The biopsy robot shown in Fig. 1 was tested *in vivo* and with excised bovine liver to measure drawbar forces. The biopsy grasper (tail of the robot) was attached to a stationary load cell. The robot speed was slowly increased as the drawbar force was recorded as shown in Fig. 6. After maximum

drawbar force was achieved, around 11 seconds, the robot wheel motion was stopped. Results demonstrate that the robot is capable of producing approximately 0.9 N of drawbar force. This amount of force is 50% greater than the target of 0.6 N in the laboratory measurements (Fig. 5). This drawbar force is therefore sufficient for sample extraction.

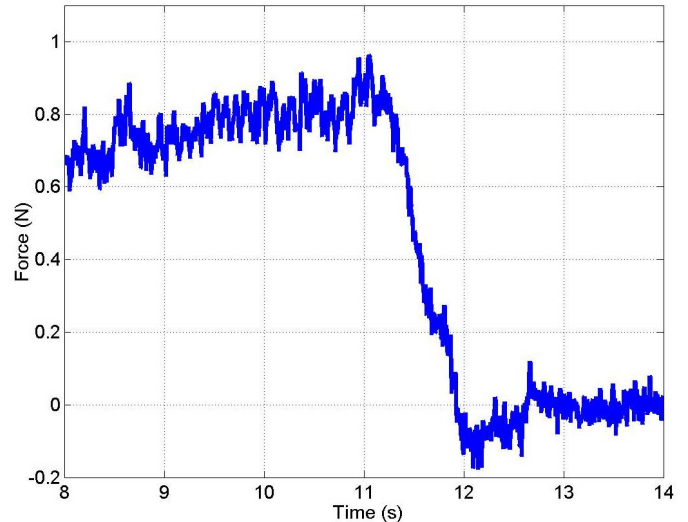


Fig. 6 Drawbar force production from biopsy robot where maximum drawbar force is produced at 11 seconds, as shown, before slowing down.

In general, *in vivo* mobility is difficult because the environment is slick, hilly, and deformable. These types of *in vivo* robots will need to traverse the abdominal organs without causing tissue damage. The forces and pressures that cause tissue damage are not well known, but during routine laparoscopic procedures grasping forces as high as 40 N have been recorded [15] with corresponding tissue pressure of approximately 400 kPa. The *in vivo* robot crawler weighs only 0.64 N, and is capable of producing a maximum drawbar force of approximately 0.9 N. These forces correspond to an approximate maximum tissue pressure of 1.5 kPa. Therefore, it is expected, and has been shown in initial *in vivo* mobility tests, that tissue damage will be negligible compared to forces applied by a surgeon during conventional laparoscopic procedures.

##### C. Actuation Design

Development of an actuation mechanism to drive the biopsy grasper and the camera was achieved through several design iterations and testing. One challenge was transforming the axis of rotation of the motor, which was perpendicular to the tube of the forceps, to a line of translation parallel with the grasper wires.

A first design concept consisted of a series of beveled gears that created a winch system. However, this system required a restoring force such as a spring. The second design concept used a lead screw turned by the motor to power a linkage. This system was prototyped, but failed to produce substantial cable forces.

The lead screw linkage design was reconsidered to increase cable tensile force as shown in the CAD design in

Fig. 7 and schematic in Fig. 8b. The lead screw was extended through the slider. The lead nut was then allowed to translate far enough so that at the point of grasper closure the linkage approaches a mechanism singularity where output force is very large. The slider is a nearly hollow cylinder and the lead nut and linkage are inside the slider near the singularity. The grasper wires are attached to this slider.

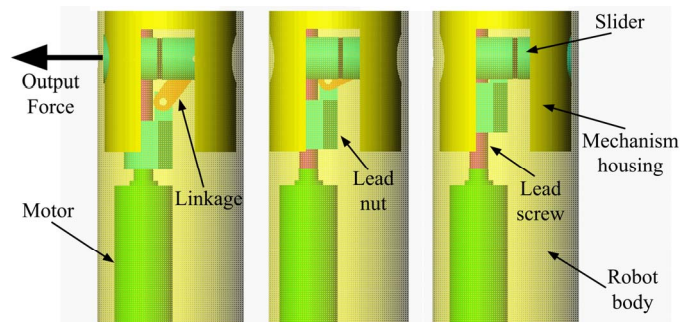
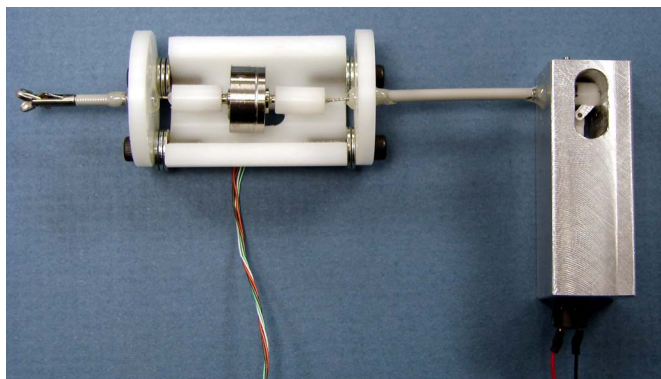


Fig. 7 CAD drawing of the biopsy mechanism implemented in the biopsy robot. The figure shows three positions as the mechanism is actuated.

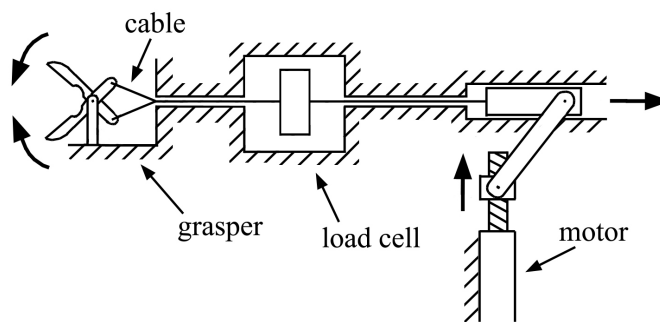
A direct current motor drives the lead screw vertically as the linkage transform the vertical motion of the lead nut to the horizontal translation of the slider, as shown in Fig. 7. This allows for a large mechanical advantage at the point when the graspers are nearly closed.

#### D. Biopsy Robot Results

The design of Fig. 7 was implemented in a test jig that included a load cell for measuring applied force. As described in Section IIIA, the load cell was placed in series with the wires to measure tensile forces during grasping. A schematic of the test jig is shown in Fig. 8. The lead screw causes a nut to translate vertically. A connecting linkage converts the vertical translation into horizontal motion of a slider. The wires that actuate the graspers were affixed to this slider.



a) Biopsy force measurement jig



b) Biopsy force measurement jig schematic  
Fig. 8 Actuation mechanism implemented on the biopsy robot.

Force measurements were made in the lab to determine the maximum amount of force that could be produced using the biopsy robot design. Representative results from these tests are shown in Fig. 9. The average maximum force produced for three samples was 9.6 +/- 0.1 N. This force is about 16% smaller than the 12 N measured during *in vivo* testing. However, the 12 N merely represents the force that was applied. It does not represent the minimum force required to biopsy the tissue. It is probable that the surgeon performed the biopsy and continued to increase the force and merely “squeezed” the sample. The surgeon applied what he/she knew to be a sufficient force rather than a minimum force. Also, the required force could also be largely reduced by simply taking a smaller biopsy sample. Reducing the contact area by 16% would produce the same applied stress.

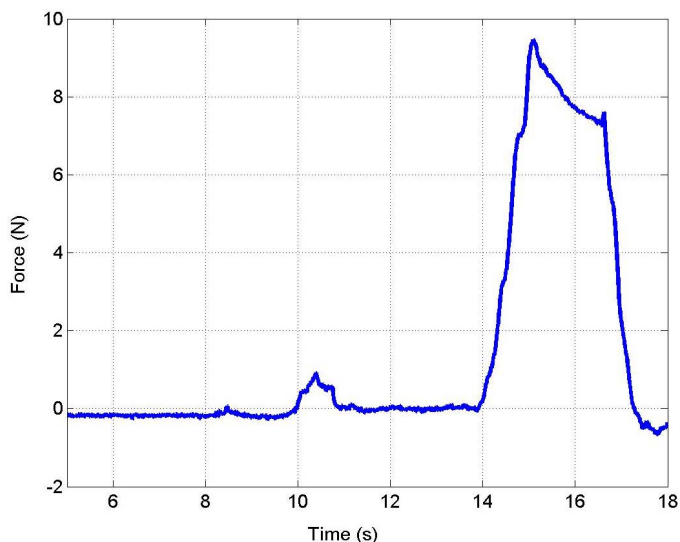


Fig. 9 Force production measured from the robot biopsy mechanism.

#### V. *IN VIVO* RESULTS

The biopsy robot has been successfully tested *in vivo* in a porcine model. The robot was first used to explore the abdominal environment while providing visual feedback to the surgical team.

*In vivo* mobility testing with this and other similar prototype robots, suggests that such a wheel design produces

sufficient drawbar forces to maneuver within the abdominal environment. Recent *in vivo* porcine tests shows that the helical wheel design allows the robot to traverse all of the abdominal organs (liver, spleen, small and large bowel), as well as climb organs two to three times its height. These tests were performed without causing any visible tissue damage. Video recorded during one of these tests was used to reconstruct the path traversed by the robot, a portion of which is illustrated in Fig. 10. The length of travel shown is approximately 0.5 m, while the total distance traveled during the test without assistance was approximately 1 m.

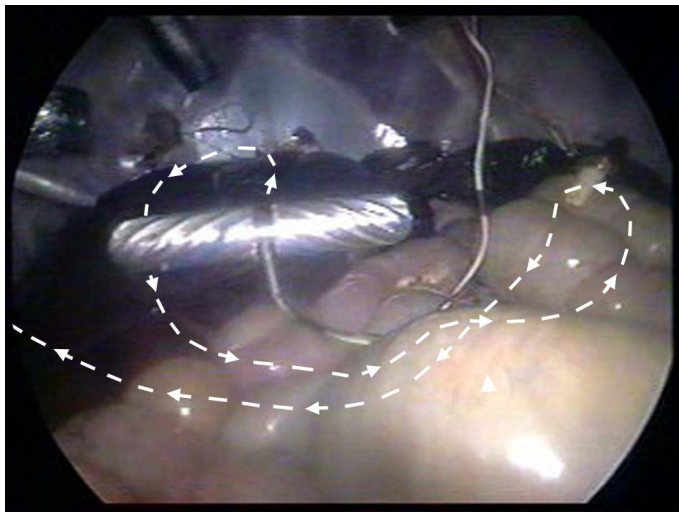


Fig. 10 *In vivo* path traced by the robot during porcine testing.

After exploring the abdominal environment, the biopsy mechanism was used to acquire three samples of hepatic tissue from the liver of the animal. The robot camera was used to find a suitable sample site. The biopsy graspers were opened and the sample site was penetrated with the biopsy forceps' spike. Then the graspers were actuated. This cut nearly all of tissue sample free. The robot was then driven slowly away from the sample site thereby pulling free the tissue sample. This tissue sample was then retrieved after robot extraction through the entry incision. This demonstrates the success of a one-port biopsy and successful tissue manipulation by an *in vivo* robot.

## VI. CONCLUSION

Experiments were performed to determine the forces required to biopsy tissue. This data lead to a successful mechanism design that is capable of producing sufficient grasper forces to sample *in vivo* porcine tissues. A successful robot wheel design has led to a robot capable of traversing the abdominal environment without causing tissue damage. This wheel design is also capable of producing sufficient drawbar forces to pull the biopsy sample free during *in vivo* testing. This robot design also incorporates an adjustable-focus camera mechanism capable of providing visual feedback from within the abdominal cavity of the patient.

Current work is focused on wireless developments and modification of the biopsy forceps to provide a clamp capable of clamping shut a severed artery. These developments are important for *in vivo* robotic use in forward environments such as battlefield situations. These achievements in tissue manipulation and visual feedback from within the abdominal cavity will further the development of *in vivo* robotics to assist surgeon in forward battlefield situations and traditional medical centers.

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