Abolfazl Pourghodrat

Department of Mechanical
and Materials Engineering,
University of Nebraska-Lincoln,
W342 Nebraska Hall,
Lincoln, NE 68588-0526
e-mail: a.pourghodrat@gmail.com

Carl A. Nelson¹

Mem. ASME
Department of Mechanical
and Materials Engineering,
University of Nebraska-Lincoln,
W342 Nebraska Hall,
Lincoln, NE 68588-0526
e-mail: cnelson5@unl.edu

Dmitry Oleynikov

Department of Surgery,
University of Nebraska Medical Center,
986245 Nebraska Medical Center,
Omaha, NE 68198
e-mail: doleynik@unmc.edu

Hydraulic Robotic Surgical Tool Changing Manipulator

Natural orifice transluminal endoscopic surgery (NOTES) is a surgical technique to perform “scarless” abdominal operations. Robotic technology has been exploited to improve NOTES and circumvent its limitations. Lack of a multitasking platform is a major limitation. Manual tool exchange can be time consuming and may lead to complications such as bleeding. Previous multifunctional manipulator designs use electric motors. These designs are bulky, slow, and expensive. This paper presents design, prototyping, and testing of a hydraulic robotic tool changing manipulator. The manipulator is small, fast, low-cost, and capable of carrying four different types of laparoscopic instruments. [DOI: 10.1115/1.4035548]

Introduction

Natural orifice transluminal endoscopic surgery (NOTES) is a future trend in surgery due to the potential benefits it offers. NOTES has not been well adopted yet in the operating room due to several shortcomings such as the difficulty of operating in a confined space, lack of visual/tool triangulation, and lack of a multitasking platform [1]. The relatively high number of instruments and the need to exchange them in many laparoscopic procedures is one of the most important hurdles that should be addressed to perform “pure” NOTES. The total number of different instruments required in a laparoscopic procedure (e.g., laparoscopic gastric bypass, hiatal hernia repair, removal of gastric band) can be as high as nine with 50 total instrument changes [2]. Manual tool exchange requires transportation of the new instrument from the external environment to within the body, removal of the old instrument outside of the body, and change of functional tips. This process is time consuming and may lead to complications such as bleeding, bowel perforation, and splenic injury due to increased chance of contact between tool edges and internal organs/tissues, endangering the safety of the patient.

Manually actuated endoscopes need to be flexible for ease of introduction and passage through the gastrointestinal (GI) tract. On the other hand, rigidity is required for tissue manipulation. With standard endoscopes, mobility is constrained, tactile feedback is unsatisfactory, field of view is narrow, depth perception is inadequate, and tool management is difficult [3]. Traditional endoscopes are not capable of providing necessary force capacity and tool manipulation for many advanced abdominal procedures [4].

To circumvent these limitations and in an effort to improve upon the current flexible endoscopes used in NOTES, researchers have leveraged robotic technology to develop novel surgical platforms. Harada et al. [5] built robotic modules that are meant to be ingested and assembled into a reconfigurable articulated mechanism inside the stomach to perform screening and interventions in the GI tract. Lehman [6] built a tethered bimanual NOTES robot

that is inserted through the mouth, enters the peritoneal cavity through the esophagus and an internal incision in the stomach, and attaches magnetically to the abdominal wall. Unstable anchoring of the robot, a compromise between the size of the robot and its speed and dexterity, and lack of a multifunctional tool were limitations of this robot. Recent development has focused on design of snake-like robots for NOTES. Son et al. [7] designed and prototyped a semi-autonomous snake robot for NOTES. This 11 DOF multisegment robot is driven and controlled using embedded servo motors at each joint. In a separate work, two generations of a snake robot for NOTES have been designed and built [8,9]. Several versions of a multiple-instrument manipulator have been developed to attach to these robots [2,9,10]. These designs use miniature DC motors for tool exchange and actuation. Miniature electric motors have limited power capacity in terms of speed and torque, resulting in a compromise between size and power. To augment the output torque and deliver adequate forces for tissue manipulation, previous designs have used relatively big gearheads and spur and/or bevel gears. Accordingly, these electric-motor driven manipulators are still bulky (outer diameter = 28 mm, length = 104 mm [10])—not suitable for NOTES applications with tight spaces for insertion and operation of the tools. With the use of miniature electric motors and large gearing, there comes slow tool exchange and actuation and high cost as seen in previous designs.

Cable-driven robotic endoscopy devices have been described in the literature, such as in the work of Phee et al. [11]. The robotic manipulators are controlled by long tendons actuated externally by DC motors. Frictional losses, loss of precision through cable stretch, and stick/slip behavior are major drawbacks associated with long tendon manipulation.

In an attempt to overcome the size-power balance with electric motors, researchers have tried to take advantage of fluid power with its inherent power density to develop potent and swift robotic surgical devices [12–14]. Stilli et al. [15] developed a soft robotic manipulator using a hybrid actuation mechanism combining pneumatic and tendon-driven actuators.

However, these platforms use complex designs which are difficult to scale for in vivo applications. None of these systems has

¹Corresponding author.

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tool exchange capability. The designs have not been thoroughly tested and/or validated.

This paper presents design, prototyping, and testing of a hydraulically actuated multifunctional manipulator which is half the size in both diameter and length, much faster, and more cost-effective than the electric motor-driven versions [2,9,10]. The vision of this project is to build a fully hydraulic miniature robot for NOTES with this tool changing manipulator attached to it.

Methods

Design Requirements. This section outlines the design requirements specified prior to the start of design efforts. The manipulator is intended to attach to each arm of a bimanual robot for NOTES. This provides at least twice as many instruments as a manipulator can typically carry at the site of surgery. An ideal bimanual robot equipped with two of the tool-exchanging manipulators may be capable of carrying as many as nine instruments (see Introduction section) and incorporate channels for insufflation, suction, and irrigation. This design presents the first generation of a hydraulically driven tool-exchanging manipulator and does not address the need for the auxiliary channels. A manipulator capable of carrying four instruments shall be created for the first generation. A typical adult esophagus inner diameter measures about 22 mm [2]. The manipulator's outer diameter (OD) and length shall be smaller than 22 mm and 100 mm to enable introduction and passage through the esophagus. Slow tool exchange is one of the limitations of standard endoscopy and has been reported as one of the drawbacks of previous designs. A tool exchange with the hydraulic multiple-instrument manipulator shall not take longer than 10 s. A pinch force on the order of 3 N shall be delivered at the tool tip [6]. The hydraulic system shall use water as the hydraulic fluid for safety of the patient.

Design and Prototyping. Figure 1 shows the electrohydraulic multifunctional manipulator with two different surgical instruments deployed, a laparoscopic grasper and surgical scissors. The

Fig. 1 Robotic surgical tool changing manipulator with a grasper (left) and scissors (right) deployed

Fig. 2 Instrument cartridge [16]

manipulator is 55 mm long with an outer diameter (OD) of 14 mm. The manipulator diameter is well below that of a typical human esophagus, which is nearly 22 mm [2]. The robotic tool changing manipulator consists of a multiple-channel cartridge storing four different kinds of combined piston-instruments and a master actuation system. Four commercially available miniature single-acting hydraulic cylinders (Sub-Miniature Minimatic[®] Cylinder, SM-3-4) with an OD of 4.8 mm and a bore of 4 mm were cut open, the pistons were extracted with caution to not damage the seals, and the outer tubes were sized to the desired length of 47 mm. The outer tubes were then attached to a four-channel manifold as seen in Fig. 2. Four miniature polyurethane tubes with an OD of 2 mm and internal diameter (ID) of 1.2 mm were connected to the manifold to transfer the hydraulic fluid (water) from the master system to the cylinders stored in the cartridge (slave system). The piston rods were cut to the desired length of 7 mm. The inserts of four different types of 2 mm laparoscopic instruments were also cut to proper sizes. Each modified instrument was connected to a modified piston using a laser-cut coupling. A preloaded spring was used in the piston-instrument assembly (Fig. 3) to bias the tools for unidirectional actuation. All plastic parts except for the couplings were fabricated out of ABS material using a 3D printer. A stopper (Fig. 3) was added to the piston-instrument assembly to stop the surgical instruments from unwanted rotation when deployed (see Fig. 3). The diameter of the stopper is a little larger than the ID of the corresponding holes in the cartridge to stop further advancement of the tool and allow it to open as the fluid pressure rises.

Fig. 3 Piston-instrument assembly [16]

Fig. 4 Scissor-piston assembly model

The preloaded compression spring makes the laparoscopic instruments normally closed. The instruments open when pressurized water is applied to the piston-instrument assembly, and close when the pressure is released.

The instruments slide in and out of the slave cylinders (cylinders in the cartridge as shown in Fig. 2) with an ID of 4 mm. Thus, the OD of the spring must be smaller than 4 mm. The ID of the spring should be larger than the OD of the instrument shaft (1.5 mm). The length of the spring is determined according to the spring stiffness, deflection required to provide the desired force, and length of the slave cylinders. A model, depicted in Fig. 4, was created to perform force analysis on the surgical scissors instrument as follows.

A relatively higher level of force is required for closing of the scissors due to high friction between the scissor blades as well as tissue resistance. The minimum force required to close the scissors manually (F_c) was measured to be 2.5 N. To keep the scissors closed under normal conditions (default), the spring should be preloaded. The force exerted from the spring to the piston (F_{pre}) can be calculated using

$$F_{pre} = kx_0 \quad (1)$$

where k is the spring constant and x_0 is the preloaded spring deflection. To open the scissors, the water pressure is applied to the piston, and the spring is compressed by x_1 .

The total force exerted on the piston from the spring can be calculated using

$$F_{sp} = k(x_0 + x_1) = kx_0 + kx_1 \quad (2)$$

Substituting kx_0 from Eq. (1) in Eq. (2), F_{sp} can be determined as follows:

$$F_{sp} = F_{pre} + kx_1 = F_c + kx_1 \quad (3)$$

According to the free-body diagram shown in Fig. 4 and Eq. (3), the force required to open the scissors (F_{op}) can be found from the following equation:

$$F_{op} = pA = F_c + kx_1 \quad (4)$$

where p is the pressure applied to the piston and A is the cross-section area of the piston. F_c is constant (2.5 N) as is A (10.349 mm²). To achieve a full opening of the scissors (an angular displacement of 64 deg), the scissors' shaft should displace about 2.5 mm ($x_1 = 2.5$ mm). According to Eq. (4), the higher the spring constant (k) the higher the pressure needs to be to fully open the scissors. The pressure rating for the "weakest link" in the system (plastic tubing) is 0.689 MPa (100 psi). Substituting $p = 0.689$ MPa in Eq. (4), k was calculated to be 1.852 N/mm.

Table 1 Scissors' spring specifications

Specification	Value
Manufacturer	W.B. Jones Spring Co.
Part#	C04-016-016
ID	2.2 mm (0.088 in.)
OD	3.1 mm (0.12 in.)
Length	12.7 mm (0.5 in.)
Spring constant	1.471 N/mm (8.40 lbs./in.)

Commercially available springs with equal or lower stiffness and proper ID and OD and length as described previously were searched. A compression spring with the specifications listed in Table 1 was selected. Using this spring constant in Eqs. (1) and (4), x_0 and p were calculated to be approximately 1.7 mm and 0.597 MPa (86.6 psi), respectively.

The higher the pressure applied in the lower chamber of the slave cylinder, the higher the stiffness of the spring which could be used, and the higher pinch and cutting force could be delivered by the instruments. However, the limiting factor here is the pressure rating of the hydraulic system components, with its minimum being 0.689 MPa (100 psi) for the plastic tubing as the "weakest link" of the system. Using MATLAB software, a model (described by Eqs. (5)–(16)) was created. The purpose of this model is to calculate the pinch force of the grasper and the water pressure as a function of the angular opening of the grasper. Figure 5 shows the grasper link lengths and angles.

$$\alpha = \sin^{-1} \left(\left(\frac{l_c}{l_b} \right) * \sin \theta \right) \quad (5)$$

$$\alpha_0 = \sin^{-1} \left(\left(\frac{l_c}{l_b} \right) * \sin \theta_0 \right) \quad (6)$$

$$X = l_b + l_c - (l_b * \cos \alpha) - (l_c * \cos \theta) \quad (7)$$

$$X_0 = l_b + l_c - (l_b * \cos \alpha_0) - (l_c * \cos \theta_0) \quad (8)$$

$$F_{rod} = k * (X - X_0 + x_0) \quad (9)$$

$$F_{pin} = \frac{F_{rod}}{2 * \cos \theta} \quad (10)$$

$$\sum M_0 = 0 \quad (11)$$

$$F_{tip} * l_a - F_{pin} * l_b * \sin(\theta + \alpha) = 0 \quad (12)$$

$$F_{tip} = \frac{F_{pin} * l_b * \sin(\theta + \alpha)}{l_a} \quad (13)$$

Fig. 5 Grasper force analysis

Table 2 Grasper spring specifications

Specification	Value
Manufacturer	W.B. Jones Spring Co.
Part#	C05-021-010
ID	2.7 mm (0.106 in.)
OD	3.8 mm (0.148 in.)
Length	7.9 mm (0.313 in.)
Spring constant	4.605 N/mm (26.3 lbs./in.)

$$F_{\text{tip}} = \frac{1}{2} * \frac{l_b}{l_a} * F_{\text{rod}} * \frac{\sin(\theta + \alpha)}{\cos \theta} \quad (14)$$

$$p = \frac{F_{\text{rod}}}{A} \quad (15)$$

$$\Upsilon = \alpha - 12.93 \quad (16)$$

where X is the grasper rod displacement (equal to zero when Θ is zero), X_0 is the rod displacement when the grasper is closed, x_0 is the rod displacement caused by the preloaded spring, k is the spring constant, F_{rod} is the force applied to the piston by water pressure and transferred to the grasper shaft, F_{tip} is the pinch force delivered by the grasper jaws, p is the water pressure in the system, and Υ is half the angle between the grasper jaws.

It is desired to achieve as high a pinch force (F_{tip}) on the order of 3 N (required for tissue manipulation [6]) as possible with a water pressure less than 0.689 MPa (100 psi) for a maximum opening of 46 deg (similar to the opening of the scissors). Different spring constants (selected from a commercially available spring catalog) and varying x_0 were input to the model and the output pinch force and the required water pressured were examined in worst-case conditions (jaw fully open with least mechanical advantage). Finally, a spring with the specifications listed in Table 2 was selected. Figures 6 and 7 show the pinch force and the required water pressure to provide corresponding pinch force versus grasper opening. With an x_0 value of 1 mm, the pinch force is 1.7 N and the pressure is below 100 psi for an opening of 46 deg.

A master–slave system was devised to control opening and closing of the instruments (Fig. 8). The master system consists of a master motorized cylinder, a pressure transmitter (ProSense, SPT25-10-0150 A), three solenoid valves (three-way, two-position valve, STC Valve 3S012-1/8-A), and a microcontroller board (Arduino Uno with motor shield).

The master motorized cylinder consists of a double-acting hydraulic cylinder (Bimba Manufacturing, University Park, IL, BR-011-D) with a bore of 8 mm and stroke of 25.4 mm coupled to

Fig. 6 Pinch force versus angular opening **Fig. 7 Water pressure versus angular opening**

a linear stepper motor (Anaheim Automation, Anaheim, CA, 11AV102AX06), as seen in Fig. 9.

In a standard hydraulic system, a hydraulic motor–pump with a high flow rate is used; flow control is usually achieved using a manual or expensive proportional flow control valves. Very fine (resolution on the order of 0.25–0.5 mm³) flow control was essential in order for our design to successfully function. The flow control scheme needed to be inexpensive because the ultimate goal of this design was to build a “reposable” (limited to a specific number of uses) manipulator. It was deemed difficult to achieve a fine flow control using traditional approaches. In our design, a novel method was devised to build an inexpensive and simple but accurate flow-controllable pump. A master cylinder (acting as a pump) was coupled to a linear stepper motor with approximately 0.01 mm positioning accuracy. A fine flow control with a resolution of 0.5 mm³ per motor step can be accomplished with this setup. This closed system removes the risk of leaking high pressure fluid with continuous flow into the abdominal cavity. The master cylinder has a larger bore than the slave cylinders, which may seem contrary to the main advantage (mechanical advantage) hydraulic systems offer. However, a larger bore provides higher suction per stroke of the cylinder. A high suction compensates for the pressure losses occurring in valves, fittings, and tubing. It also helps overcome the friction between the piston and cylinder during closure and retraction of instruments.

The working principle of the robotic tool changing manipulator is illustrated in Fig. 10. A master–slave methodology is adopted. The multiple-instrument manipulator (the slave system) is an electronics-free system which is intended to attach to a NOTES robotic arm and be placed in vivo. The entire master system with all electronics would be placed ex vivo. In contrast to previous

Fig. 8 Master–slave system

Fig. 9 Hydraulic cylinder coupled with a stepper motor [16]

Fig. 10 Schematic of the master-slave system [16]

Table 3 Solenoid valves sequencing scheme [16]

	Valve 1	Valve 2	Valve 3	
Instrument 1	■		■	ON Off
Instrument 2		■		
Instrument 3			■	
Instrument 4			■	

designs, larger motors can be used without compromising the load capacity and speed since the space constraints which exist in vivo are not applicable ex vivo. This would also help compensate for the aforementioned low mechanical advantage.

Tool exchange involves four steps: advancement, opening, closing, and retraction. Here, we outline a simple scenario and explain how the system works. When the user decides to deploy instrument 1 (see Fig. 10), the user input is passed to the microcontroller. The microcontroller outputs signals to energize valves 1 and 3. A known amount of fluid volume needs to be displaced to deploy each instrument. This displaced fluid volume is converted to motor rotation (the number of steps the stepper motor needs to run). The motor shield connected to the microcontroller sends a signal to the stepper motor. The motor rotation is converted to a linear displacement using a built-in lead screw. The motor is coupled to the master cylinder. The master cylinder contracts,

which makes the slave cylinder extend. The tool is deployed. When the user decides to manipulate tissues, the instrument needs to be opened. Opening of the instrument is done in the same fashion as the advancement of the instrument; however, higher pressure is required in this stage to compress the spring. To close the tool, the motor starts spinning in the opposite direction; the hydraulic fluid (water) is sucked back toward the master cylinder until the pressure drops below 0.034 MPa (the pressure transducer measures the system pressure); the energy in the spring is now released, closing the instrument. The back pressure can be adjusted to set the amount of applied force. In the retraction stage, the system works the same way as the advancement stage except that the motor rotates in the opposite direction. See Table 3 for the solenoid valves sequencing scheme.

Testing Results. All parts of the electrohydraulic manipulator system were assembled. The manipulator was tested with two instruments and without the pressure transducer to verify the functionality of the system. The entire manipulator and the master cylinder were submerged in water to fill the hydraulic fluid (water) into the system. A syringe was used to further inject water into the system. Bleeding the air out of the hydraulic system was performed without difficulty due to the opening at the top of the slave cylinders in the cartridge; however, preventing air infiltration during closure and retraction stages (suction) required plumbing sealant (Loctite 1366077).

All four stages of tool exchange worked as expected. Tool exchange time is a function of the velocity of the stepper motor in the master motorized cylinder. The higher the velocity of the stepper motor, the higher the fluid flow rate, and therefore the shorter the tool exchange time. The velocity of the stepper motor was set at two values, 50 rpm and 120 rpm, and the manipulator was tested separately for each velocity. With the velocity of 50 rpm, the tool advancement/retraction time and the tool actuation time were measured to be approximately 4 and 1.5 s, respectively. With the velocity of 120 rpm, the tool advancement/retraction speed and tool actuation were measured to be approximately 1.35 and 1 s, respectively. These results indicate a significant improvement over manual interchange and/or previous designs [2,10] (see Table 4). The coupled motor-cylinder pump created around 0.345 MPa of pressure with 5 V input and approximately 700 mA of current. The pinch force of the grasper was measured to be 1 N for an angular opening of 28 deg. This experimental result is close to the 1.25 N found from the model described previously. The scissors successfully opened up 46 deg and closed with a pressure on the order of 100 psi. Although the pressure is higher than the 87 psi predicted by the model, it is still acceptable considering the safety factor used in building hydraulic components.

Conclusions

The electrohydraulic robotic tool changing manipulator presented in this paper offers several advantages over previous electric motor-driven designs. Smaller size and faster tool exchange are the main advantages (see Table 4). The electrohydraulic manipulator is capable of carrying four different instruments and is more compatible with the harsh in vivo environment of the human body. The tools in the manipulator have a peak force which is a function of the spring stiffness and the system back pressure. This reduces the risk of applying excessive forces to tissues that could lead to tissue perforations. In this design, all

Table 4 Advancement and tool actuation time comparison

Design	OD (mm)	Length (mm)	Advancement time (s)	Tool actuation time (s)
Nakamura [2]	30	~110	~22	6
Seow et al. [10]	28	104	~15	~2
Pourghodrat (design presented in this paper)	14	55	1.35	1

electronics are placed *ex vivo*. This helps with sterilization of the manipulator after the surgery and improves the safety of the patient by eliminating the possibility of leaking electricity or transferring heat produced by motors to the tissue. The electrohydraulic manipulator cost is low, much less than the electric motor-driven versions, making it an ideal tool for single-use (disposable) *in vivo* robotic applications. Replacing the manipulator's metallic parts with nonferrous materials, it could be used for MRI-guided robotic surgery [16].

Future work includes improving priming of the hydraulic system and sealing of all connectors, adding the pressure transducer and additional instruments to the system, and further miniaturizing the manipulator. The manipulator OD can be reduced to 12 mm by using cylinders with 3 mm bore. The manipulator length can be decreased to 50 mm by shortening the length of the coupling and the piston on the piston-instrument assemblies.

The vision of this work is to create a fully hydraulic bimanual robot for NOTES. In Ref. [17], we have presented design and testing of a fluid-powered robotic arm using the hydraulic tool changing manipulator and novel fluidic linear and rotary actuators. Further development, verification testing (bench-top and animal testing) and validation testing (human trial study) are necessary before this work can become commercially available to the mass market.

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