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Towards Active Variable Stiffness Manipulators for Surgical Robots

Huu Minh Le^a, Thanh Nho Do^b, Cao Lin^{a,*}, and Soo Jay Phee^a

^aRobotics Research Centre, the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798.

^bCalifornia NanoSystems Institute, University of California, Santa Barbara, Elings Hall, Mesa Road, Goleta, USA, 93106

*Corresponding author, Email: lin.cao@ntu.edu.sg

Abstract – Variable stiffness for robotics are attracting increasing attention from researchers, especially in the surgical field. A surgical robot that can access the human colon or stomach via natural orifices must be flexible enough to pass through tortuous paths and to work in a confined space. Meanwhile, the robot must also be stiff enough to ensure pushability and to hold payloads during the surgery. Thus, a surgical robot which allows active stiffness control is desirable. This paper presents a new design concept for variable stiffness manipulators using a thermoplastic material—Polyethylene Terephthalate (PET)—and a flexible stainless steel sheath as a heating solution. The stiffness of PET can be significantly adjusted through temperature. Experiments and validations are carried out at different conditions. The results show that our proposed design is at least as flexible as a typical commercial endoscope when flexibility is desired and meanwhile at least 9 times stiffer than the endoscope when stiffness is desired. A tendon-driven manipulator based on the proposed concept was also developed. Validation tests showed that the manipulator in compliant mode can be significantly bend through cable actuation, and the manipulator in stiff mode can hold its shape against considerably large loads.

I. INTRODUCTION

Surgical robots are gaining increasing popularity in the field of Natural Orifice Transluminal Endoscopic Surgery (NOTES), an endoscopic surgical intervention technique for treatment within the intraperitoneal cavity through natural orifices such as mouth, vagina and anus [1]. In NOTES, a flexible endoscope (or manipulator) with a camera, a light source, and a channel for liquid or gas is used to transverse through the winding and narrow channels in human bodies. The endoscope also provides channels for the surgical robot end-effectors, e.g., graspers or electrocautery knives, enabling the doctors to perform treatments. In this case, the endoscope serves as a working platform for these end-effectors. Therefore, the endoscope in NOTES, on one hand, needs to be flexible to transverse through tortuous paths in human bodies without damaging human tissues; on the other hand, it has to be stiff enough to be pushed forward and to hold its shape against external forces when the end-effectors are working with the target. The stiffness variation in these two cases is significant, and existing endoscopes fail to fully meet these two conflicting requirements, which limits the performance and the use of surgical robots. To advance the endoscope design for these requirements, this paper proposes a novel variable stiffness manipulator whose stiffness can be actively adjusted significantly.

In the literature, the principles for variable stiffness can be divided into two categories: structures and materials. In the former category, stiffness change is achieved by reorganizing and/or reconnecting parts in the structure. For instance, Vargas

[2] used a locking mechanism based on sliders and blockers to switch compliant and rigid states of cannula system. Cheng et al. [3] applied the reversible jamming of granular media (sand or coffee powder) and vacuum pressure to transit from compliant to solid state. Shiva et al. [4] proposed a continuum silicon-based variable stiffness manipulator using an antagonistic actuation scheme. In that design, the combination in antagonistic fashion of tendons which are embedded into the manipulator's wall and pneumatic actuation enables the variation of general stiffness. These working principles are feasible but the manipulators based on these principles have either limited stiffness-changing properties or too complex and bulky bodies to be miniaturized [5].

Materials with special features have also been used for stiffness changing, including electrorheological fluids, magnetorheological fluids [6-8], low melting point (LMP) phase changing alloy (PCA) [9], and thermoplastic polymers [10-12]. Electrorheological and magnetorheological fluids, which change their states between liquid and quasi-solid states in electric and magnetic fields, respectively, have been used for catheters and penile. The advantage of this approach is short activation time. Yet, high voltages and currents are required, which is risky in surgical robots. Furthermore, these materials in rigid state are not stiff enough for sole stiffening mechanism [5]. A continuum manipulator was designed and prototyped using Field's metal an alloy of bismuth (32.5 wt%), indium (51 wt%), and tin (16.5 wt%), with a relatively low melting temperature (62°C), low viscosity in the liquid state, and high stiffness in the solid state. A high applied current is the main drawback for this design (4A) [9]. In another study, Huan et al. [13] developed a stiffness varying mechanism using a low melting point polymer, Polycaprolactone (PCL). This material was melted at about 60°C with the heat transmitted via copper wire and braided stainless steel tube. The paper reported that the achieved flexural modulus of the manipulator in rigid state was 225 MPa that is relatively low. Using similar method but different materials, researchers in [11, 12] have employed thermoplastic polymers PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) as variable stiffness solutions and shape memory alloy as heating method for changing stiffness of fabrics. The shortcoming of PLA is brittleness [14], and that of ABS is high glass transition temperature (105°C.).

In this paper, we propose a new variable stiffness method using PET ([Polyethylene terephthalate](#)), whose stiffness significantly decreases upon heating. Besides substantial stiffness change, PET is chosen also because of its biocompatibility, high strength, relatively low glass transition temperature (67°C), high chemical resistance, and low cost [15]. Along with a flexible stainless steel spring as a heating

media, a novel variable stiffness manipulator based on PET is proposed. The flexibility and stiffness of the proposed manipulator was measured and evaluated using a commercial endoscope. The preliminary results show that our proposed design is at least as flexible as the commercial endoscope when flexibility is desired and meanwhile at least 9 times stiffer than the endoscope when stiffness is desired.

For the paper organization, materials and methods for the proposed system are detailed in Section II. Section III introduces the experiments set up for the stiffness measurements of the proposed manipulator and the commercial endoscope. All the results and comparisons are presented in Section IV, followed by Section V with the validation of the design concept. At the end, the conclusion and future work are given in Section VI.

II. MATERIALS AND METHOD

Developed in the 1940's, PET (Polyethylene terephthalate) is a thermoplastic (or thermosoftening) material that turns to the rubbery state from the glass state once its temperature goes beyond the glass transition temperature (67 °C). PET is considerably stiff in the glass state but highly flexible in the rubbery state. In this study, we took advantage of this thermoplastic feature to design a new type of variable stiffness tube. Furthermore, PET poses some other properties that make it a great candidate for medical applications such as biocompatibility, clearness, lightweight, high strength, stiffness, favorable creep characteristics, low flavor absorption, high chemical resistance, barrier properties, low cost, relatively low transition temperature [15]. The PET tube is commercialized and supplied by Vention Medical Inc.

Regarding heat transmission, Thomas et al. [11] have employed shape memory alloy (SMA) cable with current supplied. The disadvantage of this idea is that the design will have undesirable shape change due to SMA's shape memory effect. In our proposed design, we used a flexible stainless steel coiled sheath from Asahi Intecc Japan, Inc. Compared to SMA used in [11], stainless steel does not have shape memory effect and thus does not result in undesired shape change. Stainless steel is also biocompatible and has high electrical resistance. Moreover, the chosen stainless steel coiled sheath is highly flexible and thus has little effect on the stiffness of the manipulator in the rubbery state.

Fig. 1. The variable stiffness tube structure and working principle.

The design and working principle are depicted in Fig. 1. Our variable stiffness tube (VST) is made of two different tubes including outside PET tube and inside flexible stainless steel sheath (tube). In the room temperature, our tube is quite stiff relying on the PET tube. If we supply the current into the stainless steel sheath, thanks to its electrical resistance, the sheath and PET tube will be heated. After temperature passes the glass transition threshold, PET tube will change from glass to rubbery state, making our VST soft and flexible.

III. EXPERIMENTS

Experiments were conducted to compare the Young's Modulus of the proposed VST and a commercial endoscope in compliant and rigid states.

Three-point bending tests were performed using the Instron 5569 material testing machine with a 500N loadcell from Instron Singapore ITW Pte Ltd.

A. VST bending tests

The experiment setup is shown in Fig. 2. 3 kinds of tubes were tested, single PET tube, a VST in the glass state and VST in rubbery state. All the components are off-the-shelf items and their size are as follows: the length for both PET tube and sheath is chosen as 115 mm while the sheath size possesses OD of 1.45mm and thickness of 0.3 mm. The OD and ID of our proposed tube is similar as PET tube's OD and flexible sheath's ID respectively. Note that the interested property, Young's Modulus, is independent of the sizes of components.

The support span was set at 50 mm for all the tests. The samples were loaded at 2 mm/min until the deflection reached 7 mm for the single PET tube and VST in glass state and 15 mm for the VST in rubbery state. The bending test for glassy VST was conducted at room temperature, while that of rubbery VST started 30s after supplying 0.3A into the stainless steel sheath. This was so because it took around 30s for the VST to change from the glass state to the rubbery state when 0.3A current was applied.

Fig. 2. VST bending tests. (a) Instron 5569 material testing machine. (b) Bending test with single PET tube. (c) Bending test with VST in glass state. (d) Bending test with VST in rubbery state.

B. Endoscope bending tests

To compare our proposed VST with a commercial endoscope in terms of stiffness and flexibility, the endoscope GIF-2T240 from Olympus Co. was also tested. Bending test was carried out at four different positions in the endoscope: the middle of the flexible tip, and the positions which are 20cm, 40cm, and 60cm away from the end of flexible tip. For each position, the endoscope was tested in two different modes: locked mode and unlocked mode. The endoscope is stiff in locked mode and compliant in unlocked mode. The experiment setup is described in Fig. 3. The endoscope was loaded with the speed of 2mm/min, and the maximum deflection was set as 4mm.

Fig. 3. Olympus endoscope bending tests. (a) The midst of flexible section. (b) 20cm from the end of flexible tip position. (c) 40cm from the end of flexible tip position. (d) 60cm from the end of flexible tip position.

IV. RESULTS AND COMPARISONS

With three-point bending tests, all the results including VST, locked endoscope, and unlocked endoscope are plotted in Fig. 4, Fig. 5, and Fig. 6, respectively. In each case, the measurement data is presented in term of force versus deflection.

From Fig. 4, it is noted that the stiffness (slopes of the lines in the figure) of the VST in glass state and rubbery state were significantly different. Meanwhile, the stiffness of the PET tube and the glassy VST were close, meaning that the flexible stainless steel sheath was very flexible and did not contributed much to the stiffness of the VST in glass state for the single PET tube and glassy VST. The Young's modulus was

calculated using the equation of the middle point deflection of an elastic beam of length L loaded by a central force F in three-point bending test [16]:

$$\delta = FL^3 / 48EI, \quad (1)$$

where δ is the mid-point deflection, F is the central load, E is the flexural modulus, and I is the second moment of area. The calculated flexural modulus of glassy and rubbery VST are 2.141 GPa and 38.88 MPa respectively. It can be seen that the stiffness of VST drops 55 times when shifting from the glass state to the rubbery state.

Fig. 4. Bending test results for VST.

Fig. 5. Bending test results for unlocked endoscope.

Fig. 6. Bending test results for locked endoscope.

The bending experimental results of unlocked and locked endoscope are shown in Fig. 5 and Fig. 6, respectively. It can be seen that the endoscope is stiffer in locked mode than in unlocked mode thanks to the cable tension. It is also noted that the further the section is from the distal end, the stiffer it will be, for instance, among the 4 testing points, the 60cm point in the locked endoscope has the largest stiffness and the mid-point in the unlocked flexible tip has the smallest stiffness. The Young's Modulus values at these two critical positions were used to compare with the proposed VST. The second moment of area for the endoscope was calculated based on the endoscope specification from Olympus [17]. The principle moments of inertia of area for the endoscope are 144.5 mm^4 and 155.68 mm^4 . Finally, with the bending formula and testing results, the flexural modulus of different points in the endoscope were calculated and given in Table 1.

Table 1. Flexural modulus of different points in the endoscope

	Locked endoscope	Unlocked endoscope
E_{Tip}	49-53 MPa	35-38 MPa
E_{20cm}	105-113 MPa	102-110 MPa
E_{40cm}	142-153 MPa	140-151 MPa
E_{60cm}	211-227 MPa	192-207 MPa

Given this table and the above calculated flexural modulus of the VST in glassy state (2.141 GPa) and rubbery state (38.88 MPa), the flexibility and stiffness of the VST and those of the endoscope's tip and body can be compared.

Compared to the tip of the endoscope, the rubbery VST is as flexible as the unlocked endoscope's tip, while the glassy VST is about 40 times stiffer than the locked endoscope.

Compared to the body of the endoscope, the rubbery VST is approximately 2.5 times more flexible than the unlocked endoscope (20 cm position). Meanwhile, the glassy VST is 9 times stiffer than locked endoscope (at 60 cm position).

Thus, the following conclusions can be made: when flexibility is desired, our proposed VST is at least as flexible

as the most flexible part of the current commercialized endoscope; when stiffness is desired, our proposed VST is 9 times stiffer than the stiffest part of the endoscope.

V. CONCEPT VALIDATION

In this section, we apply this VST design concept into a tendon driven manipulator, which have been used in many surgical robots [18-20]. The design of the manipulator is shown in Fig. 7. This manipulator consists of a PET tube, a stainless steel coiled sheath, four spacers, and four tendons. The four spacers are fixed on the PET tube with even distance. With each tendon going through all the spacers, the shape of the manipulator can be adjusted by pulling the tendons at the proximal end. The outer diameter and inner diameter of the PET tube are 4 mm and 2.22 mm, respectively. The diameters of the spacer and the tendon are 5.5 mm and 0.23 mm. The total length of the manipulator is 60 mm.

Fig. 7. Design of the variable stiffness manipulator

The first experiment was conducted to confirm the ability to bend in rubbery state. Fig. 8 shows that this VST in rubbery state can be bend more than 90° by pulling the appropriate tendon.

Fig. 8. Rubbery VST can bend more than 90°

The next two experiments are to measure the time length for the manipulator to become flexible with two different currents being applied. With $(0.3 \pm 0.02) \text{ A}$ current and 10g weight attached at the end, the VST started becoming soft after 5s, and its stiffness dramatically dropped after 30s. With $(0.45 \pm 0.03) \text{ A}$ current being applied, the VST began to bend at 3s and its stiffness significantly dropped at 10s (Fig. 9). We

also observed that there are some changes in current when the stainless steel changed is heated up.

Fig. 9. Configurations of the manipulator with 10 g load at the distal end and different currents being applied. (a) With the current of 0.3 ± 0.02 A; (b) Current of 0.45 ± 0.03 A.

The last test further demonstrated that, after being bend in rubbery state and turn off the current in 20s with ambience cooling, the VST can hold up to 120g external weight without cable tension (see Fig. 10).

Fig. 10. VST (in glass state) holding weight after heating and ambience cooling.

VI. CONCLUSIONS AND FUTURE WORK

We have developed a new and promising concept for variable stiffness manipulators using a PET tube and a flexible stainless steel sheath. Three-point bending tests were conducted to compare the stiffness and flexibility of a proposed VST with a commercial endoscope. The results show that our proposed design is at least as flexible as a typical commercial endoscope when flexibility is desired and meanwhile at least 9 times stiffer than the endoscope when stiffness is desired. A tendon-driven manipulator based on the proposed concept was also developed. Validation tests showed that the manipulator in compliant mode can be significantly bend through cable actuation, and the manipulator in stiff mode can hold its shape against considerably large loads. In addition, the compliant mode was reached within a very short period of time (13 seconds) with 0.45A input current.

In the future, we will investigate the characterization of variable stiffness in terms of the dimension of PET, flexible sheath, and current applied. A detailed characterization is the first step for control and optimization design. Design a robust stiffness control algorithm with appropriate cooling methods and environment uncertainties are our next goals. Ultimately, real applications for surgical robot components such as endoscopes and robotic end-effectors will be developed, and in-vivo experiments will be conducted.

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