Mechatronics 53 (2018) 109–123

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Design and modelling of a variable stiffness manipulator for surgical robots☆

Le Huu Minh[a], Cao Lin[a,*], Do Thanh Nho[b], Phee Soo Jay[a]

[a] Robotics Research Centre, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore
[b] California NanoSystems Institute, University of California, Santa Barbara, Elings Hall, Mesa Road, Goleta, 93106 USA

ARTICLE INFO

Keywords:
Minimally Invasive Surgery (MIS)
NOTES
Surgical robot
Variable stiffness robot
Variable stiffness material

ABSTRACT

In Natural Orifice Transluminal Endoscopic Surgery (NOTES), a surgical robot that can access the human colon or stomach via natural orifices should have sufficient flexibility to pass through tortuous paths and to be operated in a confined space. In addition, the robot should possess an acceptable stiffness level to hold payloads during the surgery. This paper presents a new design concept for variable stiffness manipulators using thermoplastic material Polyethylene Terephthalate (PET) and a flexible stainless steel sheath as a heating media. The stiffness phases of PET can be actively adjusted through temperature. Experiments at different conditions showed that the proposed design was at least as flexible as a typical commercial endoscope in compliant mode and at least 9 times stiffer than the endoscope in stiff mode. In addition, flexural modulus of the proposed manipulator with respect to temperature, current, and time was modeled and validated through both simulation and experiments. A tendon-driven flexible robotic arm integrated with a variable stiffness spine was also developed, and ex vivo tests on fresh porcine tissue were conducted. The manipulator in compliant mode can be easily controlled through the tendons, and it is able to hold its shape against considerably large loads in stiff mode. The results demonstrate not only the high potential of the design concept for the future medical application but also the first steps toward building a complete surgical robotic system with fully controlled variable stiffness.

1. Introduction

Surgical robots are gaining 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 [1,2]. 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; one 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, but existing endoscopes fail to fully meet these two conflicting requirements, which limits the performance and the use of surgical robots. To advance endoscope design for these requirements, this paper proposes a new variable stiffness manipulator whose stiffness can be actively adjusted significantly. Apart from being crucial for endoscopes, variable stiffness also plays the same important roles in other surgical applications such as flexible robotic arms, catheters, surgical tools [3–5]. These medical devices have to be flexible to follow the tiny, non-linear paths inside human body and guarantee safety, and they also need to be stiff enough to transmit force during biopsies or grasping tasks, support other tools or increase the positioning and surgical accuracy [5].

In the literature, the working principles of variable stiffness can be categorized into two different domains: structures and materials. In the former category, stiffness is adjusted by reorganizing and/or reconnecting parts via attachable/detachable links inside the structure. Compliance is obtained when parts are detached, and high stiffness is obtained when parts are reattached [6]. For example, Yagi et al. [7] developed an outer sheath with a pneumatic driven slider linkage lock for endoscopic surgery. In this design, multiple cylindrical pieces consisting of the sheath, link, sliders, and channels are connected serially. If the inner channel is empty, all the parts stay in compliant mode. In contrast, rigid state is achieved if the air is applied into fluid channel,

☆ This paper was recommended for publication by Prof. Bijan Shirinzadeh.

* Corresponding author.
E-mail address: lin.cao@usask.ca (L. Cao).

https://doi.org/10.1016/j.mechatronics.2018.05.012
Received 14 August 2017; Received in revised form 13 March 2018; Accepted 23 May 2018

resulting in higher friction force between the piece and the slider. Although being advanced, the design is quite complex due to many small parts involved and the use of air pressure. In addition, the structures are too bulky to be used in the confined spaces in human. In other studies, cable tension was employed to stiffen cable-driven surgical robots [8–11]. The main disadvantage of using cable tension is the need of highly durable cables and links. Recently, particle jamming technology based on granular materials, e.g., dry sand or coffee beans, is gaining wide attentions [12–16]. The benefits of this approach include fast response and dramatic stiffness change between two states. However, high stiffness requires substantial volume of granular materials, resulting in bulky structures. In a recent study [17], a variable stiffness robotic link consisting of a cylindrical silicon outer tube and an inner plastic embedded mesh was developed. Stiffness is controlled by air pressure, resulting in large structure dimensions and therefore it is not suitable for surgical applications.

Phase-change materials are the other candidates for stiffness control, including electrorheological fluids, magnetorheological fluids [18–20], low melting point alloy (LMPA), phase changing alloy (PCA) [21,22], and thermoplastic polymers [23–26]. 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 prosthesis penile. Although this approach is able to provide short activation time, high voltages and currents are required that is risky in surgical applications. Furthermore, these materials in rigid state are not stiff enough for use in some applications [6]. Recently, a variable stiffness manually operating platform using a mixture of indium, gallium and stannum was developed for stiffness adjustment in laparo-endoscopic single site surgery (LESS) [22]. There still exist several limitations in this design. For example, the stiffness difference between compliant and rigid mode is only four times. Both the time of the phase change from rigid to flexible mode and the time of the reverse phase change are considerable, 22 s with 89 °C hot water and 15 s with 18 °C cold water respectively. Field's metal alloy (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 was used to develop a continuum manipulator [21]. However, a high current of around 4 A is required for this design and therefore it is not safe for use in human. Although LMPA have relatively low transition temperatures, but they are not stable (rubidium and Gallium) and even toxic (Cerrolow 117). In addition, they do not possess high stiffness in rigid mode [5,27,28]. As a consequence, they are not ideal candidates for variable stiffness designs for surgical applications. In another study, Huan et al. [29] 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 [24,25] have employed thermoplastic polymers polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) as variable stiffness solutions and shape memory alloy as heating method to change the stiffness of fabrics. However, PLA is too brittle in stiff mode [30], and ABS' glass transition temperature (105 °C) is too high for human body. In addition, although encouraging preliminary results have been obtained in these studies, there is a lack of studies on the comparison between the proposed designs and existing devices such as commercialized endoscopes, the modeling and control of these designs, etc.

In this paper, a new variable stiffness method using Polyethylene Terephthalate (PET) is proposed. The stiffness of the proposed structure can be significantly decreased upon heating using a flexible stainless steel sheath as an electrical resistor. Apart from immense stiffness change, PET was selected among other thermoplastic materials due to its biocompatibility, high strength, relatively low glass transition temperature (around 67 °C), high chemical resistance, and low cost [31]. The variable stiffness tube (VST) made of PET tube and flexible sheath was constructed and tested and compared to a commercial endoscope. The proposed design is at least as flexible as the commercial endoscope when flexibility is desired and at least 9 times stiffer than the endoscope when stiffness is desired. The flexural modulus of the proposed manipulator with respect to temperature, current, and time was modeled and validated through both simulation and experiments. To further demonstrate the effectiveness of the design, the VST was also validated in ex-vivo experiment (fresh pig tissue) with a flexible manipulator. Note that this paper is the extended version of our previous conference paper [32].

The detailed design, working principle, and preliminary testing results are given in Section 2, followed by Section 3 with stiffness modeling and related validation experiments. Section 4 describes the variable stiffness robotic arm, and Section 5 presents the conclusions and future work.

2. Conceptual design and preliminary experiment results

2.1. Materials

Thermoplastic materials are potential candidates for variable stiffness structures due to their flexibility upon heating and rigidity upon cooling. To provide variable stiffness manipulators for surgical applications, the materials should satisfy the following criteria: (1) high stiffness variation ratio; (2) glass transition temperature, i.e., the temperature at which the stiffness of the material changes dramatically; (3) biocompatibility; (4) high strength. Table 1 shows these properties of common thermoplastic materials [33–36]. Among the current thermoplastic materials, Nylon and PET (Polyethylene terephthalate) have outstanding features to fulfill the requirements. Due to the humidity-dependent transition temperature of Nylon that can result in challenges for future control problem, PET was selected eventually.

Developed in the 1940's, PET 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

Table 1
Properties of common thermoplastics [33–36].

Acronym	Polymer	Glass transition temperature $T_g(^oC)$	Flexural modulus (GPa) in glassy state	Flexural strength (MPa)
ABS	Acrylonitrile butadiene styrene	110–125	2.07–4.14	50–80
PMMA	Poly(methyl methacrylate)	85–110	2.24–3.17	70–127
PLA	Polylactic acid	60–65	2.39–4.93	48–110
Nylon 6	Nylon 6	47–57 (humidity dependent)	0.7–2.83 (humidity dependent)	35–108 (humidity dependent)
Nylon 6,6	Nylon 6,6	–15–77 (humidity dependent)	1.21–2.96 (humidity dependent)	42–123 (humidity dependent)
PET	Polyethylene terephthalate	68–80	2.41–3.1	82–124
PVC	Polyvinyl Chloride	75–105	2.07–3.45	65–94
PC	Polycarbonate	150	2.34	93.1