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Compact and Lightweight Variable Stiffness Mechanism Using Elastic Band for Medical Robots

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***Abstract*—Current surgical robots for Minimally Invasive Surgery are generally rigid to achieve tasks with high precision. Therefore, there is a risk of injury to surrounding organs due to unexpected contact (e.g., while the surgical tool is invisible from the endoscopic view). In order to solve this problem, we introduce a Variable Stiffness Mechanism (VSM) that can actively change the joint stiffness of manipulator according to the situation. Although a number of studies have been conducted to provide VSM, it is difficult to implement them for surgical application where compactness and lightweight with a sufficient range of variable stiffness are required for not impeding the surrounding medical staffs and environment. In this study, we propose a new VSM that utilizes large deformation of elastic bands. The proposed mechanism let the stiffness be variable by changing the effective length of the elastic band shaped as a part of ring, minimizing the size and weight of the structure. The preliminary experiments showed the stiffness was successfully changed linearly, although the demonstrated range of stiffness was smaller than the previously presented VSMs. The reason of the limited range of stiffness was identified as the prototype implementation, and found to be further improved in the next research step.**

***Index Terms*—actuator, variable stiffness, surgical robot**

I. Introduction

In general, robots for precise manipulation are highly rigid, thus often these robots are large and heavy. This also applies to surgical robots that require a series of fine manipulation of organs during the surgery. In natural human behavior, the mechanical impedance of the human musculoskeletal structure is variable, and effectively used in daily life [1]. For example, the muscles are tensed to improve the movement accuracy in precise task such as writing small letters. Contrary, the body can be flexible by releasing the tension to decrease the impact for unexpected collisions in coarse movements such as picking up a thing on the floor, or fumbling for a light switch in the dark. This suggests that the current surgical robots perform tasks always in a tensed state, although the risk of serious damage to the surrounding organs are imminent in some cases (e.g. approaching to the surgical area with a relatively higher speed, and/or (a part of) surgical tool is invisible from the endoscope). In order to mitigate the risk of injury, we propose a Variable Stiffness Mechanism (VSM) with a compact and lightweight design, specifically developed for the surgical application. To change the robot's stiffness, there's also a method by introducing force sensors on the robot, and control the position according to the input from the force sensor, rendering the different stiffness of structure — known as admittance control [2]. However, there are some issues to be solved when introducing it to a surgical application:

- In order to sufficiently reduce the mechanical impedance, it is necessary to increase the control gain, which may cause the system to become unstable.
- The energy device used in the surgery becomes a noise source, which may cause malfunction of electrical force sensors such as strain gauges.
- Robots inserted into the body like laparoscopic surgery robots can come in contact with various surrounding tissue, thus a number of force sensors would be required to measure the force in multiple axes.
- Sensors that come into direct contact with the patient's body need to be sterilizable, but there is no such force sensor available in the market.

VSM that can change the mechanical stiffness using an additional actuator and mechanical element, has been widely studied [3]. As VSM works mechanically, the issues of admittance control in surgical robots described above, are not posed to VSM.

In VSA-II [4], four-bar-linkage mechanisms and linear springs are combined to make non-linear springs, and the stiffness is varied by changing the preload of this non-linear springs arranged antagonistically. However, this method requires a large amount of energy to maintain high stiffness due to its structure of the mechanism. On the other hand, in AwAS [5], AwAS-II [6], QA-Joint [7], FSJ [8] and SVSA [9], the stiffness is varied by changing the reduction ratio of the spring and the load. The AwAS and AwAS-II use a ball screw to change the lever length ratio by changing the pivot point, the QA-Joint uses a cam bar and rollers, the FSJ uses cam disks and rollers and SVSA uses an archimedean spiral relocation mechanism to change the lever length ratio. In VSJ [10] and MASA [11], the stiffness is varied by changing the effective length of the spring. In VSJ, leaf springs are located in the radial direction, and the effective length is changed by using a four-bar-linkage mechanism. In MASA, leaf springs are located in the axial direction, and the effective length is changed by using a double-tripod parallel mechanism. However, with these existing mechanisms, it is difficult to

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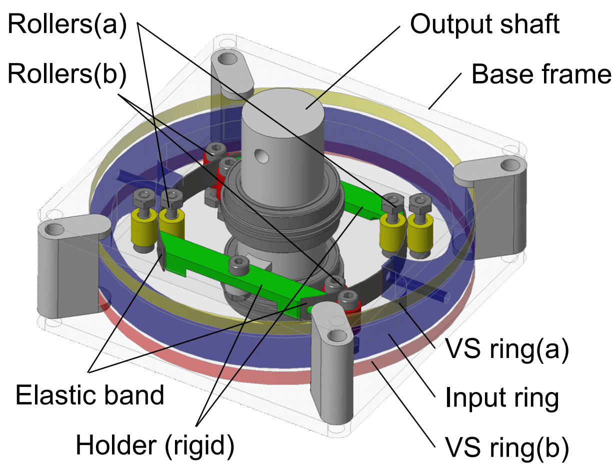


Fig. 1 CAD model of the proposed mechanism.

achieve both a wide variable stiffness range and a compact and lightweight configuration which is necessary for surgical robots.

In this paper, we present a compact and lightweight VSM using large deformation of elastic bands that can be implemented on a surgical robot, is described. In section II, the concept of proposed mechanism and its implementation are described. The section III describes the preliminary experiment. At last, the section IV describes the discussions and future outlook of this study.

II. Proposed Mechanism

A. Requirements

The required specifications were considered as follows.

- Size: $\phi 100 \times 100$ mm or less.
- Weight: less than 1 kg.
- Range of Variable stiffness: 125.7 Nm/deg or more at maximum, 0.63 Nm/deg or less at minimum.

We assumed a forceps with a length of 300 mm and a manipulator with an arm length of 300 mm, and the variable stiffness range was set as the error becomes less than 1 mm when lifting 2 kg at the maximum stiffness, while allowing 10 mm of displacement at the minimum stiffness.

B. Proposed Mechanism

The concept of proposed mechanism is shown in Fig.1, while Fig.2 shows the exploded view of concept CAD model. The mechanism consists of a base frame, an input ring, an output shaft, Variable Stiffness (VS) ring (a) and (b), two elastic bands, two band holders and rollers (a) and (b). As the motion input, the rotational motor can be connected to the input ring, while the output with the variable stiffness can be provided from the output shaft. The elastic bands are key elements in the concept to provide the compliance in the mechanism. Two elastic bands are connected to the band holders, making a both side-cut circle, and the band holders

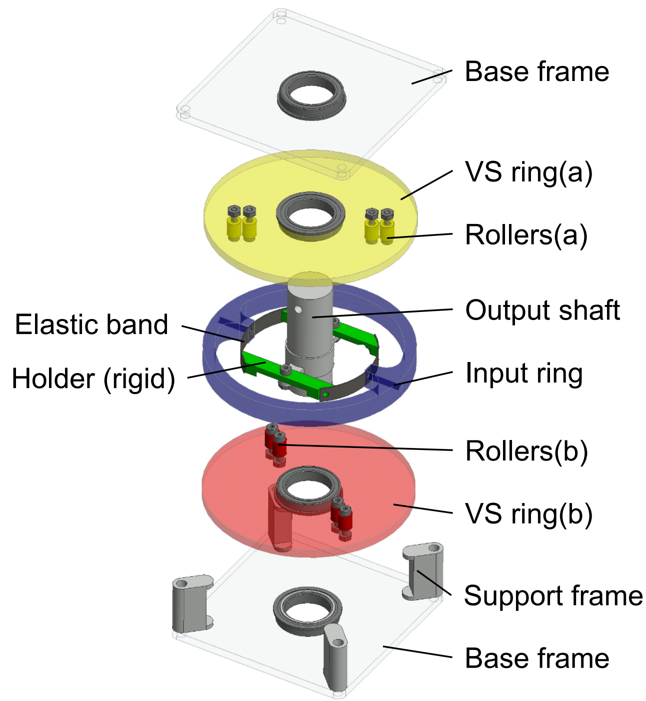


Fig. 2 Exploded view of the proposed mechanism.

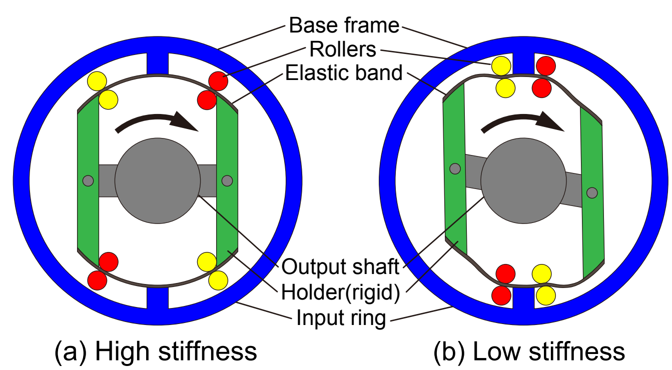


Fig. 3 Working principle of the proposed mechanism as VSM.

are connected to the output shaft, while the elastic bands are connected to the input ring via the rollers. The rollers (a, illustrated in yellow) and (b, illustrated in red) are used to change the stiffness. Two sets of four rollers (a) and (b) are holding the elastic band from the both ends, and its position can be changed along with the elastic band, by rotating the VS ring (a) and (b) respectively. When the rollers are close to the holder, the effective length of elastic band becomes close to zero, thus provide high stiffness (Fig.3-(a)). When the rollers are apart from the holder, the effective length of elastic band is increased, thus provide high compliance (Fig.3-(b)). Note that the VS ring (a) and (b) can be actuated differentially, thus can be implemented by a single motor by introducing a differential mechanism (e.g., bevel gear). Therefore, two motors are required for the proposed mechanism, one for the actuation, and the other for the variable stiffness.

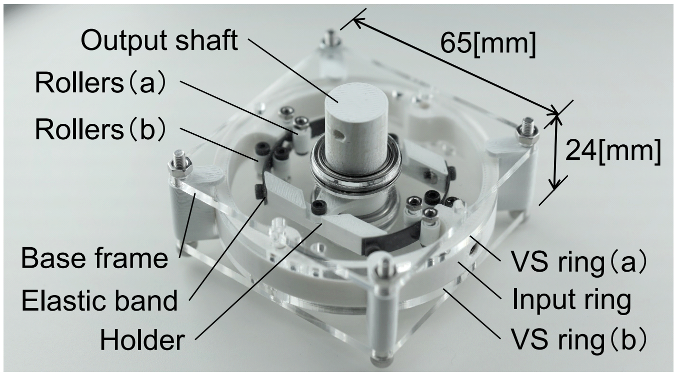
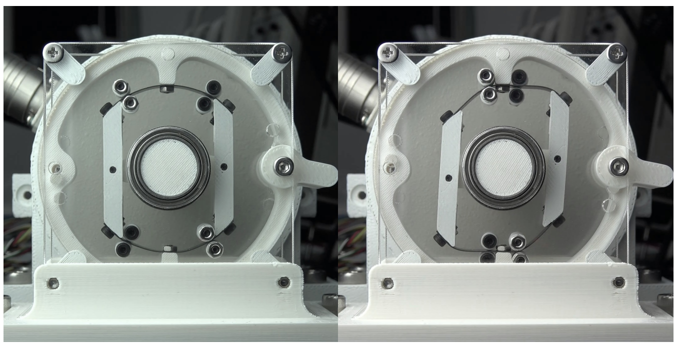


Fig. 4 Implemented prototype.



(a) High stiffness (b) Low stiffness

Fig. 5 Elastic band deformation.

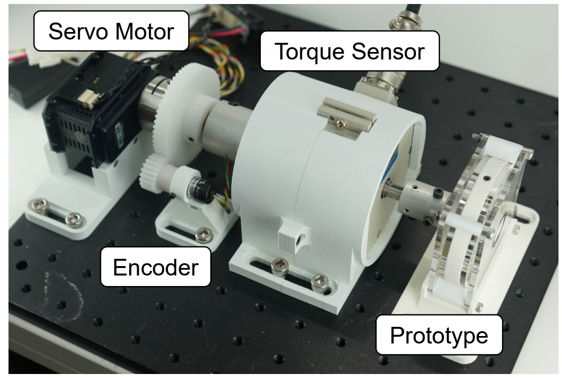


Fig. 6 Experimental setup.

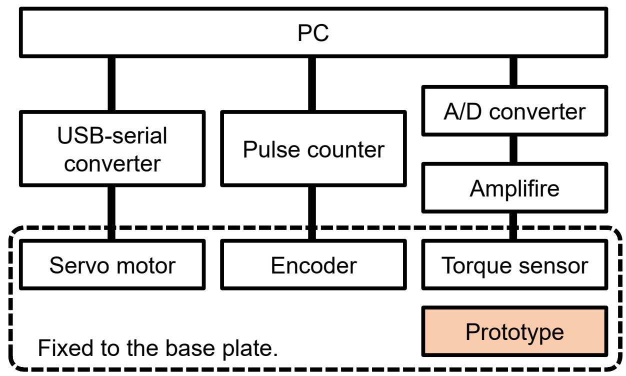


Fig. 7 Diagram of experimental setup.

The most notable advantage of the proposed mechanism is that the elastic bands are located circumferentially to the mechanism, minimizing its size.

C. Prototype Implementation

The prototype was implemented to evaluate the performance of the proposed mechanism (Fig.4). Ni-Ti band was used as the elastic band. To test the feasibility, we implemented two types of prototype — one with the elastic band thickness in 0.3 mm, the other 0.6 mm by stacking two 0.3 mm bands. The input ring, holder, output shaft, and rollers were made of ABS resin using a 3D printer (F170, Stratasys, U.S.) and the VS ring and base frame were made of acrylic using a laser cutter (VLS2.30, Universal Laser Systems, U.S.). M2 screws were used for the rotating shafts of the holders and rollers. Length of each side of base frame was 65 mm and the height except the output shaft was 24 mm, and the weight was 104 g.

The example of varied stiffness performed on the prototype are shown in Fig.5. When the stiffness is high, the deformation of the elastic band and the angular displacement of the output shaft are small with external torque (Fig.5-(a)). When the stiffness is low, the elastic bands are greatly deformed and an angular displacement occurred on the output shaft (Fig.5-(b)).

III. Experiment

Experiment was conducted to evaluate the stiffness change characteristics and the relationship between the thickness of elastic band and the varied stiffness.

A. Experimental setup

The experimental setup and its diagram are shown in Fig.6 and Fig.7. The input ring and VS ring (a) and (b) were fixed to the base frame. The output shaft was fixed to a servo motor (Dynamixel MX-106T, ROBOTIS, Korea) via a torque sensor (TP-20KCD, Kyowa Electronic Instruments, Japan) using a rigid coupling. An encoder (MEH-9-1000PST16C, MTL, Japan) was connected to the shaft between the torque sensor and servo motor using a gear.

B. Method

External torque was applied to the output shaft of the prototype by giving an angular position command to the servo motor, then the outputs of the encoder and torque sensor were recorded. The measurement was repeated while increasing the target angle of the servo motor until the measured torque reaches to 0.9 Nm, then decreasing the torque until the target angle returns to the initial position.The measurement was conducted with the effective length of elastic bands: 0, 25, 50, 75, 100%, on two types of prototype — 0.3 mm and 0.6 mm thickness of elastic bands.

C. Results

Fig.8 and Fig.9 show the representative results of the measurement with the elastic band thickness of 0.3 mm and

TABLE I Comparison of VSM specifications.

	Minimum stiffness (Nm/deg)	Maximum stiffness (Nm/deg)	Stiffness change rate (-)	Size (mm)	Mass (kg)
Proposed mechanism (Elastic band thickness: 0.3mm)	8.34×10^{-2}	3.01×10^{-1}	3.68	$70 \times 70 \times 24$	0.104
AwAS	5.24×10^{-1}	2.27×10^{1}	4.33×10^{1}	270×130	1.8
AwAS-II	0	∞	∞	180×140	1.1
QA-Joint	3.49×10^{-1}	1.31×10^{1}	3.75×10^{1}	-	1.2
FSJ	9.15×10^{-1}	1.44×10^{1}	1.58×10^{1}	$\Phi 92 \times 118$	1.41
VSJ	4.40	6.37×10^{1}	1.45×10^{1}	$\Phi 146 \times 144$	4.95
MASA	1.24	3.02	2.44	$156 \times 112 \times 83$	1.7
SVSA	2.97×10^{-2}	2.63	8.86×10^{1}	$\Phi 75$	2.4

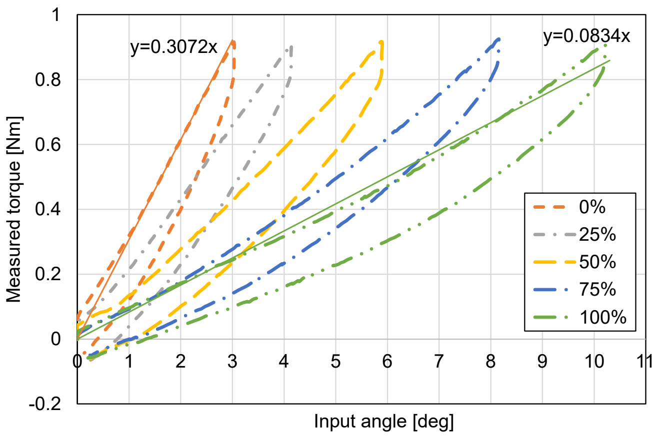


Fig. 8 Rotational stiffness at each elastic band effective length (0.3 mm).

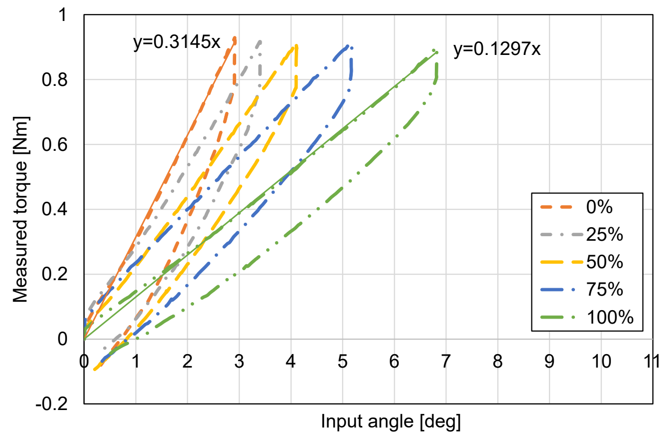


Fig. 9 Rotational stiffness at each elastic band effective length (0.6 mm).

0.6 mm, respectively. Note that each measurement was conducted five times, showing the high reproducibility. On each stiffness setting, the measured torque was gradually increased along with the increased input angle. After reaching to the maximum torque of 0.9 Nm, the input angle was returned to zero, along with the decreased measured torque. The cause of the hysteresis observed on each measurement, was supposed to be the internal friction between the parts, and the gear backlash. This might be improved in the implementation for the further research step, by producing the mechanical parts in metal.

With the thickness of elastic band 0.3 mm, the maximum stiffness was 0.3072 Nm/deg and minimum stiffness was 0.0834 Nm/deg, while the maximum stiffness was 0.3145 Nm/deg and minimum stiffness was 0.1297 Nm/deg with 0.6 mm in thickness. The stiffness was 1.56 times larger with the 0.6 mm band than that of the 0.3 mm, this suggests that the proposed mechanism can change the range of variable stiffness by changing the rigidity of the elastic band. When considering the deformation of the elastic band as the bending of a cantilever beam, the displacement due to external force is expressed by the following equation, while δ is the displacement of the beam, P is external force, L is length of the beam, E is Young's modulus and I is a sectional moment of inertia.

$$\delta = PL^3/3EI \tag{1}$$

Since the prototype with an elastic band thickness of 0.6 mm has a structure in which two elastic bands are stacked, P becomes $P/2$ and the displacement becomes δ to $\delta/2$. The rotational stiffness was expected to be twice larger in 0.6 mm than 0.3 mm, however, it was 1.56 times. Therefore the experimental result suggests that the stiffness was deteriorated due to the deformation of non–elastic parts. This suggests that the implementation with metal parts would improve the stiffness, particularly when the high stiffness was set.

IV. Conclusion

In this paper, we presented a new VSM that was designed specifically for surgical applications. The notable feature of the proposed mechanism is its compact and lightweight implementation by the use of elastic band located circumferentially around the joint. The range of variable stiffness was found to be adjustable, by changing the rigidity of elastic bands.

Table I shows the comparison of range of variable stiffness with the previous researches. The stiffness change rate that was computed by dividing the maximum stiffness by the minimum stiffness, was found to be 3.68 in the proposed mechanism. The reason that the rate was rather small than that of the previously presented devices, is the low stiffness in the maximum stiffness. As the presented prototype was implanted for a feasibility study, the mechanical parts were fabricated from ABS resin and acrylic, that largely deteriorated the rigidity, thus affected the maximum stiffness. On the other hand, the minimum stiffness performed by the proposed device was lower than that of the previously presented devices. This clearly shows the advantage of the proposed device. Further, the implementation of the prototype by metal parts would improve the maximum stiffness, thus the range of variable stiffness. We are currently working on the prototype fabricated from metal as a next research step. Also, stiffness modeling and a detailed evaluation of the relationship between the shape of the elastic band and the variable stiffness range is planned.

ACKNOWLEDGMENT

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