TrC-IFToMM Symposium on Theory of Machines and Mechanisms, Izmir, Turkey, June 14-17, 2015

A Haptic Device for Simulating the Entry into the Throat in Endoscopy

Anirudh N. Katti
Indian Institute of Science
Bengaluru, India

Shanthanu Chakravarthy
Indian Institute of Science
Bengaluru, India

G. K. Ananthasuresh
Indian Institute of Science
Bengaluru, India

Abstract—*One of the principal uses of an endoscopy simulator is training personnel who perform endoscopy. The most important skill to be acquired in Gastrointestinal (GI) endoscopy is precise and safe insertion of the endoscope through the throat by avoiding damage and causing minimal discomfort to the patient. In this work, we focus on this aspect and present a haptic device with which novice endoscopists can be trained. The device consists of a single degree-of-freedom compliant mechanism that emulates controlled and responsive circularly shaped opening. The mechanism is designed in view of the anatomy of the throat and the special maneuver required for intubation of the endoscope. The device is actuated by a direct-drive motor controlled by a dSPACE controller. The haptic device is developed to be integrated with the upper GI tract simulator developed by our group. Any standard endoscope can be used in this system. In this paper, we describe the design, fabrication, and experimentation with the throat-haptic device and its integration into the simulator system.*

Keywords: Compliant mechanism, Intubation, Endoscopic simulator

1Introduction

In this work, we present the design and prototyping of a novel single-layer planar compliant mechanism for throat haptic simulation. The compliant mechanism is designed to be retrofitted into the in-house developed endoscopic simulator. We start our discussion by introducing Virtual Reality (VR) based simulators for endoscopy followed by compliant mechanism and its use in the haptic device.

Endoscopy is a minimally invasive procedure where a flexible tube is inserted through the digestive tract for medical examination and also for surgical interventions. Doctors practising endoscopy screen patients using a tool called endoscope. Upper Gastro Intestinal (GI) endoscopy where the endoscope is inserted through the mouth into the GI- tract is a complex procedure carried out by skilled clinicians[1]. In some countries, clinicians planning to practise endoscopy have to undergo rigorous and extensive training on the simulator before they try endoscopy on human subjects. Virtual Reality (VR) offers a flexible and cost-effective method for training these doctors for endoscopy [2, 3]. Other methods of training include plastic models and cadavers. However, these methods are not flexible, expensive over a long period of usage, and pose complications in handling. On the other hand, VR-based training devices have many advantages that include: economical over long term usage as different cases can be repeated any number of times; the training model can be flexible and include in situ cases; they can be used for identifying mistakes and quantitatively assessing trainee skill levels; and the accessibility to the training environment can be increased.

Most of the existing VR-based training systems lack haptic feedback and thus fail to provide an immersive training environment. [4-6] are some of the efforts at realizing haptic feedback in endoscopic simulation. We have designed a haptic simulator for endoscopic training[7]. This design is a novel three DoF haptic interface that provides force feedback in longitudinal, rotational, and radial directions. This design is a specialized design for upper GI endoscopy training and not a generic design as reported in [4-6]. The radial DoF is specially designed to simulate insertion through the throat. Insertion through the throat region of the GI tract is the most critical part of upper GI training. In the current simulator, a circumferentially actuated radially foldable mechanism is employed to simulate the radial DoF. The fabrication and use of multilayered rigid-body mechanism gives rise to undesirable play and additional friction in joints that are not desirable for haptic device. To overcome these issues, we propose a novel single-layer compliant mechanism for use in throat haptic simulation. The design, fabrication, and prototyping of the single layer compliant mechanism for use in throat haptic system are presented in this paper. Fig.1 shows the Computer model of the developed system.

Compliant mechanisms [8] transmit and transform motion/force using elastic deformation. Compliant mechanisms are joint-less mechanisms that provide an excellent alternative to rigid-body mechanisms as they are free from backlash, play, and friction in joints. Because of these features, compliant mechanisms have gained popularity in medical applications. Medical devices such as compliant hemostats, forceps, and kidney manipulator have been developed using compliant mechanisms[9, 10]. A compliant mechanism was

anirudh@mecheng.iisc.ernet.in
sc@mecheng.iisc.ernet.in
suresh@mecheng.iisc.ernet.in

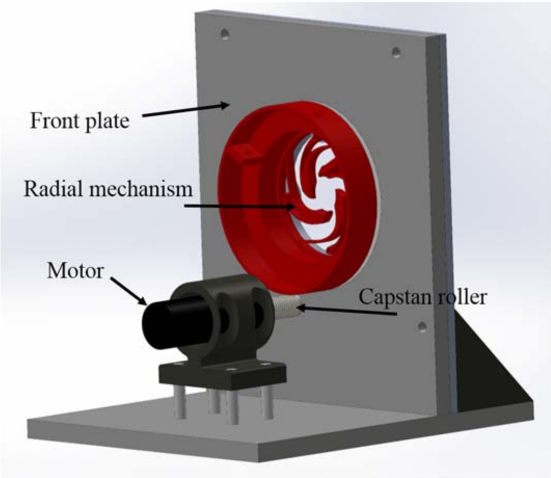

Fig. 1. CAD model of the System.

employed in haptic laparoscopic device to create variable-stiffness components [11].However, other uses of these mechanism in haptic applications are limited. With this work, we explore design and integration of the compliant mechanism for use in a haptic device.

The rest of the paper is organized as follows, Endoscopic haptic simulator and anatomy of insertion through the throat is discussed in Section II. Design details of the force-reflecting mechanism are described in Section III; prototyping and testing of the throat haptic simulator are presented in Section IV followed by concluding remarks in Section V.

II. Endoscopic Throat Simulator

Fig. 2 shows the upper GI-endoscopic simulator developed in our lab. The device consists of a three DoF haptic device together with visualization and force computation models. The device has a novel mechanism to simulate the insertion through the throat. As the user inserts the endoscope through the simulator, graphics scene on the screen is updated to show the inside of the GI-tract. The three-DoF haptic device recreates the insertion and other forces to provide immersive training to the user.

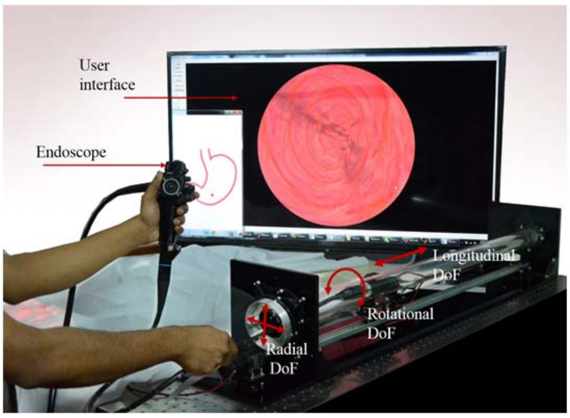

Fig.2. Upper GI-endoscopic simulator developed in IISc, Bengaluru.

A. *The anatomy of the throat relevant to Upper GI Endoscopy*

Fig.3 shows the anatomy of the throat as it leads to the GI-tract. During the endoscopy procedure, the endoscope passes through the oral cavity, around the cricoid cartilage through either one of the left and right pyriform fossa or directly behind the larynx, down into the hypopharynx which continues into esophagus along a narrow opening in the post-cricoid region. The entry into the esophagus is constricted and surrounded by fibromuscular tube. As the endoscope passes through the pharynx, it is in constant contact with the fibromuscular wall creating resistance to the motion of the endoscope. At the entrance of the esophagus, the narrowing of the muscles apply radial forces on the surface of the endoscope. These forces may vary from one subject to another. This intubation of endoscope into the narrow esophagus is a critical step in endoscopy training.

B. *Throat endoscopy simulation*

In the throat haptic simulation, we develop a virtual reality-based haptic device replicating the effect of forces acting on the endoscope during insertion through the throat. As discussed previously, radial forces are to be applied on the endoscope. These precise radial interaction forces cannot be recreated with a longitudinal DoF that applies tip-force on the endoscope. In the endoscopic throat simulator, we develop a device that can be programed to simulate the fibro-muscular walls of the pharynx. It essentially is a device that can apply precise radial forces on the endoscope. Furthermore, this device is designed to be retrofitted into the existing endoscopic haptic simulator.

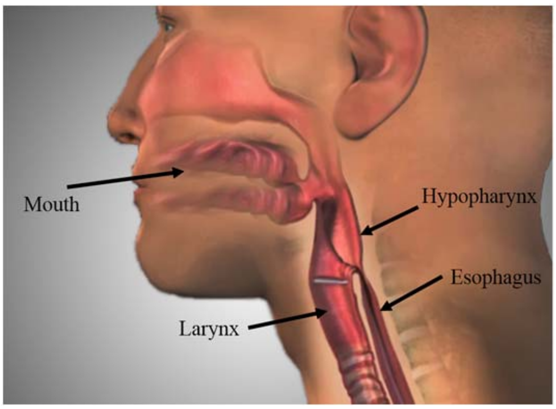

Fig.3. The anatomy of the throat.

III. Design of a mechanism that reflect radial forces

Our force-reflecting mechanism is designed to apply radial force on the endoscope with a single actuator. In the current design, rigid-body circumferential mechanism is used to simulate insertion through the throat. The existing rigid-body mechanism forms the basis for the design of the compliant mechanism developed in this work.

A. Rigid body mechanism

Radially foldable mechanisms are interesting as they show radial motion with single DoF actuation. The concept of General Angulated Elements (GAE) is commonly used to describe radially foldable mechanism. A GAE is simply a ternary body connected to three other bodies. Patel and Ananthasuresh [12] developed the kinematic basis of GAE based deployable mechanisms. They derived the kinematic condition for designing circumferentially actuated angular elements (CAAE) as a special case of GAEs. They developed a radially foldable mechanism whose coupler curve traces a circle, by modelling the angulated element pair as a prismatic-revolute-revolute-prismatic (PRRP) four-bar linkage or double-slider linkage.

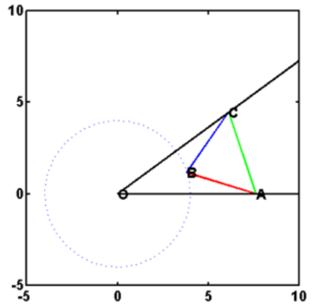

Fig.4. Motion of single CAAE element.

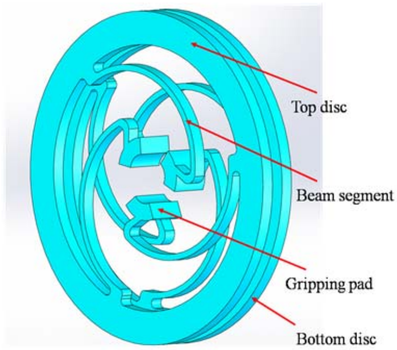

Fig. 6. Earlier design of the multi-layered radial compliant mechanism.

Fig. 4 is the snapshot from the MATLAB simulation of the motion of a single CAAE link. The construction of the circumferential mechanism makes it kinematically over-constrained. However, the pair of angulated elements that constitutes the mechanism share the same coupler curve due to which the foldability is established.

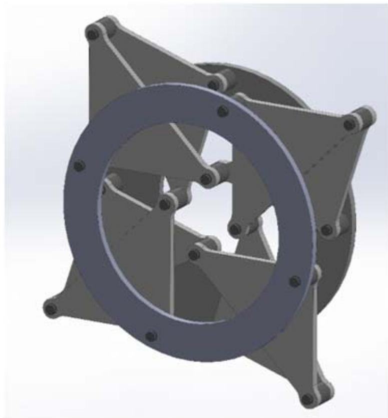

Fig.5. Computer model of the circumferentially actuated mechanism.

Fig.5 shows the computer model of the existing circumferentially actuated mechanism. Capstan drive system is used to actuate the mechanism. This circumferential actuation and eventual motion of GAE elements replicate the forces acting on the endoscope during throat insertion.

B. Compliant radially foldable mechanism

The rigid-body embodiment of circumferentially actuated mechanism has several drawbacks for use as a force-reflecting mechanism. The circumferentially actuated mechanism is a multilayer mechanism making the design and assembly complex. With the first layer of the mechanism being fixed, and the last layer being pulled due to the pre-tensioned wire of the capstan drive system, the mechanism tilts leading to jamming of the moving angulated elements. The circumferential mechanism exhibits gain singularity when two triangular elements line up. At this singular configuration, the mechanism gains an additional DoF posing problems in force-reflection. Furthermore, the mechanism has the problem of play and friction that are inherent to rigid-body mechanisms.

In order to eliminate the drawback of the rigid-body mechanisms, we designed a compliant equivalent of the circumferentially actuated mechanism. The idea of circumferentially actuated compliant mechanism was reported in [13]. The authors used the mechanism to design a pipe-crawling robot with circumferential actuation provided by Shape Memory Alloy (SMA) wires. This mechanism was also adopted for endoscopic haptic simulator in [14]. Fig. 6 shows the earlier design of the compliant mechanism used in the endoscopic simulator. However, this mechanism is still multi-layered and suffers from the tilt caused by unintended out-of-plane motions. Therefore, it requires redesign for use in the current endoscopic simulator.

Some design constraints are laid out for the design of the compliant ring-mechanism. The mechanism should be able to apply a minimum force of 5 N on the endoscopic tube. The input torque that produces 5 N contact force should be within the maximum torque developed by the motor (~170 mN.m). It is intended that the overall dimensions of the mechanism should be similar to the size of the existing rigid-body mechanism. The mechanism should be capable of working with all the standard endoscopes.

The planarity condition would ensure reduction in tilting of the mechanism. Fig. 7 shows the mechanism consisting of a polar array of four compliant mechanism each consisting of two flexible beams. One end of beam 1 is fixed to the outer ring and other end is connected to one end of beam 2 to form the gripping pad (Point C). The other end of beam 2 is anchored at Point B. The beam assembly is cast in a polar array with four beam assemblies to form a circumferentially distributed gripping pads. The gap between the gripping pads is designed to accommodate any standard size of the endoscope. When we rotate the mechanism the flexible beams move inward, applying radial load on the surface of the endoscope.

Design of the mechanism was carried out by using Finite Element Analysis (FEA) simulations. By observing the stress localization, the width of the beams used were altered to obtain the desired radial force. Based on the reaction forces obtained at the surface of gripping

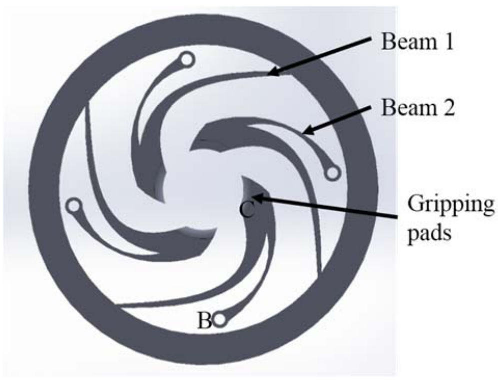

Fig. 7. Radially converging mechanism

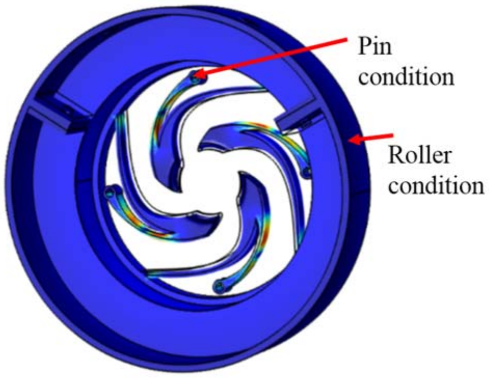

Fig. 8. Finite element simulation of the compliant mechanism

pads, the splines used to model the beams were altered until these forces complied with the prescribed design constraints. This iterative design methodology was employed to achieve the final dimensions of the mechanism. COMSOL Multiphysics software was used a FEA simulations. Fig. 8 shows the snapshot of the COMSOL simulation together with the boundary conditions. Material properties for the simulation were chosen to be similar to the prototype material (Vero Blue, E =2.5 GPa, poisons ration= 0.33). A parametric sweep of the prescribed rotation was given to the outer ring. Roller condition was applied to the circumference of the mechanism. The pins were anchored by constraining x and y motion together with the out-of-plane motion. This simulates the pure in-plane rotation. With the loading condition varying form 0 -50 N at the sensing end of the mechanism. The mechanism shows a nonlinear input stiffness that varies form 6.2 kN/m to 9.5 kN/m. The mechanism has an amplification factor that varies from 0.26 to 0.602.

Fig. 9 shows the fabricated mechanism. Objet Connex260 3D printer is used to fabricate the mechanism. Vero blue material supplied by the Objet is used for the fabrication. Pins at point B (See Fig. 7) are fixedto the back plate to restrict x-y and out-of-plane motion. However, the mechanism shows an axial drift

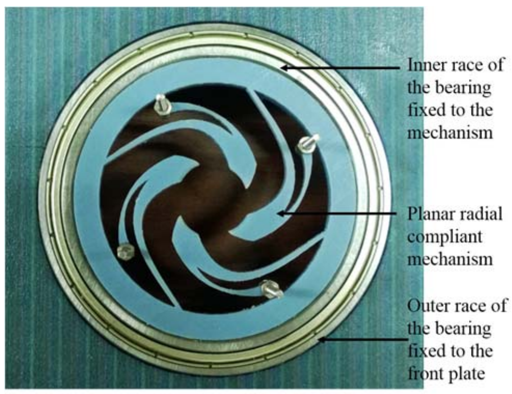

Fig. 9. Fabricated mechanism together with the outer bearing.

during circumferential actuation. To restrict the axial drift and allow for pure circumferential motion, the mechanism is housed in a deep-groove ball-bearing assemble. The outer race of the mechanism is fixed to the front plate of the haptic device as shown in Fig. 9. The final realized mechanism is planar, complaint, and it has no axial drift.

The radially foldable compliant mechanism is to be used for haptic application. Encoder attached to the motor shaft is usually employed to sense displacements. To facilitate this measurement, the mechanism is designed, such that the output displacements cause a rotational motion at the input side of the mechanism. These rotations can be sensed using the encoder attached to the motor. Lower and similar input and output stiffness give this feature to the mechanism. In a rigid-body mechanism, kinematic equations define the input-output relation for the displacement and force. However, due to the elastic nature of the compliant mechanism, these relations are not easy to derive. We employ FEA to obtain these relations. Fig. 10 shows the curve that establishes the relation between angular rotation of the disc and the output point on the gripping pads.

IV. Control Prototyping

RE series brushed DC motor manufactured by Maxon Motors, Switzerland, is used to apply torque on the radial mechanism. The motor is coupled to the capstan drive that actuates the radial compliant mechanism. After the amplification using a capstan drive, the system can apply a maximum torque of442 mN.m. Sensing device of the endoscope is a 1024 counts per revolution (CPR) optical encoder. This roughly translates to 0.35° resolution. All the control prototyping is done on a PC with MATLAB/SIMULINK and implemented on a dSPACE 1103 control prototyping board running at 1 kHz. The motor produces a torque that is proportional to the current in the circuit. Desired current is driven through

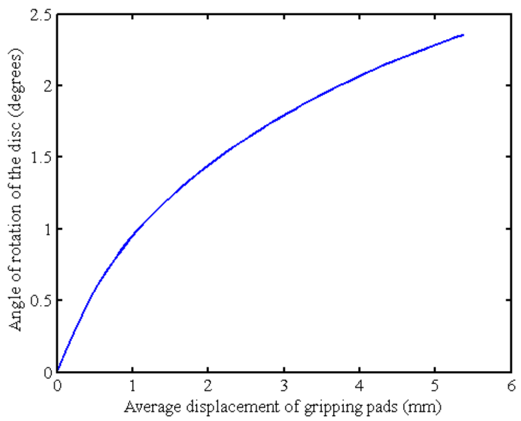

Fig. 10. Relation between angular rotation of the disc and the output point on the gripping pads.

the motors using Maxon DC motor drives (www.maxonmotor.in) operating in current control mode.

The dynamic model of the one DoF system can be expressed as follows[14]:

$$(J_m + \frac{1}{N^2} J_d)\,\ddot{\phi} + \left(b_d + \frac{K_t K_v}{R}\right)\dot{\phi} + \frac{1}{N}\tau_f = \tau_m \quad (1)$$

where J_m is the motor rotary inertia, b_d is the damping coefficient in the motor. K_t, K_v and R are the motor electrical components namely torque constant, speed constant, and resistance respectively. θ denotes the angular position of the motor shaft. J_d is the inertia of the rotating disc.

Because of the compliant nature of the radial mechanism, the output side of the mechanism offers stiffness while inserting an endoscope. This stiffness is due to the flexible radial beams. Fig.11shows the stiffness offered by the four flexible beams. This additional stiffness is not desirable for haptic simulation. We compensate this stiffness using a feedforward term in

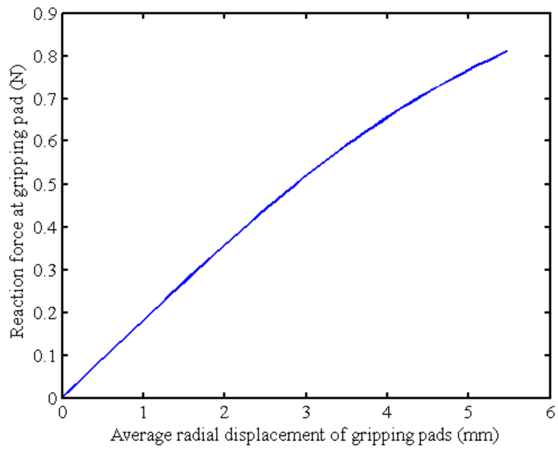

Fig. 11. Stiffness offered by the flexible beams.

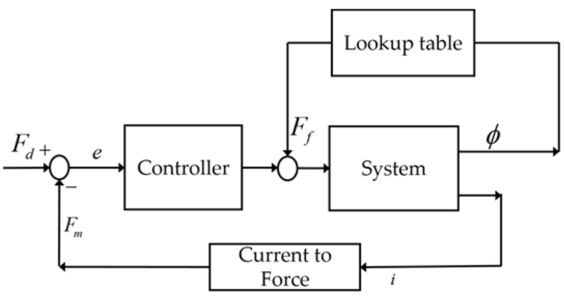

Fig. 12. Block diagram of the control system.

the control loop. Fig. 12shows the block diagram of the control system. A Proportional Integral (PI) controller is developed to maintain the error e between the desired force F_d and the measured force F_m to be minimum. The dynamics of the system from equation (1) is compensated for transparent haptic feedback. The additional stiffness due to flexible beams is also compensated using a look-up table.

V. Closure

In this paper, we presented the design and development of a novel compliant mechanism-based haptic device for simulating insertion through the throat. The main contributions of this paper are:

- Fulfilling the need for throat insertion haptics in endoscopic simulator.
- Design of a novel compliant radially foldable mechanism.
- Initial prototyping of a haptic device to simulate insertion through the throat during endoscopy.

We note that the developed device is compact and can apply radial force in excess of 5 N. In this work, we only presented the design of the compliant ring-actuator. Complete model of the compliant mechanism and testing of the prototyped device is the future course of this work.

Acknowledgement

This work is supported by the Robert Bosch Centre for Cyber Physical Systems (RBCCPS) at the Indian Institute of Science (IISc), Bangalore.

References

[1] R. Hart and M. Classen, "Complications of diagnostic gastrointestinal endoscopy," *Endoscopy*, vol. 22, pp. 229-233, 1990.
[2] B. S. Lim and J. W. Leung, "Training methods for endoscopic retrograde cholangiopancreatography," *Techniques in Gastrointestinal Endoscopy*, vol. 13, pp. 132-139.
[3] S. Haque and S. Srinivasan, "A meta-analysis of the training effectiveness of virtual reality surgical simulators," *Information Technology in Biomedicine, IEEE Transactions on,* vol. 10, pp. 51-58, 2006.
[4] E. Samur, L. Flaction, and H. Bleuler, "Design and evaluation of a novel haptic interface for endoscopic simulation," *IEEE Transactions on Haptics,* vol. 5, pp. 301-311, 2012.
[5] H. S. Woo, W. S. Kim, W. Ahn, D. Y. Lee, and S. Y. Yi, "Haptic interface of the KAIST-Ewha colonoscopy simulator II," *Information Technology in Biomedicine, IEEE Transactions on,* vol. 12, pp. 746-753, 2008.
[6] K. Ikuta, M. Takeichi, and T. Namiki, "Virtual endoscope system with force sensation," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on,* 1999, pp. 1715-1721 vol.3.
[7] S. Chakravarthy, A. Rao, and G. Ananthasuresh, "A Haptic Simulator for Upper Gastrointestinal Endoscopy," in *The Hamlyn Symposium on Medical Robotics*, 2014, p. 16.
[8] S. Hegde and G. Ananthasuresh, "Design of single-input-single-output compliant mechanisms for practical applications using selection maps," *Journal of Mechanical Design,* vol. 132, p. 081007, 2010.
[9] S. Kota, K.-J. Lu, Z. Kreiner, B. Trease, J. Arenas, and J. Geiger, "Design and application of compliant mechanisms for surgical tools," *Journal of biomechanical engineering,* vol. 127, pp. 981-989, 2005.
[10]S. Awtar, T. T. Trutna, J. M. Nielsen, R. Abani, and J. Geiger, "FlexDex™: A minimally invasive surgical tool with enhanced dexterity and intuitive control," *Journal of Medical Devices,* vol. 4, p. 035003, 2010.
[11]E. Basafa, M. Sheikholeslami, A. Mirbagheri, F. Farahmand, and G. Vossoughi, "Design and implementation of series elastic actuators for a haptic laparoscopic device," in *Proceedings of the 31st annual international conference of the IEEE/EMBS*, 2009, pp. 2-6.
[12]J. Patel and G. Ananthasuresh, "A kinematic theory for radially foldable planar linkages," *International journal of solids and structures,* vol. 44, pp. 6279-6298, 2007.
[13]P. Singh and G. Ananthasuresh, "A compact and compliant external pipe-crawling robot," *Robotics, IEEE Transactions on,* vol. 29, pp. 251-260, 2013.
[14]S. Chakravarthy, K. Avinash, G. Ramu, and G. Ananthasuresh, "Design of an Endoscopic Haptic Display System using an Integrated Ring-actuator," in *1st International and 16th National Conference on Machines and Mechanisms (iNaCoMM2013),* Roorkee, India, 2013.