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# Safe Human-Robot Interaction Using Variable Stiffness, Hyper-Redundancy, and Smart Robotic Skins

*Pinar Boyraz Baykas, Ertugrul Bayraktar  
and Cihat Bora Yigit*

## Abstract

In service robotics, safe human-robot interaction (HRI) is still an open research topic, requiring developments both in hardware and in software as well as their integration. In UMay<sup>1</sup> and MEDICARE-C<sup>2</sup> projects, we addressed both mechanism design and perception aspects of a framework for safe HRI. Our first focus was to design variable stiffness joints for the robotic neck and arm to enable inherent compliance to protect a human collaborator. We demonstrate the advantages of variable stiffness actuators (VSA) in compliancy, safety, and energy efficiency with applications in exoskeleton and rehabilitation robotics. The variable-stiffness robotic neck mechanism was later scaled down and adopted in the robotic endoscope featuring hyper-redundancy. The hyper-redundant structures are more controllable, having efficient actuation and better feedback. Lastly, a smart robotic skin is introduced to explain the safety support via enhancement of tactile perception. Although it is developed for a hyper-redundant endoscopic robotic platform, the artificial skin can also be integrated in service robotics to provide multimodal tactile feedback. This chapter gives an overview of systems and their integration to attain a safer HRI. We follow a holistic approach for *inherent compliancy* via mechanism design (i.e., variable stiffness), *precise control* (i.e., hyper-redundancy), and *multimodal tactile perception* (i.e., smart robotic-skins).

**Keywords:** variable-stiffness, hyper-redundancy, tactile feedback, smart-skin

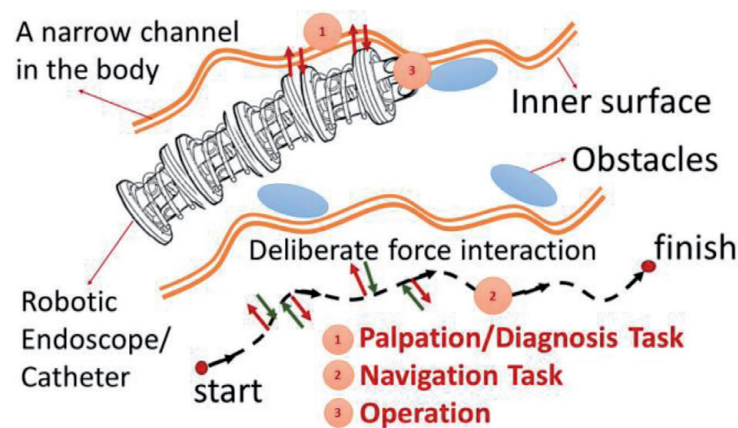
## 1. Introduction

In medical mechatronics, especially in the minimally invasive surgery (MIS) applications, the design challenge often has multiple sources. However, these

<sup>1</sup> UMay was supported by Young Investigator Award of Istanbul Technical University (2011–2016) to build a humanoid robot for rehabilitation uses on children with Autism Spectrum Disorders (ASD), supporting the co-authors of this chapter for their PhD.

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difficulties can be generally grouped in relation to mechanism/structural design, actuation selection, and perception. All three fields are affected by the fact that the room for passage, navigation, and operation is very limited. In addition to restrictions in the size of the device, the interaction between the medical device and the tissues or blood poses deeper questions regarding the accuracy of the control and safety of the patient. Regarding the robotic endoscopes/catheters, they can be used as diagnosis tasks using deliberate palpation as well. The other two obvious tasks could include safe navigation inside a narrow and torturous channel while providing adequate accuracy and stiffness at the location of the operation. This chapter presents three different novel approaches which can provide feasible solution to the design challenges while improving the safety. First, in order to improve the mechanical structure and mobility, hyper-redundant mechanisms are presented in Section 2 featuring three different module designs, emphasizing the reconfigurability and modularity. Then, for providing the adjustable forces and compliant action, variable actuator mechanisms are visited in Section 3. The last innovation path involves the perception upgrade, detailing on tactile sensors in Section 4. Involving the tactile sensing units in the robotic skin or sheath can help obtain better feedback and more accurate diagnosis and/or provide safer operation when there are obstacles in the path. All these three aspects are summarized in **Figure 1**.



**Figure 1.** An endoscopic robotic platform performing diagnosis, navigation, and operation having a hyper-redundant structure, featured in [1, 2].

## 2. Hyper-redundant mechanisms

Modern surgical robots have been designed and implemented to help surgeons in operations requiring high dexterity and minimal invasiveness. Although great versatility and control have been realized using large, rigid, and serial-link robots such as Da Vinci, catheter-type robotic platforms having smaller dimensions can present an alternative and less expensive solution especially for minimally invasive surgery [3].

In conventional medical use, catheters are manually controlled devices for diagnosis, drug delivery, and basic operations which do not require intricate motion patterns or application of a well-controlled force on the surgical site. Catheters often have a tendon-driven guidewire and a sheath to cover the guiding mechanism which may or may not feature a surgical head/clipper or a micro-mechanism to operate on sensitive tissues. Although originally being passive medical devices, the catheters can be re-designed to gain features such as

multiple degrees of freedom, mobility, controllability, and perception. With these improvements in their structure, the catheters can become autonomous or semi-autonomous surgical platforms which can travel in difficult passages in the human body without harming the inner tissues and help the operation itself to be more successful with superior position and force control.

Most of the hyper-redundant or piecewise continuum structures still use rigid or semirigid backbones or general frames. Recently proposed hyper-redundant modular structures can be found in [4–6]. In [4], high dexterity and stiffness requirements are met, whereas the design has poor flexibility, limited compliance, and intricate mechanical structure which can be difficult to miniaturize for medical applications. Other prototypes can feature stiffness control [5] but may fall short in module-based controllability. It is even possible to see applications with better control [6] featuring continuum elastic backbone while segmenting the structure into modules using coupling plates; however, the size and compactness criteria are not fulfilled. The cable-driven structures are lightweight and compact, but there is an inherent limitation of such mechanisms due to cable friction and interdependency between the sections of the modules. As the limitations and drawbacks of such mechanisms are given, in the next section the advantages are highlighted to draw attention to their potential in medical robotics.

## **2.1 Advantages: modularity and controllability aspects**

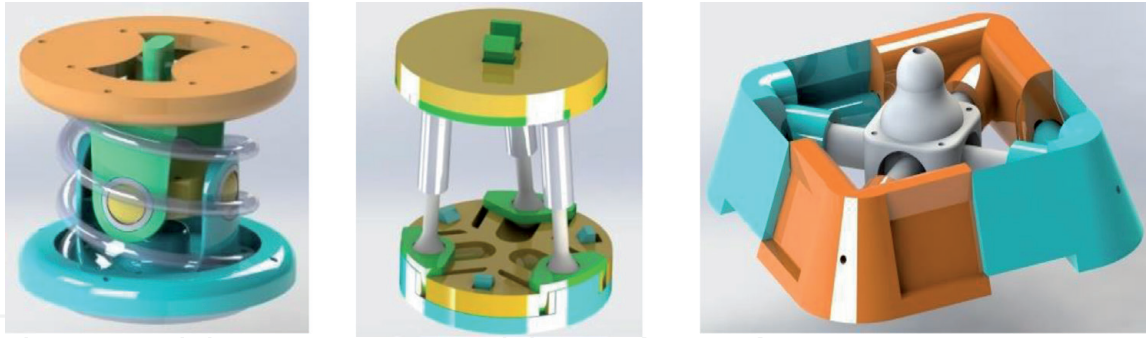
The main idea of a hyper-redundant robotic platform with a modular building block is to increase the controllability and maneuverability of the robot. Increasing the number of DOF seems to be the main advantage; however, it is surpassed by the fully continuous robot (i.e., tubular/telescopic pre-curved continuum robots) that can be manipulated in 3D space without the need of complicated inverse kinematic calculations due to their inherent compliancy. Although fully continuum robotic platforms have this advantage, for most of the cases, the segment-based local control is not possible to obtain, and in most of the continuum prototypes despite their inherent compliancy, the stiffness control is not possible. Therefore, in this section, we would like to highlight the modular hyper-redundant robotic designs that can offer segment-based position control as well as adjustable stiffness. When the robotic catheter has both the position and the stiffness control, the navigation of the robotic catheter inside the torturous channels becomes an optimal control problem where the position and force are controlled with varying priorities according to the path planning and the operation task. This greatly increases the inherent safety of the robotic catheter. In the following section, designed mechanism modules are introduced and compared using workspace and stiffness analysis.

## **2.2 Example applications of hyper-redundant mechanisms**

A recent hyper-redundant manipulator can be found in [7] which has electro-magnetically actuated manipulator. Early examples of hyper-redundant manipulators with full solution on kinematics and dynamics are given in [8–10]. However, control algorithms suggested for such mechanisms are still in progress. For example, a modular control scheme is proposed in [11].

In this section, the design of hyper-redundant and modular robotic structures is detailed by emphasizing the functional properties such as independent module/segment controllability and variable-adjustable stiffness. The proposed designs [12] are aimed at improving both position and force control of such structures employing whole-body shape control and local stiffness control in the robotic catheter.





**Figure 2.** Modules for hyper-redundant backbone construction, from left to right: Hybrid module, radially reconfigurable 3x SPS parallel kinematic mechanism, and seahorse tail section, featured in [12].

Three different module designs for hyper-redundant mechanisms are depicted in **Figure 2**. The first mechanism is called “hybrid” and essentially a universal joint placed in between two parallel plates and supported by a concentric shaft. This mechanism has three DOF per module, having pan and tilt for adjusting the heading angle while using the translational movement to shrink or elongate while adjusting its stiffness.

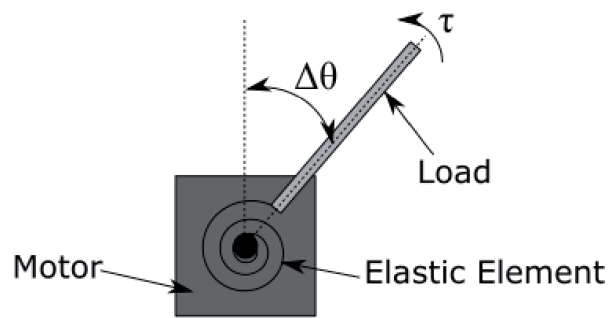
The second mechanism is 3x SPS having spherical-prismatic-spherical joints in each strut and is essentially a reconfigurable parallel mechanism. This mechanism provides stiffness adjustments by relocating the connection points of the struts on the lower plate. The struts can also elongate and contract along their axis so that the hyper-redundant platform can be adjusted when passing along difficult cavities.

Finally, the last module is named after the seahorse tail since it is inspired by the cross section of the biological counterpart. This mechanism can radially contract and widen to mimic the function of oblique muscles in seahorse tail structure. The modules are connected by a spherical joint in the middle. Since the radial struts are spring-loaded, the radial stiffness can be adjusted.

The main advantage of hyper-redundant mechanisms is that each segment can be controlled separately, and the multi-degree-of-freedom makes it possible to control the whole-body shape of the manipulator to reduce the risk of harming the tissues during the navigation task. If the modules also have variable stiffness or re-configurability as it is shown here, the versatility and the safety of the hyper-redundant platforms increase. Since robotic platforms should accomplish tasks such as navigation, diagnosis, and operation, they may have to support different levels of stiffness when required. This type of adjustability can be achieved via special actuators as well. The next section expands on this view by supporting these mechanisms with variable stiffness actuators.

### 3. Variable stiffness actuators

Rehabilitation is known as the process of regaining the deceived somatic talents as a result of an illness or accident, all of which are necessary for survival, quality of life, and living together with their families and society. With the advancement of technological development, specialized mechanisms and devices are used more frequently to resolve some of the issues related with physical interaction between humans and robots. Also these mechanisms or devices operate in clinical environments; some of them are designed to provide mobility for daily usage. Namely, exoskeletons are the wearable types of these mechanisms. Among military usage, civilian purposes, and industrial applications, exoskeletons are for rehabilitation



**Figure 3.**  
 Schematic representation of series elastic actuators (SEA) or variable stiffness actuators (VSA).

or acquisition of lost actions of people with disabilities. Commonly, similar to other mechatronic systems, exoskeletons comprise sensing, control, and actuation components.

Since rehabilitation is a human-centered therapy to overcome the impairments of the motor functions, it is required to be for exoskeletons to provide safe interaction and mimicking human motions [13]. Compliance is a prerequisite for safety, which can be maintained by software or hardware solutions. Software-based solutions allow controlling impedance [14] by implementing control techniques on rigid joint structures [15]. On the other hand, hardware-based solutions imply flexible joint structures with passive compliance [16, 17]. Also, the interface surface between the patient and the mechanism is covered by soft materials to increase comfort. In addition, adequate amount of force/torque should be supplied to perform the predefined tasks successfully while maintaining a lightweight mechanical structure [18].

Safety is a trending topic within industrial robotic applications. To increase precision, robot joints are designed as stiff as possible; however, Pratt et al. [19] proposed to connect motor and load with elastic components. Consequently, passive compliance is obtained, but it is comprehended that single stiffness value is not suitable for different robotic tasks. Variable stiffness actuators (VSAs) or in general variable impedance actuators (VIAs) are able to adjust the stiffness/impedance within a specific range (see **Figure 3**).

Besides the need of excessive number of human therapists for ordinary rehabilitation techniques, they are time-consuming for labors [20]. Furthermore, these techniques are deficient to measure the performance of rehabilitation outputs for objective analysis. Inflexibility due to different level of treatments, namely, impersonal aims, can be counted as another drawback for traditional rehabilitation therapy methods. In this section, VSA-based exoskeleton/rehabilitation mechanisms are presented as possible solutions to these problems.

### 3.1 Operational principles of VSAs

Conventional robot joints are designed to track a motion profile and try to keep the position against external effects after reaching the goal position. On the contrary, in the SEA mechanism, there are elastic elements between the load and the motor, which allow the external influences to change in the joint position. The elastic element herein has constant output stiffness ( $k$ ), and the relation between torque ( $\tau$ ) and position ( $\theta$ ) is linear as follows:

$$k = \frac{d\tau}{d\theta} \quad (1)$$

$$\tau = k\Delta\theta \quad (2)$$

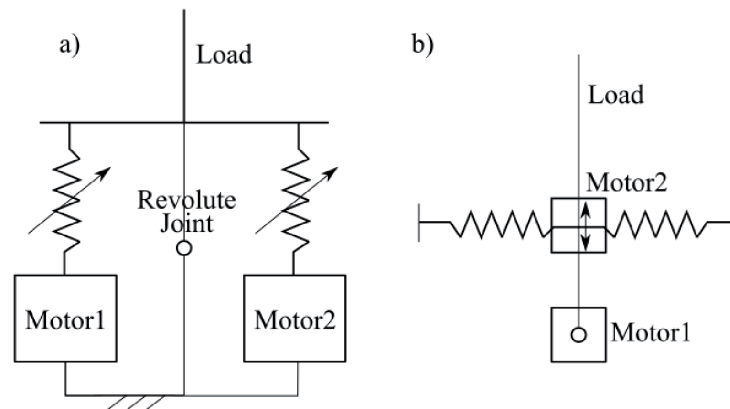
where  $\Delta\theta$  denotes the deflection of the elastic element. VSA mechanisms are designed to have nonlinear  $\tau$ - $\theta$  relation yielding variable output stiffness as given in Eq. 3:

$$d\tau = f(\theta)d\theta \quad (3)$$

where  $f(\theta)$  is the nonlinear stiffness function. Regarding the change in stiffness, the reaction of the joint for external effects can be adjusted according to the desired task. The stiffness adjustment mechanisms are classified in three main categories in [21]: (i) spring preload, (ii) changing transmission between load and spring, and (iii) physical properties of the spring. The system, in which a couple of springs and motors run in a reciprocal manner, namely, antagonistic springs, is the first type. The working principle resembles biological musculoskeletal system in the first category. To obtain a linear stiffness variation, two quadratic springs are utilized in [22] by using a cam mechanism with a linear helical spring. In [23], the importance of quadratic springs in the design of VSAs is shown. The second type provides nonlinear torque-position relation by changing the distance between rotation center, the linear spring connection points, and/or tip point [24]. The last kind exploits natural characteristics of linear springs. In [25], nonlinearity of helical springs under bending and compression determines stiffness variation. Moreover, mechanism in [26] specifies the number of active coils of helical spring which results a change in stiffness. General schematic representations of the first two types are given in **Figure 4**.

VSAs are generally actuated by conventional electrical motors; however, in [27] stiffness variation is obtained by a pneumatically artificial muscle. Hobby servo motors are another alternative to conventional motors which is used in a modular VSA design to lower the cost [28]. Similar to actuation units, elastic components can vary in different mechanisms. Although it is not implemented in an actuator, a nonlinear spring mechanism in [29] includes rubber, and in [30], a timing belt is introduced as the source of elasticity.

VSAs are superior to conventional actuators according to energy efficiency under various working conditions and performing highly dynamic task. Energy-efficient gait is performed by using compliant actuators because of the energy storage capability of the elastic element. However, when the environment or the walking speed is changed, natural dynamics of the mechanism is expected to maintain efficiency. In [31], running motion energy cost of a legged robot, *Edubot*, decreases about 40% when it is compared to fixed stiffness legged robots. In addition, dynamic tasks that cannot be accomplished with classical robots can be done by these mechanisms due



**Figure 4.** Stiffness adjustment types: (a) spring preload; (b) changing transmission between load and spring.

to the energy storage feature. An optimal control strategy is implemented to the mechanism to maximize ball-throwing distance in [32]. Benefits of stiffness adjustment is presented in the study by comparing variable and fixed stiffness performances. A detailed analysis of the VSA designs can be found in [21].

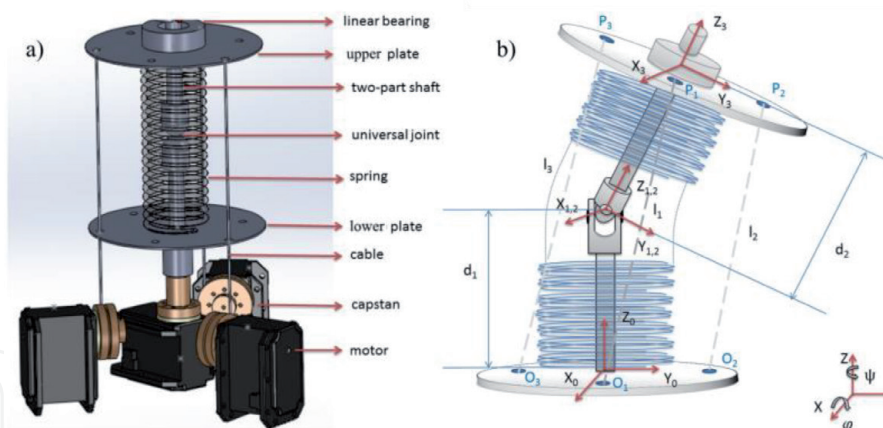
### 3.2 Example applications of VSA

Modern studies towards medical mechatronic systems are performed as interdisciplinary collaboration conducted with physicians, therapists, and scientists among engineering community. Recent approach to these systems serves the emergence of new perspectives beyond the advantages of robot-assisted therapy. Principally, practical studies can be divided into two parts depending on the intention of mechanisms to the upper body and lower body.

Upper body exoskeleton applications are mostly focused on the upper limb and elbow parts. A torque-driven and lightweight exoskeleton called *Limpack* is proposed to sustain therapeutic aid for upper limb rehabilitation in [33, 34]. Suitable dimensions for wearable functionality and impairment quantification can be taken into account as further characteristics as well as rotational hydro-elastic actuator as being a new type of SEA. There also exist different control modes such as compliant impedance and stiff admittance. In [16, 17], a 4-DOF wearable passive exoskeleton mechanism for elbow rehabilitation, named as NEUROExos, driven by a variable impedance antagonistic actuator, is presented. The double-shell link structure of NEUROExos contributes to ergonomics, and the joint position and stiffness are controlled separately by passive compliant actuation system. The experiments conducted including a human subject show that the increase in the joint stiffness causes smaller angular error during the motion in the reference trajectory. This is a result of ensuring the proper torque transmission relation between the human and exoskeleton. AVSER [35] is another study towards elbow rehabilitation using an active variable stiffness exoskeleton. Within AVSER, there is an active variable stiffness elastic actuator (AVSEA) composed of two DC motors, one for controlling joint position and the other one is for varying stiffness that is produced by a leaf spring. The effective length of the leaf spring, which is controlled by AVSEA, affects the motion characteristics of AVSER, which can be active or passive. Human-included experiments are conducted using the data gathered from two encoders for motor and elbow angles, a linear potentiometer for linear spring deflection and two active electrodes for electromyogram (EMG) signals. The results display the compatibility of AVSER for active-passive elbow rehabilitation tasks with its capabilities of stiffness adjusting, safety, and energy efficiency.

Lower body assistance can be in forms of full support to the legs, or it can affect only dysfunctional part such as the ankle or knee. Exoskeletons and rehabilitation mechanisms are widely used in the lower limb to regain locomotion of disabled or patients who have difficulty with walking. In addition to gait assistance, standing up motion is provided with the help of exoskeletons. A brace about the foot which is called as ankle-foot orthosis (AFO) is a usual treatment for drop-foot gait. A variable impedance actuator with force and position sensors is assembled to an AFO in [36]. It is shown that during different phases of the gait, adjusting impedance values increases the benefits of AFOs. Sit-to-stand task is a torque demanding task especially for knee joints. In [37], a lever arm mechanism based on VSA for knee exoskeleton is presented, and design methodology is explained in detail. Moreover, the effects of different stiffness values are evaluated for standing task. It is not only necessary to supply sufficient torque to knee joint but also to understand the intention of the user. Instead of splitting task into phases to control stiffness or impedance in [28], muscle activity of the patient is collected via EMG in order to detect patient





**Figure 5.** Variable stiffness neck joint. (a) Components of the mechanism and (b) reduced kinematic model [25].

intention and correct stiffness values in [29]. Along with functional design of VSAs in rehabilitation mechanisms, researchers are inspired from the human muscle structure and designed full lower limb orthosis to improve impaired gait of patients by using pneumatic [38] and wire-based artificial muscles [20]. Furthermore, VSAs are expected to mimic human joint behaviors and have a great potential [39, 40] to be used in rehabilitation purposes. In [25] a VSA which resembles a human neck joint is presented. The schematic representation of the mechanism is given in **Figure 5**. Cable-driven lightweight structure brings simplicity. Also, there is no additional hardware other than a helical spring for stiffness variation. Although the middle shaft restricts the motion due to its revolute-revolute-prismatic (RRP) structure, actuation principle is similar to parallel mechanisms.

All in all, robot-assisted rehabilitation studies and applications are still attractive research areas. Human motion imitation for mechanisms used in rehabilitation is emphasized for successful results. To this end, VSAs are comprised within rehabilitation systems. More information about the latest progress can be found in [41–43]. These findings reveal that robot-assisted technologies will result in less human labor time consumption with increasing quality of observable rehabilitation outputs.

## 4. Smart robotic skins

For connecting the robot to its environment, visual sensor channels are usually preferred and widely applied. The tactile sensor applications are limited to certain locations, which tends to be the tip of the device especially for robotic catheters. In this part of the chapter, a large-area application for the tactile sensors to form an artificial skin on the robotic catheter is covered. The large-area, skin-like applications of tactile sensors can empower the robotic catheters to have better perception output during diagnosis/palpation while helping to obtain higher safety levels during operations.

### 4.1 Tactile sensors for medical robotics

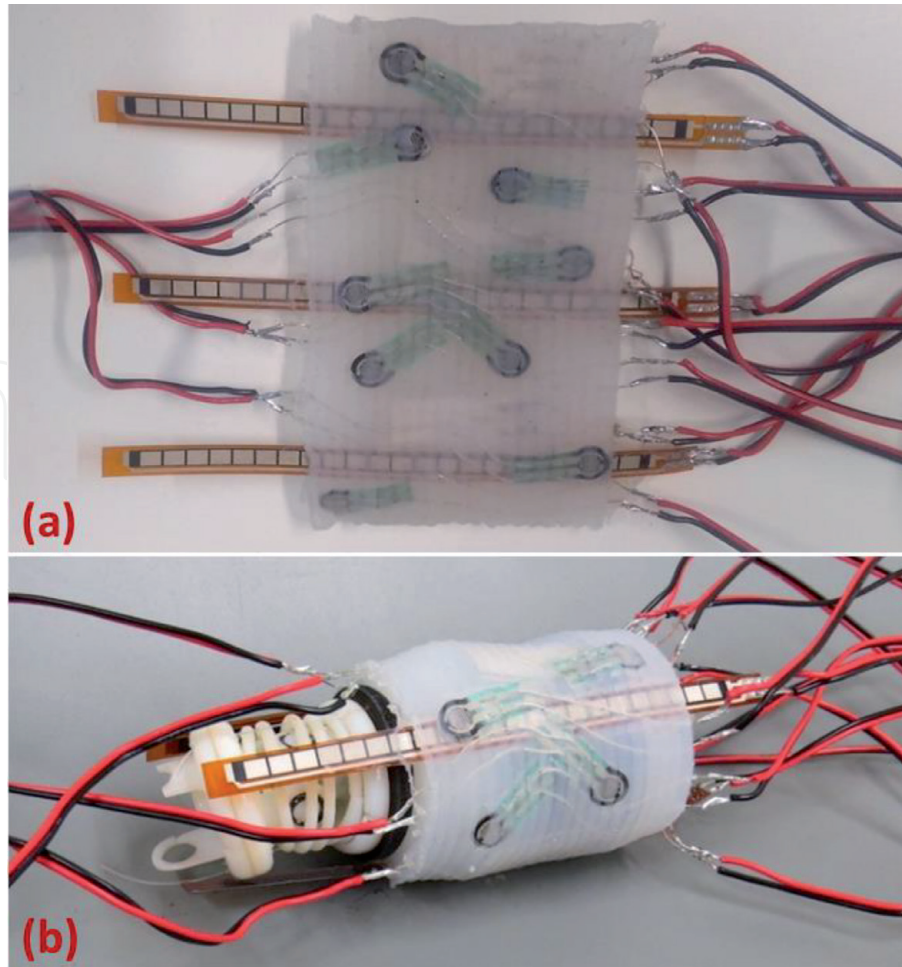
In one of the recent surveys on state-of-the-art tactile sensing for minimally invasive surgery (MIS) [44], it is clearly stated that the best place to include sensing elements in MIS device is on the instrument shaft inside the patient's body. The force sensors on the tip of the endoscopic tools are not strongly suggested, because

the space is very limited. Incorporating a tip sensor involves either having a larger gripper or manufacturing of extremely small transducers. The general overviews on the tactile sensors without a specific focus on use in the surgical robotics can be seen in [45–48]. In [46], the focus of the overview was extended to electronic skin technologies, whereas in [45] the effective utilization of the tactile skin takes the contact condition into special consideration. Some overviews focus on the wearable features [47], and the others explain the difficulties in the development of tactile sensor units emphasizing its complexity involving multiple transduction ways [48]. In order to develop tactile sleeves/sheaths for MIS endoscopic robotic platforms, a broader perspective of current tactile technology development is needed. Although the application is very different and does not contain any tactile modalities, in [49] a flexible and wearable skin for health monitoring interface is reported. These types of advanced skin patches can even be used for scheduled drug delivery [50]. Some of the relevant studies can be found from soft robotics literature. For example, in [51] a shape-tracking algorithm using polyvinylidene fluoride (PVDF)-based sensors on the hyper-flexible beams is used. Although the beam is in 2D, the proposed method can be extended to 3D providing a spatial ego-motion tracking for flexible endoscopic robots. The research [52] reports a discrete piezo-ceramic sensor array embedded in soft substrate, therefore offering a solution to accuracy problems in film-based piezo material but at the same time providing some compliance and stretchable behavior. Although the piezo-electric transduction is very widely used, there are also alternative methods based on optical modality. For example, in [53], a large-area sensor for pressure measurement was suggested using organic field-effect transistors (OFETs). Similarly, in [54] an optical principle is used to measure data through employing fiber Bragg grating and waveguides inside the compliant substrate material. The waveguide approach is also used in [55] but employing PDMS as the substrate this time.

## 4.2 Example application of tactile sensors as robotic skin

Herein, an example application is presented from AvH Project, MEDICARE [1], together with the measurement methodology it uses. The manufacturing of the tactile sleeve is achieved using multiple layers of silicone substrate in an additive manner to embed the piezo sensors in the desired depth and location. The silicone substrate was selected as Eco-flex 00-10 because of its relatively easy vacuuming and curing procedures. In addition to these advantages, the mechanical properties of Eco-flex are very close to the human tissue, and it is relatively low-cost. The distance between pressure sensors is large in this setup; however, ideally, they can be arranged with 4 mm separation in each active cell. The data cables connecting the sensors to the data acquisition circuit are soldered carefully, and meandering shapes are given to the bare wires to prevent fractures within the substrate when the sleeve moves with the backbone. It must be stated that using off-the-shelf sensors limits the stretchability of the sensing areas; still, the sleeve remains flexible enough to be wrapped around a robotic backbone. The tactile sleeve is produced in a flat sheet (**Figure 6a**) having slanted edges and was connected to the backbone in cylindrical form (**Figure 6b**) in the second step. The slanted angles at the edges allowed connecting the sleeve without having a bulk on the connection line. As it can be seen in **Figure 6**, the silicone sleeve features a ripple structure on the outer surface. This structure is a first attempt to increase the perception capacity of embedded sensors using the structural computation.

The measurement methodology of the sleeve when the outer surface of the silicone sleeve contacts with a rough surface, the ripples would help create a high-frequency interpretation of the surface properties in the sensor output. Although



**Figure 6.** Robotic sheath for endoscopic hyper-redundant platform developed in AvH project by Dr. Boyraz at Leibniz University of Hannover: (a) flat; (b) wrapped around the robotic platform, featured in [2].

being very simple, the surface ripple structures can be elaborated to include multiscale ripples in a fractal manner to interpret different surface structures having different frequency in the vibration pattern.

## 5. Conclusion

In this chapter, three different enabling technologies at research frontiers have been discussed to support safe interactions between robots and humans in different fields of robotics, mainly focusing on service, medical, and rehabilitation areas. We provided an extensive overview of variable stiffness, hyper-redundancy, and smart-skin structures in application cases. All these structures are only some of the enablers for safe HRI, and future studies should concentrate on integrating them in service robotics for the full benefit. While the variable stiffness offers inherent compliance during interaction and adaptability of the structures, the hyper-redundancy may allow better controllability of available degrees of freedom. Finally, the smart robotic skins can provide crucial feedback for safer interactions. As a holistic approach to safe HRI, inherent or structural compliance, enhanced controllability, and improved tactile feedback can bring significant safety built in robotic structures. In future work, the robotics platform that can integrate all of them may even have synergistic effects of the combined subsystems as the tactile feedback may directly be linked to variable stiffness adjustment or reconfigure the active links in a hyper-redundant structure.

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