USING FLEXIBLE SHEAR STRESS SENSORS FOR ROBOTIC MANIPULATION IMPROVEMENT

Inci Rüya Temel

Andrea Adami

Leandro Lorenzelli FBK

10.53478/TUBA.978-625-6110-22-9.ch14

Using Flexible Shear Stress Sensors for Robotic Manipulation Improvement

Inci Rüya Temel
Fondazione Bruno Kessler (FBK)

Andrea Adami
Fondazione Bruno Kessler (FBK)

Leandro Lorenzelli
Fondazione Bruno Kessler (FBK)

Abstract

Mimicking the human ability to dexterously manipulate objects requires sensor arrays to measure the normal and shear force distributions and orientations. This chapter discusses the use of flexible shear stress sensors in medical robotics to improve manipulation. Shear force sensors are critical for enhancing robotic manipulation because they provide tactile perception, which is essential for robots to interact with their environment and handle objects with precision (Jiang et al., 2024). These sensors enable robots to detect and measure the lateral forces applied to their grippers or end effectors, which is crucial for tasks that require delicate handling or fine motor skills. The ability to perceive shear forces allows robots to adjust their grip strength and manipulate objects without slipping or causing damage, thereby improving the dexterity and versatility of robotic systems (Howe, 1993). Therefore, shear force sensors have potential applications in medical-assisting devices, minimally invasive surgeries, and other areas of medical robotics. The use of non-invasive diagnostic and intervention techniques is increasing in modern medicine, and future electronic skins aim to improve the sensitivity, dynamic range, response time, relaxation time, and detection limit (Dahiya, 2019; Navaraj et al., 2019; Soni & Dahiya, 2020; Yeo et al., 2016). This chapter presents the gap between the human sense of touch and the tactile sensors reported in the literature.

Keywords
Flexible electronics, Tactile sensing, Shear stress sensor, Medical assisting devices, Minimally invasive surgery

Introduction

The rapid progress in AI-powered robotics involving the integration of advanced technologies has provided new horizons for healthcare and medical applications. In fact, modern medicine is taking a route towards non-invasive diagnostic and intervention techniques. Emergent technologies are being utilised to enhance the quality, efficiency, and precision of medical procedures, diagnosis, and treatment. Medical robotics holds great potential for transforming healthcare by improving patient outcomes, enhancing the efficiency of medical procedures, and helping surgeons improve their accuracy. Robotic technology is being used to develop and improve a wide range of medical applications, from surgical robots to rehabilitation robots, and from diagnostic tools to drug delivery systems.

Surgical robots are a well-known application of medical robotics and are designed to assist surgeons during minimally invasive procedures such as laparoscopic surgery and robotic-assisted surgery. The minimally invasive surgical approach allows the surgeon to reach the internal organs of the patient through two or three small incisions of the skin using specifically designed low-profile surgical instruments or flexible catheters (Seibold et al., 2005). Reduced incision size has the advantage of not only reducing intraoperative blood loss, postoperative infection, complications, and trauma, but also offers a better cosmesis as the surgeon leaves less visible scars associated with the operation (Nisky et al., 2012; Zhou et al., 2023). Non-invasive methods have the advantage of improving patient comfort by reducing pain, shortening recovery time, and reducing hospitalisation time (Okamura, 2009). Additionally, robotic technologies offer enhanced precision, dexterity, and control, thereby allowing surgeons to perform complex procedures with greater accuracy and less tissue damage. The DA VINCI robotic surgical system (Intuitive Surgical) is among the most popular state-of-the-art medical devices used for minimally invasive surgical procedures. Despite the advancements in robotic technology, the absence of haptic feedback remains a significant limitation. Haptic feedback is crucial in surgical procedures because it enables surgeons to accurately perceive tissue properties and manipulate delicate structures. Lack of tactile feedback can lead to complications and suboptimal outcomes, emphasising the need for the development of technologies that enhance the effectiveness and safety of minimally invasive surgical procedures.

Advancements in medical robotics have extended beyond surgery and revolutionised various aspects of healthcare delivery. For instance, automation in pharmacies and healthcare facilities enhances medication management accuracy and efficiency, while minimising the risk of errors through automated medication- dispensing and drug-delivery processes. Moreover, medical robotics enables telemedicine and remote surgery, thereby allowing healthcare professionals to provide care from a distance. Telepresence robots equipped with cameras and screens enable doctors to interact remotely with patients and provide real-time assistance during consultation from remote locations. However, the lack of tactile feedback poses a significant challenge to remote healthcare delivery. To address this issue, interactive screens with tactile feedback capabilities are required. These screens enable doctors to assess patient injuries or physical conditions remotely by providing sensory information, thereby improving healthcare providers' ability to diagnose and treat patients remotely and enhance access to quality healthcare services.

Technological advancements have revolutionised healthcare training by providing simulation-based platforms that enable medical professionals to enhance their skills and expertise. Medical robotics, such as simulators, offer realistic responses to external stimuli, allowing for the practise of procedures in safe and realistic settings. The integration of soft materials, contractile actuators, and flexible sensors in soft robotics, as well as artificial intelligence and augmented reality in software development, has created opportunities for the development of sophisticated body-part simulators that can replicate the mechanical properties, motion, and function of human tissues (Maglio et al., 2021). These simulations can minimise the need for animal or patient tests and standardise medical procedures. However, haptic feedback is often lacking or limited in these simulations, making the use of actual body mimics for training purposes more effective.

Assistive robots have been created to aid individuals with physical or cognitive limitations in performing daily tasks, such as mobility, personal care, and household chores. These robots provide repetitive, task-specific training to help patients improve their motor skills and enhance their independence. For instance, robots are utilized in rehabilitation to provide therapy and restore motor abilities (Tefertiller et al., 2011). Rehabilitation robots are designed to assist patients in regaining mobility and function after an injury or illness (Kang et al., 2016). Soft robotic gloves with embedded sensors can be used for hand rehabilitation, and soft robotic prosthetics require portability and controllability similar to assistive and rehabilitation devices (Mutlu et al., 2016). Assistive robots also offer a solution for various needs, such as tremor suppression (Manto et al., 2003) and personal care for elderly individuals (Sawik et al., 2023).

As technology continues to advance, we anticipate even more innovative applications of robotics in the medical field. Despite the usefulness of rigid components in everyday tasks, a more precise approach to medical devices is essential for safe surgery, endoscopy, and drug delivery. Laparoscopic surgery presents various challenges due to mechanical constraints at the incision point. Cable-based systems experience friction and interference with the wearer's body, hindering effective force transmission. Pneumatic actuators offer an alternative solution to overcome this issue (Connelly et al., 2010; Ilievski et al., 2011). Furthermore, the directional movements of the surgeon's hand result in opposite deflections of the working end of the laparoscopic instrument, causing a discrepancy between visual and proprioceptive feedback (Smith et al., 2001). This phenomenon, known as the "*fulcrum effect*", leads to altered force sensations due to mechanical advantage and friction at the incision point (Nisky et al., 2012). Flexible instruments, although highly manoeuvrable, are often used in conjunction with minimally invasive surgical procedures. However, they are lengthy and have a swiveling tip, reducing dexterity once they reach the surgical site. Additionally, these instruments have limited force application capabilities and lack stability.

Rapid advancements in AI-powered robotics have ushered in a new era for healthcare and medical applications, leading to the development of innovative non-invasive diagnostic and intervention techniques. This progress has significantly enhanced the quality, efficiency, and precision of medical procedures, diagnosis, and treatment. With these advancements, there is a growing need for tactile sensors that emulate the human skin to augment robotic manipulation and interaction with the environment. These sensors are crucial for robots to safely and effectively engage with their surroundings, particularly in dynamic settings where precise modelling is challenging (Cirillo et al., 2017). They enable the detection of various stimuli such as force, texture, and temperature, which are essential for tasks ranging from personal healthcare monitoring to advanced robotic manipulation (G et al., 2022; Pang et al., 2022).

Soft robotics hold a vital position in the discipline of biomedical engineering, and biocompatibility and biomimicry are key aspects to be considered in this field. It is of paramount importance that the materials utilised in the development of soft robotics be compatible with the human body and tissues, in order to guarantee the proper functioning and acceptance by the body of the entire system. Nonetheless, the extent of compatibility is contingent upon the particular biomedical application, as evidenced by Cianchetti et al. (2018). Currently, biocompatibility is achieved by using inert materials that do not trigger an immune response, such as silicones or hydrogels. Nevertheless, to achieve biocompatibility, biomimicry, portability, and functionality, advanced active materials and novel actuation and sensing principles are needed. A significant advancement in this field would be the combination of materials science for implants and surgical tools with tissue-engineering approaches.

Interestingly, while the development of tactile sensors is inspired by the human sense of touch, achieving the complexity and sensitivity of the human skin remains a significant challenge. The multifunctionality of tactile sensors, as demonstrated by Pang et al. (2022), can recognise voice and monitor physiological signals, in contrast to the more focused applications of sensors designed for specific tasks, such as object manipulation or human-robot interaction (Cirillo et al., 2017; G et al., 2022). This highlights diverse approaches and potential contradictions in the design and application of tactile sensors. Integrating tactile sensors into robotic systems is crucial for the development of human-like interaction capabilities. These sensors are essential for enhancing perception in various applications such as healthcare and manufacturing (Jamone, 2020; Pang et al., 2022).

Inspirations from the human skin

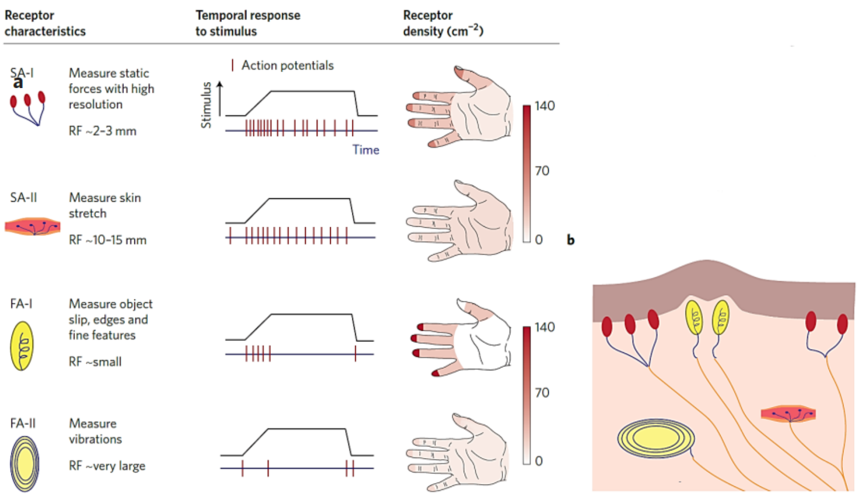
Touch is one of the five fundamental senses through which living organisms detect and interpret their physical surroundings. It involves the detection and perception of pressure, temperature, and texture by making physical contact with objects or surfaces. To perform a precise manipulation task, a person needs not only information about their body's current state, but also details about the object's physical properties, such as shape, weight, location, and temperature. The human brain can detect the resistance of objects, including their stiffness, damping, and inertia, by combining motion and force signals (Jones & Hunter, 1993; Kuschel et al., 2010; Nisky et al., 2008, 2010). Touch is a multifaceted sensory experience that involves physical sensations as well as the cognitive and emotional responses associated with it. On the other hand, tactile sensing refers to an organism or system's capacity to detect and process tactile information. Tactile sensors are devices or structures designed to imitate the human sense of touch, allowing machines or robots to perceive and interact with their surroundings. Touch pertains to the sensory experience of physical contact with objects, whereas tactile sensing refers to the ability to detect and process tactile information. Tactile sensing is crucial for enabling machines and robots to simulate the sense of touch and engage in effective interactions with the surrounding world.

The hands serve as a critical interface between humans and the world around them; their hands allowed them to craft tools for millions of years, play musical instruments and produce art, and now serves as an interface for most of the computing technology. This reflects the high density of sensory receptors (such as mechanoreceptors) in the hands, which allow for detailed tactile discrimination and fine motor control. Therefore, the representation of the hands and fingers in the somatosensory cortex is proportionally larger compared to other body regions in the sensory homunculus. The rich sensory feedback provided by the hands allows for precise tactile discrimination and intricate motor control. This importance is not only reflected in our daily activities but also in our physiology: 54 bones of the 206 bones of human skeleton are dedicated to the hands. Therefore, it's no surprise that the representation of the hands and fingers in the somatosensory cortex is particularly pronounced, underscoring their paramount role in our sensory perception and motor skills.

A substantial amount of research on the framework and features of the skin has been undertaken by Johansson and his team at the University of Umea, Sweden. Their studies in the 1970s and the 1980s focused on mechanoreceptors, including their receptive field characteristics (Johansson, 1978), densities (Johansson & Vallbo, 1979), and spatiotemporal properties (Johansson & Lamotte, 1983a; Johansson & Vallbo, 1979a, 1980). Their work contributed to the understanding of precision gripping when lifting objects (Gordon et al., 1991; Johansson & Westling, 1984; Westling & Johansson, 1984, 1987).

The skin, which is the interface between the word and body, is composed of seven types of sensory receptors: temperature, humidity, pain, and four types of mechanoreceptors (Gerardo Rocha & Lanceros-Mendez, 2008). Mechanoreceptors in the hand can be classified based on their receptive field and response time to a stimulus. Type I receptors have small and well-defined receptive fields and are located in superficial layers of the skin. Type II receptors have large, ill-defined, and roughly uniform receptive fields and terminate deeper in the dermis and epidermis (Johansson, 1978). Each type includes both fast- and slow-adapting receptors. Fast adapting (FA) receptors are sensitive to dynamic skin indentation as long as the stimulus is in motion and stops firing when the stimulus becomes stationary. Slowly adapting (SA) receptors are also sensitive to moving stimuli but respond to sustained skin indentation during static pressure with sustained discharge. Figure 1 shows the different mechanoreceptors located in the skin and their temporal responses to the stimuli.

Figure 1.
Skin receptors and transduction process. ***a,*** *Types of mechanoreceptors, their function, temporal response and density in the hand.* ***b.*** *Schematic of the location of mechanoreceptors in the skin. Adapted from (Chortos et al., 2016)*



SA-I receptors are sensitive to low-frequency (<5 Hz (Johansson & Flanagan, 2009)) dynamic skin deformations and are involved in transmitting high-resolution force information that is useful for object shape and texture representation and recognition (Weber et al., 2013). Their highest density is found in sensitive areas of the skin, such as the fingertips, where they can measure normal force distributions with a resolution of ~0.5mm (Dahiya et al., 2010; Hammock et al., 2013). The limit of detection for SA-I receptors is as low as 1 mN (Johansson & Lamotte, 1983), with a sensitivity range of 2–10 $Hz.kPa^{-1}$ (Ge & Khalsa, 2002), or a sensitivity to skin indentation of 30–160 $Hz.mm^{-1}$ (Burgess et al., 1983). SA-II receptors, on the other hand, measure tangential shear strain of the skin and respond to lateral stretching that occurs during object manipulation (Johansson & Flanagan, 2009).

FA-I receptors are responsible for measuring high-frequency (5–50 Hz (Johansson & Flanagan, 2009)) dynamic skin deformations and are insensitive to static force. They are essential for detecting changes in the position of objects in one's hand and adjusting grip force to prevent slippage. FA-II receptors are sensitive to mechanically transient and high-frequency vibrations (40–400 Hz (Johansson & Flanagan, 2009)) that propagate over largeareas through tissues and are also insensitive to static force. They play a crucial role in detecting slippage and discriminating textures.

Figure 2.

Sensory events during lifting task. ***(a)*** *Identification of goals and measurement of forces applied to reach the goal;* ***(b)*** *measurement of signals recorded from the four mechanoreceptors. Adapted from (Johansson & Flanagan, 2009)*

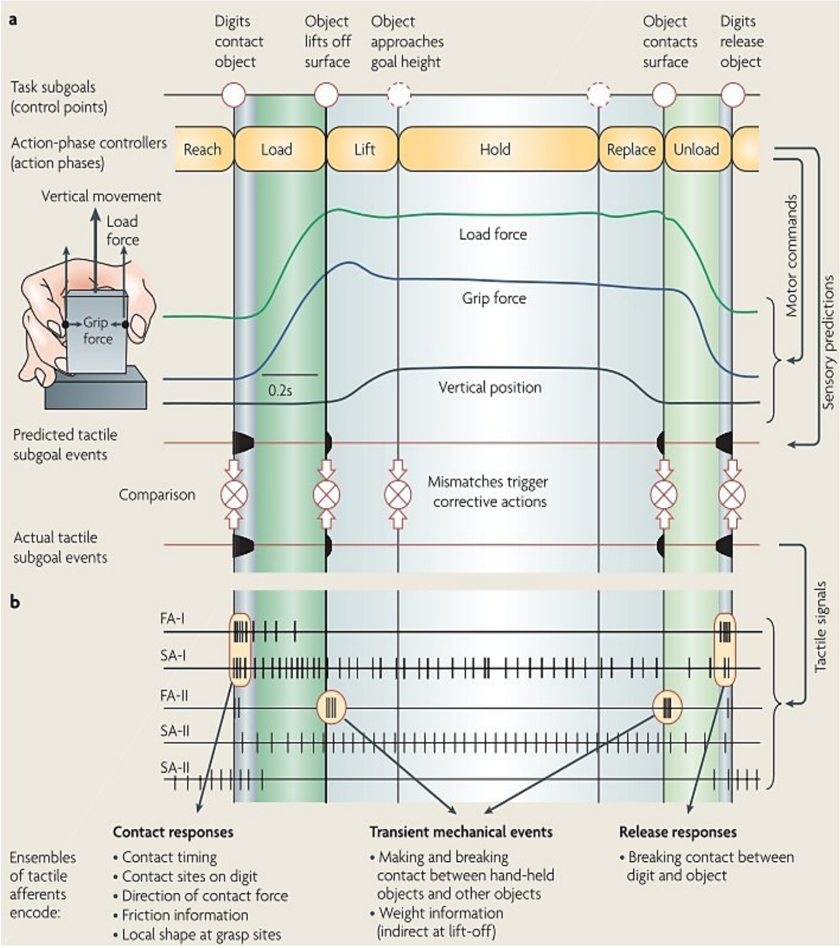


Figure 2 shows the different steps involved in sensing the contact and adapting the grip according to the physical properties of the object. Tactile afferent signals were recorded during lifting tasks. These recordings show that all four types of mechanoreceptors participate in the task, allowing the brain to monitor the progression of the task and correct any errors that can occur before the end of the lifting task. Primarily, when the fingers enter in contact with the object, the FA-I afferents fire, giving information about the contact, along with FA-II afferents responding to transient mechanical events when the object is lifted and then replaced. Second, at all times, a static force is applied to hold the object, and slow adapting afferents fire continuously.

This study shows that both static and dynamic force transductions are required to detect shear stress and strain. Mimicking the humans' ability to dexterously manipulate objects requires sensors arrays to measure normal and shear force distributions and orientations. In addition, the number and diversity of different sensors are important parameters to be included to build an electronic skin capable of detecting slip and allowing efficient grip. To meet these requirements, future electronic skin aims to improve the following key performance parameters: sensitivity, dynamic range, response time, relaxation time, and detection limit.

Recreating sensation of slip

Mimicking the intricate sense of slip allows users to interact more effectively with objects in their environment, thereby improving their overall dexterity and control. Numerous studies have reported sensors that demonstrate sensitivities equal to or better than those of the human skin. Notably, both capacitive and resistive sensors offer improved detection thresholds compared to the skin. While the skin's detection threshold stands at 1 mN, those of the capacitive and resistive sensors are respectively smaller than 0.05 mN and 0.08 mN. Furthermore, both capacitive and resistive sensors achieved significantly enhanced response times. It can reach less than 10 ms and less than 20 ms for devices based on capacitance (Schwartz et al., 2013) and resistance (Lee et al., 2016), respectively. In comparison, the response time of the skin is approximately 15 ms (Chortos et al., 2016).

All four mechanoreceptors are involved in tasks such as gripping. While slow adapting receptors transduce static force, fast adapting receptors are engaged in order to transduce dynamic force. Therefore, both static and dynamic force transduction are required to detect shear stress and strain. In addition, the number and diversity of different sensors are important parameters to be included to build an electronic skin capable of detecting slip and allowing efficient grip. Sensors capable of detecting multidirectional forces have also been reported; however, they all present a decrease in the sensitivity of sensors to shear when subjected to normal pressure (Boutry et al., 2018; Park, Lee, Hong, Ha, et al., 2014).

Recent advancements in shear force sensors, such as the development of microcolumn array dielectric layers, have addressed previous limitations, such as direction sensitivity and integration challenges, leading to sensors with high sensitivity and linearity (Jiang et al., 2024). This progress is significant given that current robotic systems often lack the flexibility and robustness needed for complex manipulation tasks and require extensive programming for specific tasks. The integration of these sensors into robotic systems can lead to significant advancements in the field, allowing robots to perform tasks with human-like dexterity and adaptability (Howe, 1993; Jiang et al., 2024). The ongoing development of these sensors and their integration with other sensory modalities are crucial for the evolution of robotic manipulation capabilities (Howe, 1993; Li et al., 2018). In this section, we discuss the various methods and technologies employed to recreate the slip sensation during robotic manipulation.

Dynamic sensing capabilities

Dynamic force transduction involves the detection and response to changes in force over time. Dynamic force sensing is essential for detecting slip events and adjusting the grip force of the artificial limbs (Rossi et al., 2017). Piezoelectric and triboelectric sensors are ideal for this application because they are sensitive to changes in force rather than the force's absolute value, which mimics the properties of fast-adapting mechanoreceptors found in human skin (Dahiya et al., 2010). Piezoelectric and triboelectric sensors produce voltage when they are mechanically deformed, causing a change in the magnitude of the dipoles in the active layer and inducing charging of the electrodes (Chortos et al., 2016). The difference between piezoelectric and triboelectric materials resides in the mechanism leading the dipole to charge. In piezoelectric materials, applying strain can alter the magnitude of the dipole in the unit cell or the number of dipoles per unit volume of the material. In contrast, triboelectric devices induce dipoles through contact electrification, where charges are separated due to differences in work function between the two materials. Ultimately, the operation of piezoelectric and triboelectric sensors allows them to generate energy autonomously through mechanical stimulation, which is known as self-powering (L. Wang et al., 2015).

Triboelectric sensors have emerged as a promising technology for dynamic force transduction in robotic manipulation, offering a high sensitivity and low energy consumption (Xiang et al., 2022). Specifically, triboelectric nanogenerators (TENGs) have been utilised in electronic skin (E-skin) sensors to detect multidimensional forces, such as normal pressure and shear force, which are crucial for robotic manipulation and human-robot interactions (Z.Wang et al., 2021). The integration of flexible, multilayer piezoelectric-based tactile sensors has shown promise in real-time dynamic force measurement, with applications in robotic grasping and tactile feedback (Xiang et al., 2022).

Piezoelectric sensors are popular because of their low cost, linear response, and high sensitivity (Alea et al., 2022; Ha et al., 2015, 2018; Parida et al., 2019; Park et al., 2015; Tao et al., 2019; Yi et al., 2019). However, their use in static force measurements is limited owing to the neutralisation of the surface charge. Interestingly, while piezoelectric sensors are typically associated with dynamic force measurements owing to their high sensitivity and fast response times (Xiang et al., 2022), advancements have been made to extend their capabilities to static force applications. This was achieved by leveraging different aspects of piezoelectricity beyond the direct piezoelectric effect (K.Kim et al., 2021). Moreover, the development of multimodal tactile sensors that combine different transduction mechanisms, such as those based on elastomers and optics, can offer a wide dynamic range and the ability to sense static forces (Wettels & Pletner, 2012). By exploring various parameters and combining different sensing technologies, tactile sensors can be adapted to accurately measure static forces, thereby expanding their utility in numerous applications (K.Kim et al., 2021; Wettels & Pletner, 2012).

Static force sensing

Static force transduction in robotic manipulation involves the measurement and interpretation of the forces exerted by objects in a stationary state. These forces typically include compression, tension, or shear forces acting on the end effector or gripper of the robot. Static force sensors are used to detect and quantify these forces, providing feedback to the robot's control system to ensure the precise and stable manipulation of objects. Various types of sensors, including strain gauges, load cells, piezoelectric sensors, and capacitive sensors, can be used for static force transduction in robotic manipulations. These sensors can be integrated into the robot's end- effector or gripper to provide real-time feedback on the forces exerted during manipulation tasks.

In resistive sensors, the output signal can originate from two different mechanisms: the measurement of the intrinsic material piezoresistivity or the change in contact resistance between a conductor and an electrode (Khalili et al., 2018). Piezoresistive sensors are integral to providing feedback for the control of robotic hands, as they can be optimised to achieve precise grasp kinematics through impedance control (Hou & Sucahyo, 1990). Their simple structure also has a simple working principle which is based on the variation in the resistivity of the conductive material in response to different magnitudes of applied pressure. They generate an output signal by either measuring the intrinsic material resistivity or by detecting changes in the contact resistance between a conductor and an electrode. In general, the resistance decreases as a given pressure is applied. Additionally, resistive sensors have been developed using materials such as graphite and polydimethylsiloxane to create thin-film layers, which are useful for localising force applications and are applicable in both industrial and healthcare settings (Sapra et al., 2019). Despite challenges, such as hysteresis and nonlinear electromechanical response, which can affect their accuracy and reliability (Ozioko & Dahiya, 2022), advancements in sensor technology and materials continue to enhance their performance and application scope (Hou & Sucahyo, 1990; Sapra et al., 2019).

The properties of resistive-type devices can be improved by inducing geometrical changes (Chossat et al., 2013) or by improving the resistivity of the material. There are two ways to modify ρ: if the material is a semiconductor, then changing its band structure will change its resistivity (Kanda, 1991); if it is a composite material, then adding conductive particles will change its percolation pathways (N. Hu et al., 2008), and thus, its resistivity (Chortos et al., 2016). Despite the fact that piezoresistive polymer composites possess a relatively low operating voltage and are highly sensitive, they are characterized by a significant amount of hysteresis and a substantial temperature sensitivity that can complicate measurements. Additionally, their pressure sensitivity is relatively poor compared to other materials.Resistive sensors capable of detecting normal force, shear force, lateral stretch, and bending have been successfully reported in the literature (N. Hu et al., 2008; Khalili et al., 2018; C. Pang et al., 2012; Y. Pang et al., 2018; Park et al., 2018; Park, Lee, Hong, Lee, et al., 2014; Su et al., 2015; Yamada et al., 2011).

On the other hand, capacitive-type sensors depend only on electrode displacement and less on changes in material properties. In capacitive sensors, the output signal is a measure of the variations in capacitance due to the movements of two electrodes separated by a dielectric layer. Its working principle remains on the change in capacitance due to the applied force (Puers, 1993). A change in capacitance will be observed either when the distance between the electrodes changes, when the overlapping area between the two electrodes is modified, or when the relative permittivity of the dielectric changes. (Mishra et al., 2021). Capacitive sensors are integral to robotic manipulation, particularly for static force transduction, owing to their high sensitivity, resolution, robustness, and stability (Ştefănescu, 2011). For instance, the development of soft capacitive sensors for soft robotics demonstrates the potential of these sensors to withstand large deformations without significant changes in sensitivity, which is crucial for static force measurements in applications where large strains occur (Alshawabkeh et al., 2023). Additionally, the use of curved electrodes in capacitive transducers has been shown to provide higher sensitivity and a wider linear dynamic range, which could be beneficial for static force measurements in robotic manipulations (McIntosh et al., 2006).

Capacitive sensors have the advantage of being able to detect both static pressure and strain, making them very suitable for electronic skin ((Boutry et al., 2018; W. Hu et al., 2013; Lipomi et al., 2011; X. Wang et al., 2013; Xu & Zhu, 2012). In addition, they demonstrate excellent sensitivity and linearity, making their response fast while requiring low power consumption and free from temperature dependency. However, they must be shielded to reduce their susceptibility to external noise sources from electromagnetic waves. Advancements in sensor design, such as the use of soft capacitive sensors and curved electrode transducers, have enhanced their capabilities, allowing accurate static force measurements even under substantial deformation (Alshawabkeh et al., 2023; Mcintosh et al., 2006). These developments highlight the potential of capacitive sensors to play a pivotal role in the evolution of robotic manipulation technologies.

In theory, for the same amount of deformation due to the applied pressure, the output signal demonstrates a greater change in resistive-type sensors than in capacitive sensors, leading to a wider dynamic range in the former. In addition, resistive-type sensors seem to be more interesting owing to their simple readout mechanisms. However, their cost efficiency is low owing to their constant and high-power consumption, and they are more difficult to fabricate because novel materials have to be considered in order to observe a wide range of conductivity changes. Compared with resistive-type sensors, capacitive sensors are much easier to fabricate and consume less power (Khalili et al., 2018).

In general, flexible sensors may be subject to hysteresis owing to the viscoelastic nature of rubber dielectrics, which represents one of the major disadvantages of flexible capacitive pressure sensors. To address this challenge, researchers have introduced air voids inside thin films of elastomers to alleviate problems associated with their viscoelastic behaviour (Mannsfeld et al., 2010; Ruth, Beker, et al., 2020; Ruth, Feig, et al., 2020; Ruth & Bao, 2020). Microengineering of the dielectric layer presents many advantages, including an increase in the effective dielectric constant owing to the collapse of the pores (Ruth & Bao, 2020) and, therefore, a higher sensitivity and a decrease in the Young's modulus and viscoelastic properties of the elastomer (J.O. Kim et al., 2019). Park et al. developed in 2014 (Park, Lee, Hong, Lee, et al., 2014) their simple bioinspired interlocked microstructures using only PDMS and carbon nanotubes. For instance, Bao et al. (Boutry et al., 2018) successfully designed a capacitive sensor with a high resolution and sensitivity using microstructures.

Towards the integration of both static and dynamic force transduction

The integration of both static and dynamic force transduction in robotic manipulation is an area of active research with various approaches being explored. This integration is crucial for enhancing the performance, accuracy, and robustness of robotic systems in various applications including industrial automation, assembly, and logistics. Tripicchio et al. and Xiang et al. (Tripicchio et al., 2023; Xiang et al., 2022) highlighted advancements in tactile sensing technologies for robotic grippers and tactile sensors, respectively, which are crucial for dynamic force measurement during object manipulation. Tripicchio et al. discussed the integration of fibre sensing elements for the real-time classification of gripper-object interactions, whereas Xiang et al. focused on a piezoelectric-based tactile sensor capable of real-time force measurements, including dynamic forces.

The integration of both static and dynamic force-sensing technologies into a single robotic system presents several technical challenges. These challenges include the development of sensor fusion algorithms and data processing techniques, as well as hardware design considerations, communication and coordination overhead, cost and maintenance issues, system scalability, and a limited workspace. Effective cooperation among multiple robot arms requires robust communication and coordination, which can lead to communication overheads and latency. Additionally, implementing and maintaining a multirobot arm system can be costly, with each extra robot arm adding to the hardware and maintenance expenses.

There are also challenges associated with accurately measuring the dynamic forces. (Ammar et al., 2022) addressed the complexities of dynamic force measurement in aerodynamic and robotic systems, noting that system dynamics can affect the sensitivity of force transducers and that static stiffness is typically greater than dynamic stiffness. (Chen et al., 2023) presented a strategy for compensating for charge leakage in piezoelectric force sensors, enabling a wide spectrum of force measurements from static to dynamic.

Adaptive control strategies have been developed to compensate for uncertainties related to an object's weight, shape, friction, or the robot's physical parameters. These strategies allow the system to adapt and adjust the control parameters in real time, thereby ensuring accurate and stable manipulation. This is particularly important for tasks requiring precise positioning and force regulation. Moreover, adaptive control can improve the accuracy of task execution by continuously adjusting the control inputs based on feedback from the sensors and the state of the system. This is crucial in cooperative manipulation scenarios that often involve complex and dynamic environments. Adaptive control strategies can make a system more robust by adapting to changes in the environment or disturbances that may affect the robots' ability to carry and manipulate an object. Additionally, ensuring compatibility and interoperability between different sensor types and robotic platforms is essential for achieving robust and reliable force sensing capabilities in robotic manipulation.

Despite these challenges, the integration of static and dynamic force transduction, with several innovative sensor technologies and compensation strategies being developed (Chen et al., 2023; Tripicchio et al., 2023; Xiang et al., 2022), is a promising area of research with ongoing efforts to improve the performance and efficiency of cooperative robotic systems. Despite these advancements, the accurate measurement of dynamic forces remains a complex issue because of the system dynamics and inherent properties of force transducers (Ammar et al., 2022). Ongoing research efforts are indicative of the potential for further improvements in robotic manipulation capabilities through enhanced force transduction.

Conclusion

Flexible shear stress sensors are essential for robots to accurately interact with their surroundings and manipulate objects. These sensors provide tactile perception, which enables robots to adjust their grip strength and prevent slipping or damage. Electronic skins have been developed for non-invasive diagnostic and intervention techniques in modern medicine, enhancing sensitivity, dynamic range, response time, relaxation time, and detection limit. Medical robotics have the potential to transform healthcare by improving patient outcomes, medical procedure efficiency, and assisting surgeons in enhancing their accuracy. Haptic feedback is vital during surgical procedures, allowing surgeons to accurately perceive tissue properties and manipulate delicate structures. Shear force sensors are necessary for enhancing robotic manipulation as they provide tactile perception, which enables robots to detect and measure lateral forces applied to their grippers or end effectors. This is crucial for tasks requiring delicate handling or fine motor skills. Recent advancements in shear force sensors, such as the development of microcolumn array dielectric layers, have addressed previous limitations, such as direction sensitivity and integration challenges, leading to sensors with high sensitivity and linearity. Integrating these sensors into robotic systems can lead to significant advancements in the field, allowing robots to perform tasks with human-like dexterity and adaptability. The ongoing development of these sensors and their integration with other sensory modalities are crucial for the evolution of robotic manipulation capabilities. One of the primary difficulties is the need to create sensors that are small, consume low power, and are resistant to interference from motion artifacts and electromagnetic fields. Additionally, these sensors must be capable of measuring both the intensity and direction of forces, which is less mature in current technologies compared to other sensing modalities like vision. The integration of sensors onto robotic platforms also presents challenges, particularly in terms of direction sensitivity and the ability to maintain performance over repeated use.

Acknowledgments

This work has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement number 861166 (INTUITIVE) and partially from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement number 952289 (EngSurf Twin). The authors would like to thank R. Hall-Wilton of *Fondazione Bruno Kessler*, and M. Ersöz of *Selçuk University* for the opportunity to extend my research

References

Alea, M. D., Safa, A., Assche, J. Van, & Gielen, G. G. E. (2022). Power-Efficient and Accurate Texture Sensing Using Spiking Readouts for High-Density e-Skins. *BioCAS 2022 - IEEE Biomedical Circuits and Systems Conference: Intelligent Biomedical Systems for a Better Future, Proceedings*, 359–363. https://doi.org/10.1109/BioCAS54905.2022.9948546

Alshawabkeh, M., Alagi, H., Navarro, S. E., Duriez, C., Hein, B., Zangl, H., & Faller, L. M. (2023). Highly Stretchable Additively Manufactured Capacitive Proximity and Tactile Sensors for Soft Robotic Systems. *IEEE Transactions on Instrumentation and Measurement*, *72*. https://doi.org/10.1109/TIM.2023.3250232

Ammar, M. M., Mohamed, M. I., Mahmoud, G. M., Hassan, S. R., Kumme, R., Zakaria, H. M., & Gaafer, A. M. (2022). A comparison between static and dynamic stiffness of force transducers for dynamic force calibrations. *Measurement: Journal of the International Measurement Confederation*, *203*. https://doi.org/10.1016/j.measurement.2022.111945

Boutry, C. M., Negre, M., Jorda, M., Vardoulis, O., Chortos, A., Khatib, O., & Bao, Z. (2018). A hierarchically patterned, bioinspired e-skin able to detect the direction of applied pressure for robotics. *Science Robotics*, *3*(24), 1–10. https://doi.org/10.1126/scirobotics.aau6914

Burgess, P. R., Mei, J., Tuckett, R. P., Horch, K. W., Ballinger, C. M., & Poulos, D. A. (1983). The neural signal for skin identation depth. I. Changing identations. *Journal of Neuroscience*, *3*(8), 1572–1585. https://doi.org/10.1523/jneurosci.03-08-01572.1983

Chen, F., Lin, H., Li, Z., Ju, B. F., & Chen, Y. L. (2023). Development of a novel strategy based on in-process compensation of charge leakage for static force measurement by piezoelectric force sensors. *Smart Materials and Structures*, *32*(7). https://doi.org/10.1088/1361-665X/acd7b5

Chortos, A., Liu, J., & Bao, Z. (2016). Pursuing prosthetic electronic skin. *Nature Materials*, *15*(9), 937–950. https://doi.org/10.1038/nmat4671

Chossat, J. B., Park, Y. L., Wood, R. J., & Duchaine, V. (2013). A soft strain sensor based on ionic and metal liquids. *IEEE Sensors Journal*, *13*(9), 3405–3414. https://doi.org/10.1109/JSEN.2013.2263797

Connelly, L., Jia, Y., Toro, M. L., Stoykov, M. E., Kenyon, R. V., & Kamper, D. G. (2010). A pneumatic glove and immersive virtual reality environment for hand rehabilitative training after stroke. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *18*(5), 551–559. https://doi.org/10.1109/TNSRE.2010.2047588

Dahiya, R. (2019). E-Skin: From Humanoids to Humans [Point of View]. *Proceedings of the IEEE*, *107*(2), 247–252. https://doi.org/10.1109/JPROC.2018.2890729

Dahiya, R., Metta, G., Valle, M., & Sandini, G. (2010). Tactile Sensing—From Humans to Humanoids. *IEEE Transactions on Robotics*, *26*(1), 1–20. https://doi.org/10.1109/TRO.2009.2033627

Ge, W., & Khalsa, P. S. (2002). Encoding of compressive stress during indentation by slowly adapting type I mechanoreceptors in rat hairy skin. *Journal of Neurophysiology*, *87*(4), 1686–1693. https://doi.org/10.1152/jn.00414.2001

Gerardo Rocha, J., & Lanceros-Mendez, S. (2008). *Sensors: Focus on Tactile Force and Stress Sensors* (J. Gerardo Rocha & S. Lanceros-Mendez, Eds.).

Gordon, A. M., Forssberg, H., Johansson, R. S., & Westling, G. (1991). Integration of sensory information during the programming of precision grip: comments on the contributions of size cues. *Experimental Brain Research*, *85*(1), 226–229. https://doi.org/10.1007/BF00230004

Ha, M., Lim, S., Cho, S., Lee, Y., Na, S., Baig, C., & Ko, H. (2018). Skin-Inspired Hierarchical Polymer Architectures with Gradient Stiffness for Spacer-Free, Ultrathin, and Highly Sensitive Triboelectric Sensors. *ACS Nano*, *12*(4), 3964–3974. https://doi.org/10.1021/acsnano.8b01557

Ha, M., Lim, S., Park, J., Um, D. S., Lee, Y., & Ko, H. (2015). Bioinspired interlocked and hierarchical design of zno nanowire arrays for static and dynamic pressure-sensitive electronic skins. *Advanced Functional Materials*, *25*(19), 2841–2849. https://doi.org/10.1002/adfm.201500453

Hammock, M. L., Chortos, A., Tee, B. C.-K., Tok, J. B.-H., & Bao, Z. (2013). 25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress. *Advanced Materials*, *25*(42), 5997–6038. https://doi.org/10.1002/adma.201302240

Hou, E. S. H., & Sucahyo, N. (1990). Multi-sensor system for an articulated robotic hand. *[Proceedings] IECON '90: 16th Annual Conference of IEEE Industrial Electronics Society*, 627–630. https://doi.org/10.1109/IECON.1990.149214

Howe, R. D. (1993). Tactile sensing and control of robotic manipulation. *Advanced Robotics*, *8*(3), 245–261. https://doi.org/10.1163/156855394X00356

Hu, N., Karube, Y., Yan, C., Masuda, Z., & Fukunaga, H. (2008). Tunneling effect in a polymer/carbon nanotube nanocomposite strain sensor. *Acta*

Materialia, *56*(13), 2929–2936. https://doi.org/10.1016/j.actamat.2008.02.030

Hu, W., Niu, X., Zhao, R., & Pei, Q. (2013). Elastomeric transparent capacitive sensors based on an interpenetrating composite of silver nanowires and polyurethane. *Applied Physics Letters*, *102*(8). https://doi.org/10.1063/1.4794143

Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X., & Whitesides, G. M. (2011). Soft robotics for chemists. *Angewandte Chemie - International Edition*, *50*(8), 1890–1895. https://doi.org/10.1002/anie.201006464

Intuitive Surgical. (n.d.). Retrieved April 2, 2024, from https://www.intuitive.com/en-us

Jiang, J., Lv, C., Lv, T., Lu, Y., Wang, X., Li, Q., Chen, X., & Xie, M. (2024). An Angle-Sensitive Microcolumn- Based Capacitive Shear Force Sensor for Robot Grasping. *Advanced Materials Technologies*, *9*(6). https://doi.org/10.1002/admt.202302113

Johansson, R. S. (1978). Tactile sensibility in the human hand: Receptive field characteristics of mechanoreceptive units in the glabrous skin area. *The Journal of Physiology*, *281*, 101–123. https://doi.org/10.1113/jphysiol.1978.sp012411

Johansson, R. S., & Flanagan, J. R. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. In *Nature Reviews Neuroscience* (Vol. 10, Issue 5, pp. 345–359). Nature Publishing Group. https://doi.org/10.1038/nrn2621

Johansson, R. S., & Lamotte, R. H. (1983). Tactile detection thresholds for a single asperity on an otherwise smooth surface. *Somatosensory & Motor Research*, *1*(1), 21–31. https://doi.org/10.3109/07367228309144538

Johansson, R. S., & Vallbo, A. B. (1979). Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *The Journal of Physiology*, *286*, 283–300. https://doi.org/10.1113/jphysiol.1979.sp012619

Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, *56*(3), 550–564. https://doi.org/10.1007/BF00237997

Jones, L. A., & Hunter, I. W. (1993). A perceptual analysis of viscosity. *Experimental Brain Research*, *94*(2), 343–351. https://doi.org/10.1007/BF00230304

Kanda, Y. (1991). Piezoresistance effect of silicon. *Sensors and Actuators: A. Physical*, *28*(2), 83–91. https://doi.org/10.1016/0924-4247(91)85017-I

Kang, B. B., Lee, H., In, H., Jeong, U., Chung, J., & Cho, K.-J. (2016). Development of a polymer-based tendon-driven wearable robotic hand. *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 3750–3755. https://doi.org/10.1109/ICRA.2016.7487562

Khalili, N., Shen, X., & Naguib, H. E. (2018). An interlocked flexible piezoresistive sensor with 3D micropyramidal structures for electronic skin applications. *Soft Matter*, *14*(33), 6912–6920. https://doi.org/10.1039/c8sm00897c

Kim, J. O., Kwon, S. Y., Kim, Y., Choi, H. B., Yang, J. C., Oh, J., Lee, H. S., Sim, J. Y., Ryu, S., & Park, S. (2019). Highly Ordered 3D Microstructure-Based Electronic Skin Capable of Differentiating Pressure, Temperature, and Proximity. *ACS Applied Materials and Interfaces*, *11*(1), 1503–1511. https://doi.org/10.1021/acsami.8b19214

Kim, K., Kim, J., Jiang, X., & Kim, T. (2021). Static Force Measurement Using Piezoelectric Sensors. In *Journal of Sensors* (Vol. 2021). Hindawi Limited. https://doi.org/10.1155/2021/6664200

Kuschel, M., Di Luca, M., Buss, M., & Klatzky, R. L. (2010). Combination and integration in the perception of visual-haptic compliance information. *IEEE Transactions on Haptics*, *3*(4), 234–244. https://doi.org/10.1109/TOH.2010.9

Lee, S., Reuveny, A., Reeder, J., Lee, S., Jin, H., Liu, Q., Yokota, T., Sekitani, T., Isoyama, T., Abe, Y., Suo, Z., & Someya, T. (2016). A transparent bending-insensitive pressure sensor. *Nature Nanotechnology*, *11*(5), 472–478. https://doi.org/10.1038/nnano.2015.324

Li, Q., Natale, L., Haschke, R., Cherubini, A., Ho, A.-V., & Ritter, H. (2018). Tactile Sensing for Manipulation. *International Journal of Humanoid Robotics*, *15*(01), 1802001. https://doi.org/10.1142/S0219843618020012

Lipomi, D. J., Vosgueritchian, M., Tee, B. C. K., Hellstrom, S. L., Lee, J. A., Fox, C. H., & Bao, Z. (2011). Skin- like pressure and strain sensors based on transparent elastic films of carbon nanotubes. *Nature Nanotechnology*, *6*(12), 788–792. https://doi.org/10.1038/nnano.2011.184

Maglio, S., Park, C., Tognarelli, S., Menciassi, A., & Roche, E. T. (2021). High-Fidelity Physical Organ Simulators: From Artificial to Bio-Hybrid Solutions. *IEEE Transactions on Medical Robotics and Bionics*, *3*(2), 349–361. https://doi.org/10.1109/TMRB.2021.3063808

Mannsfeld, S. C. B., Tee, B. C. K., Stoltenberg, R. M., Chen, C. V. H. H., Barman, S., Muir, B. V. O., Sokolov, A. N., Reese, C., & Bao, Z. (2010). Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers. *Nature Materials*, *9*(10), 859–864. https://doi.org/10.1038/nmat2834

Manto, M., Topping, M., Soede, M., Sanchez-Lacuesta, J., Harwin, W., Pons, J., Williams, J., Skaarup, S., & Normie, L. (2003). Dynamically responsive intervention for tremor suppression. *IEEE Engineering in Medicine and Biology Magazine*, *22*(3), 120–132. https://doi.org/10.1109/MEMB.2003.1213635

McIntosh, R. B., Mauger, P. E., & Patterson, S. R. (2006). Capacitive transducers with curved electrodes. *IEEE Sensors Journal*, *6*(1), 125–138. https://doi.org/10.1109/JSEN.2005.854137

Mishra, R. B., El-Atab, N., Hussain, A. M., & Hussain, M. M. (2021). Recent Progress on Flexible Capacitive Pressure Sensors: From Design and Materials to Applications. *Advanced Materials Technologies*, *2001023*, 1–34. https://doi.org/10.1002/admt.202001023

Mutlu, R., Alici, G., in het Panhuis, M., & Spinks, G. M. (2016). 3D Printed Flexure Hinges for Soft Monolithic Prosthetic Fingers. *Soft Robotics*, *3*(3), 120–133. https://doi.org/10.1089/soro.2016.0026

Navaraj, W., Smith, C., & Dahiya, R. (2019). E-skin and wearable systems for health care. In *Wearable Bioelectronics* (pp. 133–178). Elsevier. https://doi.org/10.1016/B978-0-08-102407-2.00006-0

Nisky, I., Baraduc, P., & Karniel, A. (2010). Proximodistal gradient in the perception of delayed stiffness. *Journal of Neurophysiology*, *103*(6), 3017–3026. https://doi.org/10.1152/jn.00939.2009

Nisky, I., Huang, F., Milstein, A., Pugh, C. M., Mussa-Ivaldi, F. A., & Karniel, A. (2012). Perception of stiffness in laparoscopy - the fulcrum effect. *Studies in Health Technology and Informatics*, *173*, 313–319. http://www.ncbi.nlm.nih.gov/pubmed/22357009

Nisky, I., Mussa-Ivaldi, F. A., & Karniel, A. (2008). A regression and boundary-crossing-based model for the perception of delayed stiffness. *IEEE Transactions on Haptics*, *1*(2), 73–83. https://doi.org/10.1109/TOH.2008.17

Okamura, A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. In *Current Opinion in Urology* (Vol. 19, Issue 1, pp. 102–107). https://doi.org/10.1097/MOU.0b013e32831a478c

Ozioko, O., & Dahiya, R. (2022). Strain sensors for soft robotic applications. In *Sensory Systems for Robotic Applications* (pp. 75–90). Institution of Engineering and Technology. https://doi.org/10.1049/PBCE097E_ch4

Pang, C., Lee, G. Y., Kim, T. Il, Kim, S. M., Kim, H. N., Ahn, S. H., & Suh, K. Y.

(2012). A flexible and highly sensitive strain-gauge sensor using reversible interlocking of nanofibres. *Nature Materials*, *11*(9), 795–801. https://doi.org/10.1038/nmat3380

Pang, Y., Zhang, K., Yang, Z., Jiang, S., Ju, Z., Li, Y., Wang, X., Wang, D., Jian, M., Zhang, Y., Liang, R., Tian, H., Yang, Y., & Ren, T. L. (2018). Epidermis Microstructure Inspired Graphene Pressure Sensor with Random Distributed Spinosum for High Sensitivity and Large Linearity. *ACS Nano*, *12*(3), 2346–2354. https://doi.org/10.1021/acsnano.7b07613

Parida, K., Xiong, J., Zhou, X., & See, P. (2019). Nano Energy Progress on triboelectric nanogenerator with stretchability , self-healability and bio-compatibility. *Nano Energy*, *59*(January), 237–257. https://doi.org/10.1016/j.nanoen.2019.01.077

Park, J., Kim, J., Hong, J., Lee, H., Lee, Y., Cho, S., Kim, S. W., Kim, J. J., Kim, S. Y., & Ko, H. (2018). Tailoring force sensitivity and selectivity by microstructure engineering of multidirectional electronic skins. *NPG Asia Materials*, *10*(4), 163–176. https://doi.org/10.1038/s41427-018-0031-8

Park, J., Kim, M., Lee, Y., Lee, H. S., & Ko, H. (2015). Nanomaterials: Fingertip skin-inspired microstructured ferroelectric skins discriminate static/dynamic pressure and temperature stimuli. *Science Advances*, *1*(9). https://doi.org/10.1126/sciadv.1500661

Park, J., Lee, Y., Hong, J., Ha, M., Jung, Y. Do, Lim, H., Kim, S. Y., & Ko, H. (2014). Giant tunneling piezoresistance of composite elastomers with interlocked microdome arrays for ultrasensitive and multimodal electronic skins. *ACS Nano*, *8*(5), 4689–4697. https://doi.org/10.1021/nn500441k

Park, J., Lee, Y., Hong, J., Lee, Y., Ha, M., Jung, Y., Lim, H., Kim, S. Y., & Ko, H. (2014). Tactile-direction- sensitive and stretchable electronic skins based on human-skin-inspired interlocked microstructures. *ACS Nano*, *8*(12), 12020–12029. https://doi.org/10.1021/nn505953t

Puers, R. (1993). Capacitive sensors: When and how to use them. *Sensors and Actuators: A. Physical*, *37– 38*(C), 93–105. https://doi.org/10.1016/0924-4247(93)80019-D

Rossi, M., Nardello, M., Lorenzelli, L., & Brunelli, D. (2017). *Dual Mode Pressure Sensing for Lower-Limb Prosthetic Interface*. 593. https://doi.org/10.3390/proceedings1040593

Ruth, S. R. A., & Bao, Z. (2020). Designing Tunable Capacitive Pressure Sensors Based on Material Properties and Microstructure Geometry. *ACS Applied Materials and Interfaces*, *12*(52), 58301–58316. https://doi.org/10.1021/acsami.0c19196

Ruth, S. R. A., Beker, L., Tran, H., Feig, V. R., Matsuhisa, N., & Bao, Z. (2020). Rational Design of Capacitive Pressure Sensors Based on Pyramidal Microstructures for Specialized Monitoring of Biosignals. *Advanced Functional Materials*, *30*(29), 1–12. https://doi.org/10.1002/adfm.201903100

Ruth, S. R. A., Feig, V. R., Tran, H., & Bao, Z. (2020). Microengineering Pressure Sensor Active Layers for Improved Performance. *Advanced Functiona Materials*, *30*(39), 1–31. https://doi.org/10.1002/adfm.202003491

Sapra, S., Nag, A., Han, T., & Gooneratne, C. P. (2019). Localisation of thin- film resistive sensors for force sensing applications. *2019 13th International Conference on Sensing Technology (ICST)*, 1–6. https://doi.org/10.1109/ICST46873.2019.9047720

Sawik, B., Tobis, S., Baum, E., Suwalska, A., Kropińska, S., Stachnik, K., Pérez-Bernabeu, E., Cildoz, M., Agustin, A., & Wieczorowska-Tobis, K. (2023). Robots for Elderly Care: Review, Multi-Criteria Optimization Model and Qualitative Case Study. *Healthcare (Switzerland)*, *11*(9). https://doi.org/10.3390/healthcare11091286

Schwartz, G., Tee, B. C. K., Mei, J., Appleton, A. L., Kim, D. H., Wang, H., & Bao, Z. (2013). Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring. *Nature Communications*, *4*(May). https://doi.org/10.1038/ncomms2832

Seibold, U., Kübler, B., & Hirzinger, G. (2005). Prototype of instrument for minimally invasive surgery with 6- axis force sensing capability. *Proceedings - IEEE International Conference on Robotics and Automation*, *2005*, 496–501. https://doi.org/10.1109/ROBOT.2005.1570167

Smith, C. D., Farrell, T. M., McNatt, S. S., & Metreveli, R. E. (2001). Assessing laparoscopic manipulative skills. *American Journal of Surgery*, *181*(6), 547–550. https://doi.org/10.1016/s0002-9610(01)00639-0

Soni, M., & Dahiya, R. (2020). Soft Eskin: Distributed touch sensing with harmonized energy and computing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2164). https://doi.org/10.1098/rsta.2019.0156

Ştefănescu, D. M. (2011). Capacitive Force Transducers. In *Handbook of Force Transducers* (pp. 87–108).

Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-18296-9_5

Su, B., Gong, S., Ma, Z., Yap, L. W., & Cheng, W. (2015). Mimosa-Inspired Design of a Flexible Pressure Sensor with Touch Sensitivity. *Small*, *11*(16), 1886–1891. https://doi.org/10.1002/smll.201403036

Tao, J., Bao, R., Wang, X., Peng, Y., Li, J., Fu, S., Pan, C., & Wang, Z. L. (2019). *Self-Powered Tactile Sensor Array Systems Based on the Triboelectric Effect*. *1806379*, 1–23. https://doi.org/10.1002/adfm.201806379

Tefertiller, C., Pharo, B., Evans, N., & Winchester, P. (2011). Efficacy of rehabilitation robotics for walking training in neurological disorders:A review. *Journal of Rehabilitation Research and Development*, *48*(4), 387–416. https://doi.org/10.1682/JRRD.2010.04.0055

Tripicchio, P., D'Avella, S., Avizzano, C. A., & Velha, P. (2023). Towards robust grasping: An analysis of in- hand object motion with FBG optical fibers as force sensing technology. *Mechatronics*, *93*. https://doi.org/10.1016/j.mechatronics.2023.102990

Wang, X., Li, T., Adams, J., & Yang, J. (2013). Transparent, stretchable, carbon-nanotube-inlaid conductors enabled by standard replication technology for capacitive pressure, strain and touch sensors. *Journal of Materials Chemistry A*, *1*(11), 3580–3586. https://doi.org/10.1039/c3ta00079f

Wang, Z., Bu, T., Li, Y., Wei, D., Tao, B., Yin, Z., Zhang, C., & Wu, H. (2021). Multidimensional Force Sensors Based on Triboelectric Nanogenerators for Electronic Skin. *ACS Applied Materials and Interfaces*, *13*(47), 56320–56328. https://doi.org/10.1021/acsami.1c17506

Wang, Z. L., Chen, J., & Lin, L. (2015). Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy and Environmental Science*, *8*(8), 2250–2282. https://doi.org/10.1039/c5ee01532d

Weber, A. I., Saal, H. P., Lieber, J. D., Cheng, J. W., Manfredi, L. R., Dammann, J. F., & Bensmaia, S. J. (2013). Spatial and temporal codes mediate the tactile perception of natural textures. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(42), 17107–17112. https://doi.org/10.1073/pnas.1305509110

Westling, G., & Johansson, R. S. (1984). Factors influencing the force control during precision grip. *Experimental Brain Research*, *53*(2), 277–284. https://doi.org/10.1007/BF00238156

Westling, G., & Johansson, R. S. (1987). Responses in glabrous skin mechanoreceptors during precision grip in humans. *Experimental Brain Research*, *66*(1), 128–140. https://doi.org/10.1007/BF00236209

Wettels, N., & Pletner, B. (2012). Integrated dynamic and static tactile sensor: focus on static force sensing. *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2012*, *8345*, 83454H. https://doi.org/10.1117/12.917391

Xiang, G., Wang, X., Cheng, N., Hu, L., Zhang, H., & Liu, H. (2022). A Flexible Piezoelectric-based Tactile Sensor for Dynamic Force Measurement. *2022 International Conference on High Performance Big Data and Intelligent Systems, HDIS 2022*, 207–211. https://doi.org/10.1109/HDIS56859.2022.9991654

Xu, F., & Zhu, Y. (2012). Highly conductive and stretchable silver nanowire conductors. *Advanced Materials*, *24*(37), 5117–5122. https://doi.org/10.1002/adma.201201886

Yamada, T., Hayamizu, Y., Yamamoto, Y., Yomogida, Y., Izadi-Najafabadi, A., Futaba, D. N., & Hata, K. (2011). A stretchable carbon nanotube strain sensor for human-motion detection. *Nature Nanotechnology*, *6*(5), 296–301. https://doi.org/10.1038/nnano.2011.36

Yeo, J. C., Yu, J., Koh, Z. M., Wang, Z., & Lim, C. T. (2016). Wearable tactile sensor based on flexible microfluidics. *Lab on a Chip*, *16*(17), 3244–3250. https://doi.org/10.1039/C6LC00579A

Yi, F., Zhang, Z., Kang, Z., Liao, Q., & Zhang, Y. (2019). *Recent Advances in Triboelectric Nanogenerator- Based Health Monitoring*. *1808849*, 1–16. https://doi.org/10.1002/adfm.201808849

Zhou, Y., Tang, Y., & Yu, Y. (2023). Technological trends in medical robotic sensing with soft electronic skin. In

Sensors and Diagnostics. Royal Society of Chemistry. https://doi.org/10.1039/d3sd00284e

About Authors

Inci Rüya TEMEL | Fondazione Bruno Kessler (FBK) |
ORCID: 0009-0001-9279-0411

Received the B.Sc degree in Life Sciences from Sorbonne University, Paris, and the M.Sc degree in Biomedical engineering from University of Montpellier. Since 2020, she is working on the MSCA ITN INTUITIVE project in the Bruno Kessler Foundation, Italy as a Marie Curie Early-Stage Researcher and pursuing her Ph.D. in the University of Glasgow, UK. She is working on flexible shear force sensors to be integrated in an electronic skin.

Andrea ADAMI | Fondazione Bruno Kessler (FBK) |
ORCID: 0000-0003-2833-7564

Received the Italian Master degree in materials engineering and the Ph.D. degree in information and communications technologies from the University of Trento, Italy, in 2003 and 2010, respectively. He is currently a Researcher with the Fondazione Bruno Kessler (FBK), where he is involved in sensors and microsystems. Since 2003, he acquired good experience on device design and development, especially on chemical sensors, micromechanical sensors, and microfluidics for several applications. His current main research interest is the development of microsystems and microfluidics, in particular for sample preparation in analytical systems. He is the author of more than 70 articles in international conferences and scientific journals.

Leandro LORENZELLI | Fondazione Bruno Kessler (FBK) |
ORCID: 0000-0003-4624-170X

(Member, IEEE) received the degree in electronic engineering from the University of Genova in 1994, and the Ph.D. degree in electronics materials and technologies from the University of Trento in 1998. In 1998, he joined the Staff of the ITC-irst Microsystems Division, and he was involved in the realization of microsystems for biomedical, environmental, and agro-food applications. Since 2005, he has been directing the BioMEMS research area at Bruno Kessler Foundation. His research interests include biosensors, nanobiotechnology, and lab-on-chip.