Soft, Wearable Robotics and Haptics: Technologies, Trends, and Emerging Applications

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Abstract

Recent advances in the rapidly growing field of soft robotics highlight the potential for innovations in wearable soft robotics to meet challenges and opportunities affecting individuals, society, and the economy. Some of the most promising application areas include wearable haptic interfaces, assistive robotics, and biomedical devices. Several attributes of soft robotic systems make them well-suited for use in human-wearable applications. Such systems can be designed to accommodate the complex morphology and movements of the human body, can afford sufficient compliance to ensure safe operation in intimate proximity with humans, and can provide context-appropriate haptic feedback or assistance to their wearers. Many soft robotic systems have been designed to resemble garments or wearables that are already widely used today. Such systems could one day become seamlessly integrated in a myriad of human activities and environments. Here, we review emerging advances in wearable soft robotic technologies and systems, including numerous examples from prior research. We discuss important considerations for the design of such systems, based on functional concerns, wearability, and ergonomics. We describe an array of design strategies that have been adopted in prior research. We review wearable soft robotics applications in diverse domains, and survey sensing and actuation technologies, materials, and fabrication methods. We conclude by discussing frontiers, challenges, and future prospects for soft, wearable robotics.

Index Terms

Soft Robotics, Wearable Robotics, Haptics, Assistive Technologies

I. Introduction

Recent advances in soft and functional materials, and methods of fabrication, have catalyzed research in soft robotics during the past decade. Among the earliest examples of wearable soft robotics were technologies for human space exploration that were developed to support the NASA Apollo program in the 1960s [1]. Inspired by the stringent demands of human space exploration, those explorations anticipate the utility of soft robotics for systems that assist humans in close proximity with the body. During the intervening decades, soft robotics has have been used in wearable systems for first responders, in rehabilitation and assistive robotics, and in wearable haptic devices.

In this article, we review recent developments in wearable soft robotics and haptics. We survey emerging application domains, including rehabilitative, therapeutic, and assistive robotics, prosthetics, haptics, and other areas. We also discuss distinguishing characteristics of soft, wearable robotic systems, including aspects of coordinated sensing, actuation, and computation. We discuss considerations arising from human-wearability in soft robotic and haptic systems, and conceptual and practical implications for their design. Enabling technologies for soft robotics have advanced rapidly as a result of intense research in numerous groups and institutions. We review many of the advances and technologies in materials, fabrication, sensing, and actuation that are contributing to the development of this promising field. We conclude by discussing the potentially transformative influence that soft, wearable robotic systems could have in many human environments and activities. We discuss some of the important challenges that we argue need to be met in order to realize this potential.

Many developments in wearable robotics are motivated by applications that involve complex, human-centered challenges that benefit from automation. The term *robotic* is frequently used to describe systems that integrate three key capabilities: sensing, thinking, and acting [2]. Sensors collect information from the environment or the robot itself; computation processes information, enacts decisions and control; and actuators perform mechanical work on the environment. In wearable robotics, the environment encompasses the human body and its surroundings. Designing wearable systems thus demands careful consideration of factors including safety, ergonomics, comfort, and reliability [3], [4]. It can be challenging to meet these requirements using conventional robotic design approaches that are based on rigid mechanical systems. Thus, a growing array of researchers and engineers have identified soft robotic technologies as being especially well suited for wearable application areas. We review recent work in several of these areas in the next section.

II. Emerging Application Domains for Soft, Wearable Robotics

Many advancements in soft robotic technologies have been driven by needs in health-related areas, including rehabilitation and disability engineering [5], [6]. Wearable soft robotics may also provide therapeutic technologies offering mental and physical

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Fig. 1. Examples of soft wearable devices in diverse application areas. A. Pneumatic glove for hand rehabilitation [13]. B. Cable-driven soft prosthetic hand [21]. C. Segmented pneumatic actuation for compression therapies [7]. D. A cable-driven suit for reducing metabolic costs of walking [9]. E. A supernumerary pneumatic arm for aiding activities of daily living [11]. F. A string-based wearable haptic interface for virtual reality [22]. G. Leggings knitted from shape memory alloy (SMA) that can contract to match the limb shape [23]. H. An expressive soft robotic garment actuated by SMAs responds to the gaze of others [24]. I. A piezoelectric garment reacts to ambient illumination [25].

benefits [7], [8]. Other researchers have investigated soft robotic technologies, including orthotic and prosthetic devices, that might augment the capabilities of the human body, by reducing the effort or energy required to perform physical activities [9], [10], or even providing additional, supernumary limbs [11], [12]. In this section, we review an array of examples in diverse application areas.

A. Rehabilitation and Assistive Devices

Physical assistance and rehabilitation are among the most actively researched biomedical application areas for soft, wearable robotics. Assistive devices are designed to restore the body's capacities for performing physical tasks or movements that are affected by injury, disease, or congenital effects. Many activities of daily living rely on the impressive capabilities of the human hand for grasping and manipulation. Consequently, some of the most promising examples of soft robotics research include devices for assisting or restoring grasping movements of the hand [13]–[16]. Technologies that interface with the hand are challenging to engineer because hands are kinematically complex, are used in a diverse variety of fine manipulation tasks, and have numerous moving joints. Impairments of the sensorimotor system often arise from neurological impairments, such as stroke or traumatic injury. Such impairments can often be remedied through rehabilitation exercises and resistance training. Several research groups have investigated soft, wearable robotic devices that address needs in rehabilitation. Many of these employ fluidic actuation. Polygerinos et al. developed a robotic glove for stroke patients, employing soft fiber-reinforced silicone-based actuators that can enact a variety of motions under fluid pressurization (Figure 1A) [13]. Several tendon-driven assistive gloves have also been developed. Kang et al. created one such glove for restoring hand movements during activities of daily living [15], [16]. In it, tendons are embedded in a polymer skin, and arranged so as to assist pinch and and other grasping movements (Figure 2J) [16]. While many other soft robotic gloves have also been developed, Zhang et al. investigated a different approach, based on wearable pneumatic rings that aid grasping (Figure 2M) [17]. Sensors in the device allow the rings to inflate in response to grasping movements of the wearer.

The larger joints of the body are kinematically simpler than the hand but often involve larger forces or displacements, and thus produce different design requirements. Galiana et al. introduced a cable-driven rehabilitation device that corrects shoulder position based on a wearer's posture, which is sensed via an Inertial Measurement Unit (IMU) (Figure 2A) [18]. Among soft, wearable robotic devices for the lower limbs, Park et al. realized an ankle-foot rehabilitation system using McKibben artificial muscles (Figure 2R) [19]. Sridar et al. created a soft-inflatable exosuit for knee rehabilitation using structured thermoplastic polyurethane (TPU) fluidic bladders (Figure 2S) [20].

B. Prosthesics and Orthotics

Prosthetics and orthotic devices augment the ability of the body to perform physical activities. Prosthetic devices provide replacements for absent limbs. Orthotic devices are used to assist with mechanical functions of the musculoskeletal system, prevent joint hypomobility and disuse atrophy, maintain fracture and joint alignment during healing, and remove damaging load to decrease pain. Several research groups have investigated soft robotic prosthetic and orthotic devices. Mohammadi et al. designed a 3D printable soft robotic prosthetic hand that has multi-articulating capabilities for daily grasping tasks (Figure 1B) [21]. Zhu et al. designed a pneumatic wrist angle correction device for the rehabilitation of carpal tunnel syndrome [26].

C. Compression Therapies

Compression therapies are used to improve lymphatic or blood circulation [27], such as lymphedema [28] or venous closure [29]. In some cases, they are combined with cold treatment to reduce pain and swelling, as in hilotherapy. Compression devices are often designed to apply static or dynamic pressure to body surfaces. Among emerging soft robotic technologies for compression therapies, Payne et al. developed a brace-like fabric device that encloses human limbs to provide dynamic pressure stimuli that mimic manual massage (Figure 1C) [7].

D. Performance Augmentation

Other wearable robotic systems are designed to improve the physical performance of healthy individuals. Many of these devices are designed to improve human movement economy by reducing the amount of energy required to complete a movement, activity, or exercise. For instance, Quinlivan et al. created a tethered, multiarticular soft exosuit that can reduce the metabolic rate of walking by nearly 23% (Figure 1D) [9]. Kim et al. created a portable exosuit for assisting hip extension, and showed that it can reduce the metabolic rate of treadmill walking or running by 9.3% and 4.0% respectively (Figure 2P) [10].

E. Extending the Human Body

Several researchers have investigated methods for augmenting the human body through soft robotic supernumary (supplemental) limbs. Soft robotic supernumary limbs have been designed to help their wearers compensate for injuries or impairments to the limbs, to extend the working space of the healthy body, to improve task performance, or enable their wearers to perform tasks that exceed their capabilities. For example, several groups have proposed wearable, supernumary fingers that assist stroke patients during object grasping (Figure 3E) [12]. Many supernumary devices have been designed to be modular, comprising arrays of moving segments that can produce substantial motion. Some integrate multiple actuators that increase the size of the kinematic workspace of the limb. Examples include pneumatic soft poly-limbs made of silicone actuators (Figure 3D) [30], and supernumary limbs based on wearable fabric actuators (Figure 1E) [11]. A recent review of supernumary devices can be found in Masia et al. [31].

F. Haptic Interfaces for Human-Computer Interaction, Virtual Reality, Human-Robot Interaction, and Other Applications

Wearable robotic systems interface with the skin, which is a major component of the human haptic system, associated with the sense of touch. The haptic system integrates the skin, musculoskeletal system, and other tissues. Over the past half-century, haptic technologies, including many wearable devices, have been investigated for applications in human-computer interaction, virtual reality, neurorehabilitation, human-robot interaction, telemanipulation, sensory substitution, and many others [32], [33]. Most haptic technologies are designed to stimulate the skin, which is the largest sensory organ of the body. It is a critically important intermediary in any physical interaction with the environment and is a fundamental constituent of our ability to perceive and interact with our environment. Such interfaces provide perceptual cues in the form of forces, displacements, electrical, thermal or other signals delivered to the skin and body [34], [35].

The properties of the skin, and associated ergonomic requirements (Section III, below), are motivating many researchers to investigate soft technologies for wearable haptics. Today, much of this research remains at the stage of technology development; we review several examples of such enabling technologies in later sections of this article. However, several researchers have already produced wearable, soft interfaces for haptic applications. Several soft, wearable haptic technologies have been designed to allow users to experience touching and interacting with virtual objects whose properties are simulated haptically. These include devices for providing touch feedback to the hand or finger (Fig. 2L, [36]) in virtual reality. Others have been designed to guide navigation or actions in in real or virtual environments, for example through belt-like garments [37], [38], or wrist-worn inflatable interfaces [39], [40].

G. Affective Haptic Interfaces

In addition to facilitating physical interactions with our environment, the human sense of touch also serves important functions in social communication and emotion. Emotional, or affective, states are influenced by physiological processes in the body driven by activity in the sympathetic, parasympathetic, and enteric components of the visceral motor system, and by exogenous tactile sensations felt by the skin [41]. Many forms of touch between individuals, such as handshakes or hugs, convey social and emotional information [42], [43] that depends on the social context involved and on the parameters governing the physical interaction, such as locations, forces, or sliding speeds [44]. Recent findings demonstrate that such parameters greatly influence the responses of tactile receptors, including multitudes of C-polymodal tactile afferents that innervate most skin regions, that drive emotional responses to social touch [45], [46].

These findings have influenced the development of new methods for haptic feedback related to emotion, also referred to as affective haptics. Emerging application areas for affective haptics include interfaces for mediating remote touch between individuals and wearable devices for haptic therapy. The important role of mechanics in the emotional processing of touch sensations, and the soft contacts that are involved in interpersonal touch, have motivated several research groups to develop affective haptic systems using wearable, soft robotic technologies. Hiroshi et al. developed four affective haptic interfaces that provide touch, squeezing, painful, and cooling sensations for therapeutic applications including anxiety disorders and Autism Spectrum Disorder [47]. Papadopoulou et al. developed a programmable shape memory alloy (SMA) actuated sleeve that provides rhythmic and thermal stimulation to promote calmness and reduce anxiety [8]. Wu et al. fabricated a segmented pneumatic sleeve that creates the illusion of a continuous lateral motion in order to mimic a stroking gesture commonly used in social touch (Figure 2F) [48].

H. Fashion, Art, and Design

Humans have employed soft, wearable technologies in the form of clothing since ancient times. Thus, it is unsurprising that designers in fashion, art, and other areas have explored soft, wearable robotic systems whose functionalities expand those of conventional garments, such as through adaptive garments. In some cases, the expanded functionalities of these garments allow them to adapt to the size, shape, or preferences of their wearer. A basic purpose of conventional garments is to insulate their wearer from their environment. Thus, it is unsurprising that many researchers have investigated adaptive garments that can respond dynamically to the environment of the wearer by altering their configuration, shape, or other attributes. Other functions of traditional garments include individual expression or social interaction, including privacy. Thus, many examples of adaptive garments respond to the social context in which they are worn, or to interpersonal interactions.

Originally envisioned in science fiction, one category of size-adaptive garments is that of self-lacing shoes. Companies including Puma and Nike have commercialized footwear with actuated, self-constricting laces in recent years [49], [50]. Many other self-fitting garments have been proposed, such as the sleeves developed by Granberry et al. that are actuated by NiTi-based shape memory alloy (SMAs) materials (Figure 1G) [23].

Aesthetics, art, and personal expression have also informed many developments in soft, wearable robotics for fashion and art. Many design researchers have also investigated the opportunities that such technologies, including sensors and actuators, can provide for interaction with a wearer's environment or others within it. Drawing inspiration from human emotion and social behaviors, Albaugh created a cable-driven collar that can hide the wearer's face when desired [64]. Farahi designed expressive, gaze-actuated garments actuated via SMAs (Figure 1H) [24]. Gao designed animated dresses that change configuration in the presence of unfamiliar people [65]. Gao also realized interactive fashion articles integrating piezoelectric materials, such as polyvinylidene fluoride (PVDF) sheets, that can react to the chromatic spectrum of their immediate surroundings (Figure 1I) [25], [66]. She also designed a pneumatic dress utilizing origami structures whose pattern changes when actuated via air pressure [67]. Extending this idea, Perovich et al. later realized a dress that unfolds when pressurized [68]. Recently, similar ideas have also manifested in prominent fashion circles. At the 2019 Paris Haute Couture fashion week, van Herpen introduced garments that, while not entirely soft, use integrated motors in order to animate a garment with rotating structures [69].

As the aforementioned examples demonstrate, emerging applications for wearable, soft robotics are diverse, including medical devices, haptic interfaces, performance augmentation systems, supernumerary limbs, and adaptive garments, among other categories. These new design methods, systems, and technologies evoke novel questions concerning how such systems can be designed to achieve their intended functionalities, while also meeting other requirements such as ergonomics, comfort, and safety. We review design considerations for soft, wearable robotics, with further illustrative examples, in the next section.

III. Soft, Wearable Robotics: Design and Engineering

Soft, wearable robotic systems are being investigated for application in diverse areas. While many of these applications are relatively established, methods for the design of soft, wearable robotics are still developing. Several properties of these systems evoke important design considerations arising from their properties and context of use. Several important design considerations relate to human wearability, including safety, stability, comfort, and wearability. Others arise from the essential softness of these systems, which involve continuum mechanical media and mechanisms and soft materials that are less established in robotics. Such considerations often weigh importantly in the selection of materials and technologies for soft, wearable robotics, in how these elements are integrated, in how they are designed for wearability, and in the design of methods and algorithms for control and interaction.

A. Tissue Biomechanics and Haptics

Another distinguishing aspect of soft, wearable robotic systems concerns how they interface with the skin, either by design, as in wearable haptic systems, or through the close connection of all wearable robotic devices with the body. Human skin is not only a prominent interface with the environment but is also the sensory organ of touch (the largest such organ in our body). Skin is a marvel of biological engineering, sufficiently sensitive to detect the tiny footsteps of a fly, while also strong enough that it can sustain extreme loads like those produced when lifting very heavy loads. There are two main categories of human skin. Glabrous skin covers the palmar surfaces of the hands and the soles of the feet; It is thicker and reinforced by networks of collagen fibers that endow it with shear strength and hyperelasticity, which are required to permit the manipulation of large

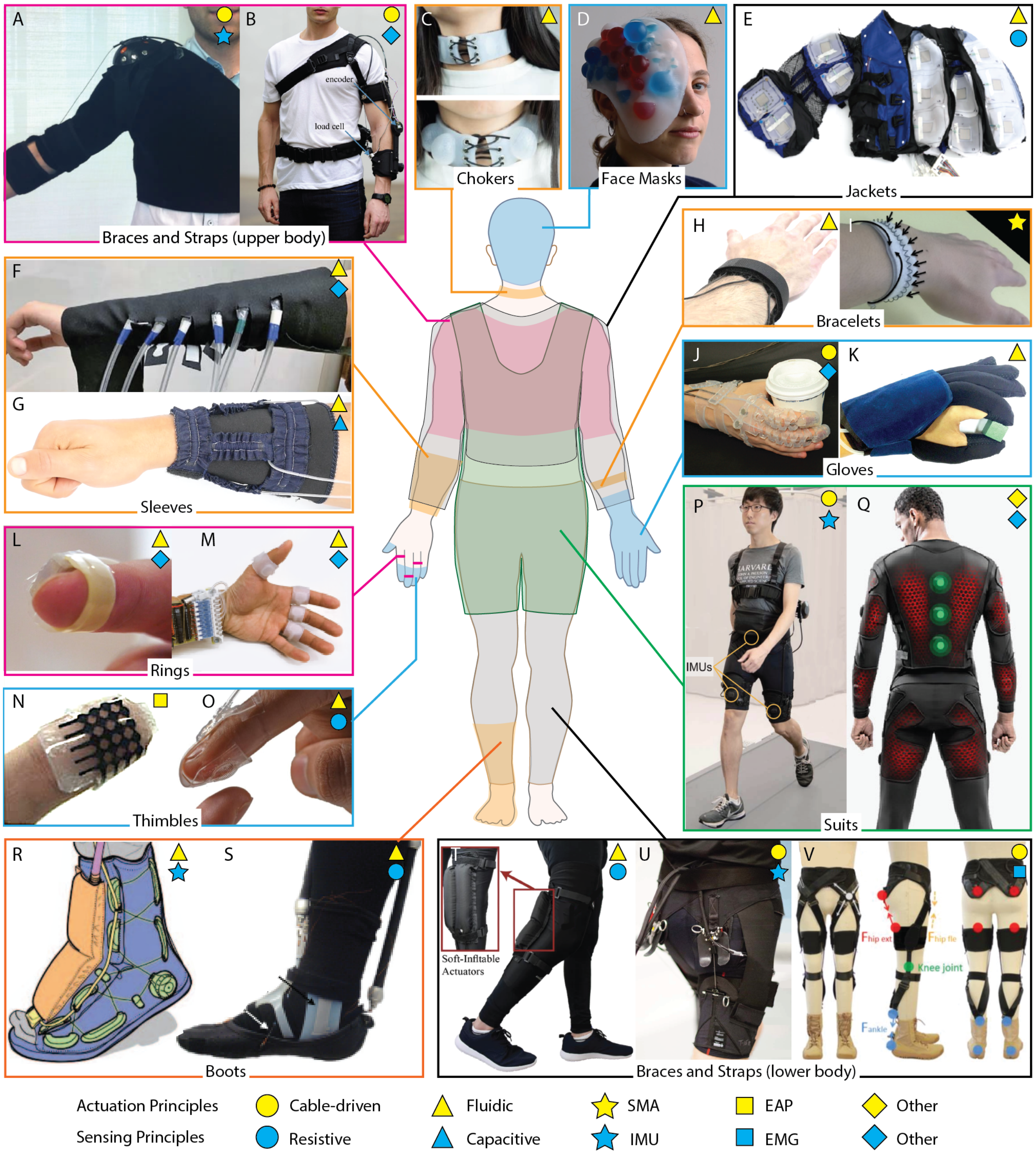

Fig. 2. Examples of soft wearable robotics and haptic devices in various wearable form factors. Yellow and blue symbols represent different actuation and sensing principles respectively. A-B. Devices consist of braces and straps on the upper body [18], [51]. C. Biometric chokers [52]. D. Responsive face prosthesis [53]. E. Haptic jackets [54]. F-G. Sleeves [48], [55]. H-I. Bracelets [56], [57]. J-K. Gloves [16], [58]. L-M. Rings on different segments of fingers [17], [36]. N-O. Thimbles [59], [60]. P-Q. Suits [10], [61]. R-S. Boots [19], [62]. T-V. Braces and straps for lower body [9], [20], [63].

loads. Hairy skin covers most of the body and possesses a thinner outer layer. Hairy skin is nearly two orders of magnitude more compliant than glabrous skin, readily displacing by a centimeter or more when subjected to loads of a few Newtons. The softness of these tissues can of course make them prone to damage or discomfort when encumbered by substantial loads. Thus, an important functional and ergonomic challenge is to design methods for stably and ergonomically anchoring wearable systems on the body, especially when substantial loads are involved.

Skin also possesses sensory capabilities that arise from dense innervation by thousands of tactile receptors – sensory nerve endings that can number thousands per square centimeter of skin. Together, they capture mechanical and thermal information from the ambient environment, transmitting this sensory information in volleys of spikes that are processed in the brain. While

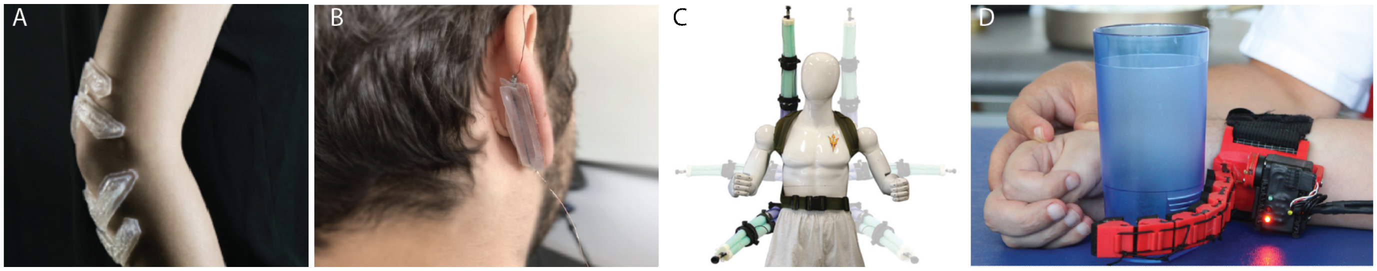

Fig. 3. Body interfaces and mounting methods that can be used in soft, wearable robotic technologies. A. Protective pads for the elbow using stiffness-tunable hydrogels adhered to the skin [70]. B. Skin-adhered tactile stickers actuated by shape memory alloys facilitate wearability at challenging body locations, such as the ear [71]. C. Mounting configurations for a supernumerary arm [30]. D. A supernumerary finger mounted on user's wrist [12].

a full account of tactile sensation would exceed the scope of this review, it is worth noting that there are several distinct sub-types of tactile sensory receptors exist in numbers that vary with body region [35], [72]. Each type responds to distinct aspects of stimuli in the tactile range. The neural signals they produce underlie the processing of touch contact with the body, the detection of painful or noxious stimuli, and the perception of object properties such as texture, shape, or hardness [35]. They also enable the remarkable feats of dexterity of the human hand. Tactile sensitivity and spatial acuity vary with body location in a matter that depends on the manner of stimulation, such as via pressure [73], sliding contact [74], or vibration [75]. Fingertips are among the most sensitive regions of the body. Thus, it can be advantageous to integrate higher actuator densities at such locations (Figure 2N) [59], [60], [72]. Skin plays a further role in homeostasis, by actively regulating body heat through capillary effects and perspiration. Thus, whether through intention or accident, soft wearable technologies often greatly affect mechanical, thermal, and sensory inputs to the body in manners that should weigh into their design.

B. Design for Wearability

While biomechanical and sensorimotor considerations can inform the design of soft, wearable robotic systems, the roles they play depend upon the application involved, including the form factor of the wearable system. Two key design considerations are wearability and ergonomics.

Placement and form language can both guide the selection of form factors for wearability. Many form factors have been investigated in prior research. Among small form factors are devices worn on the upper limbs, such as thimbles (Figure 2N,O) [59], [60], rings (Figure 2L,M) [17], [36], and bracelets (Figure 2H,I) [56], [57]. Larger form factors for the upper body include sleeves (Figure 2F,G) [48], [55], gloves (Figure 2J,K) [16], [58], and jackets (Figure 2E) [54]. Those for the lower body include footwear (Figure 2R,S) [19], [62] and trousers [76]. Many different kinds of devices have been designed to affix to different body locations via straps (Figure 2A,B,T,U,V) [9], [18], [20], [51], [63]. Such approaches have commonly been used in supernumerary devices that provide supplemental artificial limbs. The locations for mounting are closely related to the functional purposes of those devices. For supernumerary arms, common mounting locations include the shoulders, waist, or back (Figure 3C) [30], while the wrist is a typical mounting location for supernumerary fingers (Figure 3D) [12]. Centuries of development in apparel engineering have informed the design of clothing that is fitted to the whole body's shape and topology; in soft robotics research, several examples of whole body suits have been proposed (Figure 2P,Q) [10], [61]. Other soft wearables have taken the form of accessories, including hats, scarves, and jewelry, chokers (Figure 2C [52]), and face masks (Figure 2D [53]).

Other body interfaces involve devices that adhere to the skin. This can allow lightweight systems to be worn without any need for anchoring. Kao et al. designed texture-tunable skin overlays that stiffen when heated using hydrophillic gels (Figure 3A) [70]. Hamdan et al. integrated SMAs into skin-worn actuated stickers that they refer to as "Springlets" that may be worn on challenging body locations such as the ear (Figure 3B) [71].

An overarching concern in the design of form factors is the size or surface area of the device. Suits cover larger body areas than sleeves, bracelets, and thimbles, while skin adhesion allows for minimal coverage. In terms of device constraints, the size of the actuators, the means of attachment or grounding to the body, and the body location are three key considerations that must be weighed during design and garment construction.

The form factor design also depends on functional and aesthetic considerations, including the required range of motion and force, biomechanical factors, weight, comfort, perception, safety, and appearance. Wearable robotic systems that exert forces on the body do so through internal forces that necessitate that the forces applied at one location be balanced by those produced elsewhere. The means of attachment and anchoring to the body must be designed to apply these forces according to application requirements. Stability is an important consideration, because if attachments shift in configuration, device functionality, comfort, or safety could be affected. Many wearable devices are designed with adjustable attachments, such as velcro or cinched straps, which allow the device to be adjusted to the user. Friction often plays an important role, since such attachments may provide normal forces that indirectly produce the shear forces needed for anchoring via friction with the skin (Figure 2S, 2T, 2U) [20],

[63], [77]. This approach is often referred to as passive grounding. In other systems, the actuated degrees-of-freedom in the device may provide tunable attachment forces. For example, the PneuSleeve device uses pneumatic compression actuators and closed loop force control to adjust and equalize grounding forces so that haptic shear forces may be applied to the skin of users, and so that different limb girths may be accommodated (Figure 2G) [55].

Many soft, wearable robotic systems are designed to span joints of the body. In these cases, the kinematic range of motion of the joint and limb must be accounted for in the design. For example, some wearable systems are designed to arrest or assist joint motion, as in the haptic VR glove device of Hinchet et al. [78], which uses an electrostatic clutch to arrest finger movements. When no forces are intended to be applied at the joint in question, such as when the device is off or the joint is spanned by non-actuated regions of the device, it is often important that the normal motion and flexibility of the joint is affected as little as possible, to allow for normal activities. This can be achieved using stretchable materials or other structures that can freely accommodate joint motion at such locations. Some systems, such as tendon-driven wearables, employ curvilinear inextensible elements or channels. Such elements may be aligned with the body's lines of non-extension, such as the lines lateral to the knee joints, along which the skin undergoes little stretching during body motion [79].

In summary, a variety of human factors and application-dependent considerations must inform the design of soft, wearable robotics. Such considerations also inform the engineering of active elements of such wearable systems, as well as their control, as we review in the following section.

C. Control Considerations for Wearability

As noted in the introduction, robotic systems are commonly considered to integrate the three key capabilities of sensing, actuation, and computation or control. Soft robotic systems typically involve continuum mechanical media, and compliant structures, in lieu of traditional mechanisms. Control methods for such continuum systems are less mature than those that have been developed for finite degree-of-freedom systems. In addition, the central role of the wearer in these systems often introduces challenges in human-in-the-loop control. Control paradigms that have been developed for continuum systems are diverse, and include classical methods for the control of low-dimensional systems, simplified techniques that leverage the intrinsic dynamics of the structures and materials involved, and emerging methods for high-dimensional control [80].

Wearable robotic systems are often designed to sense, and responsively act, in concert with their wearer, which is the setting of human-in-the-loop control. The highly adapted nature of many body movements often leads to domain-specific approaches to human-in-the-loop control, as for example in devices that assist walking mobility [63], [81], or aid individuals in grasping with a stroke-impaired hand [13]. This setting involves distinctive control demands, because the natural biomechanics of the human body must carefully factor into any design so that the movements of the wearer are assisted, rather than encumbered, and that the system operates safely. To this end, such systems are often designed to account for the biomechanics, kinematics, and sensorimotor system of their wearer in an application- and wearer-dependent fashion [82], [83]. Due to the complexity of these systems, and to differences between individuals, such factors are often integrated in a data-driven fashion, through the collection of motion or postural data from users [84], [85]. In assistive devices, a one-size-fits-all approach rarely lends itself to optimal performance due to individual differences in ability, anatomy, biomechanics, and physiology. For example, research in walking assistance reveals that when individual factors, including walking dynamics, are not accounted for, efficiency may be reduced or control may become unstable [86].

D. Mechanical Properties of Materials for Wearability

Wearing robotic devices for extended periods of time leads to unique design challenges such as user comfort, reliability, and safety [3], [4]. Indeed, soft robotic technologies are well suited for wearable applications because their softness can be matched to the properties of the materials and structures of the body [87]. The term *soft* can refer to a combination of the extensive mechanical compliance of the structure [80] and the intensive hardness, or physical softness, of the materials themselves [88]–[90]. In fact, these two aspects are uncorrelated, which provides designers with additional freedom to select materials that also achieve other goals, such as wear resistance. Soft, wearable devices offer advantages in comfort and safety and can accommodate variations in movement that can be challenging to integrate in rigid systems, such as robotic exoskeletons. For example, Sawiki et al. found a soft exosuit to provide more effective robotic walking assistance than a rigid exoskeleton [91]. This may be due to the complex, non-idealized kinematics of motion at body joints.

Soft materials may be used to provide high mechanical compliance (inverse stiffness), allowing them to conform with the body. The axial compliance C of a structure is equal to length L divided by the product of cross-section area A and the intensive elastic modulus E, i.e., $C = L/(AE)$. Similarly, the bending compliance κ of a structure is equal to the bending moment M divided by the product of the modulus of elasticity E and the second moment of area, I, i.e. $\kappa = M/(IE)$. This illustrates how, for example, in order to maximize compliance, a material of given elastic modulus E may be designed to span a large distance L on the body and to have a small cross section area A. In particular, the elastic modulus need not necessarily be small to achieve compliance. Compliance may be achieved by high modulus materials with small cross section, such as thin films, via the patterning of high-modulus materials, or via other composite material designs. For example, garments are often constructed from filaments, such as textile fibers, with large modulus E. The compliance of the textile may be greatly altered

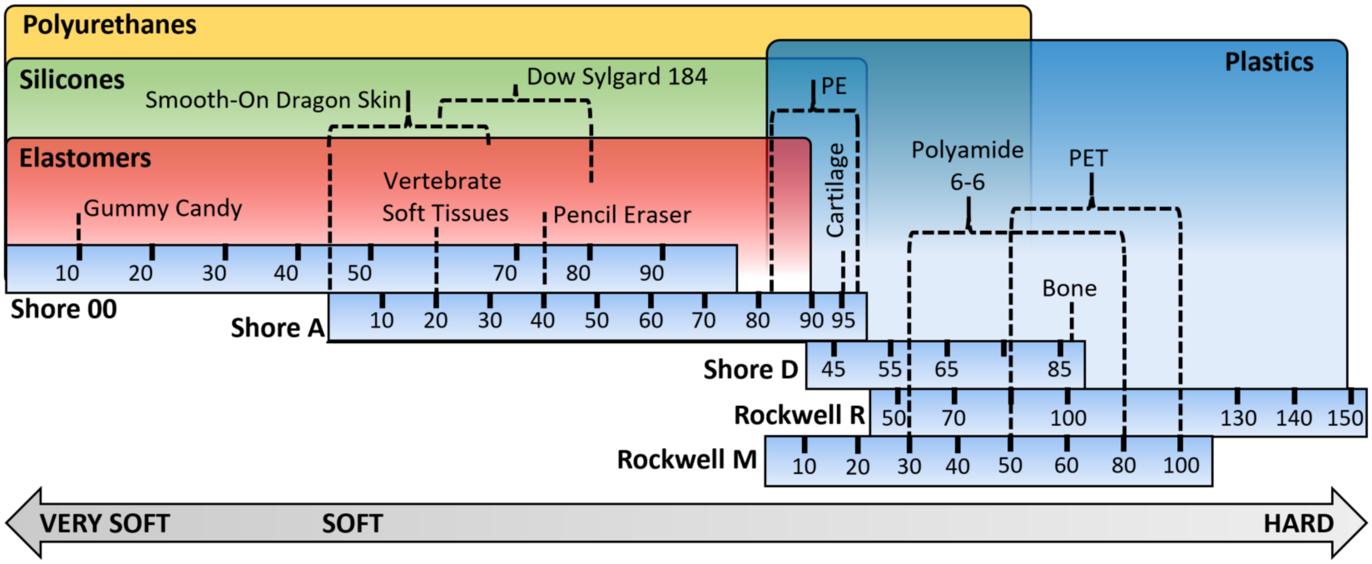

Fig. 4. A comparison of hardness, or softness, of materials suitable for use in soft wearable robots that interface with human tissues. A class of wearable materials may include those used in the construction of textiles, such as: Silicone, polyamide (nylon), cotton, silk, wool, rayon. Some materials have known hardness values and are shown in the figure. Other materials, particularly those natural materials used in commercial textiles have hardness values that are not apparent in academic literature. Typically designers will consult a manufacture and choose from the subjective experience. Other online sources such as [94], [95] compile material data for such purposes, however because polymer material properties vary significantly with temperature, humidity, and other testing conditions, the authors recommend performing individual testing for applications that require rigorous analysis. In addition, some fiber hardness data, especially that measured via nanoindentation, is reported in MPa, which is not directly comparable to traditional hardness scales. For example, the hardness of PDMS Dow Sylgard 184 can range from 20 to 50 Shore A depending on the catalyst used [96], [97] and is reported in [98] as having a hardness of 2.06 MPa. The hardness of cellulose [99], [100] is reported to range from 2.7 MPa to 240 MPa depending on temperature and humidity. The hardness of vertebrate tissues such as bone (234 to 760 MPa [101]), cartilage (2.6 MPa to 179 MPa [102], [103]), and other soft tissues [103] vary significantly depending on the test conditions and sample quality. These values have been incorporated into the figure to illustrate their general locations on the scale for comparison.

by the manner in which the fibers are arranged – how they are piled into yarns, threads, ropes, woven, or knitted. A further factor greatly affecting the mechanics of textiles is the interaction between fibers [92]. Thus, in contrast to bulk materials, the effective elasticity of textiles is often viewed as an extensive property [93]. Table I illustrates representative elastic moduli of materials that are often involved in soft, wearable robotics with bulk PDMS listed for reference.

Due to the dependence of textile mechanics on fiber arrangement, many different materials can be used to create conforming textiles, including metal fibers [93]. However, such hard materials would produce substantial abrasion of soft tissues or materials [88]. To avoid this, materials are often selected with lower hardnesses. For example, for comfort, and to avoid abrading the skin, materials should be selected with hardness less than about 20 on the Shore A scale, or 60 on the Shore 00 scale (Figure 4).

E. Soft material types in wearable robotics

The use of soft materials in the design of wearable and soft robotics is motivated by human factors considerations like those described above, and by new functionalities that emerging soft materials can provide that transcend those of conventional materials. Some advantages of many soft materials include their ease of handling, processing, and fabrication, and amenability to very large or very small scale or dimension processing [72], [80], [109]–[111]. In this section, we provide an overview of the categories of soft materials that are most frequently used in soft, wearable robotics. The discussion of functional properties of these materials for sensing and actuation are treated in later sections.

TABLE I
ELASTIC MODULI OF SELECTED MATERIALS IN WEARABLE ROBOTICS IN GPA.

Material	Reference	Max	Min	Average
Vertebrate Cartilage	[80]	—	—	0.1
Vertebrate Ligament	[80]	—	—	0.001
Wool	[104]	4.5	3.1	3.8
Cellulose (Cotton, Rayon, Viscose)	[104], [105]	57	5	31
Polyester (PET, PE)	[104], [105]	95	13.5	54.3
Polyacrylonitrile (Acrylic)	[106], [107]	3.5	2.5	3.2
Aliphatic Polyamide (Nylon)	[106], [107]	4	2	2.7
Aramid (Kevlar, Nomex)	[105]	123	71	97
PDMS	[97], [108]	0.0037	0.00057	—

a) Polymers: are organic materials that are widely used in soft and wearable robotics, for most of the reasons mentioned above. Many polymers are synthetic materials whose properties can be chemically tuned. Silicone-based polymers are often used, and they exist in great variety. They are often soft, stretchable, non-toxic, stable, and inexpensive to manufacture and purchase. This has made them a popular choice in soft robotics research. In contrast to other polymers that are based on a carbon-carbon backbone, silicone polymers are based on repeating silicon-oxygen (siloxane) groups, with two methyl groups bonded to each silicon (schematically, -R2Si-O-SiR2-). Silicone polymers are readily available in liquid forms that can be cured or cross-linked in different ways. Curable silicones are typically polysiloxanes with additional fillers, cross-linkers, and additives that allow them to match desired characteristics. The curing or cross-linking process of these elastomers is achieved through covalent bond formation between polymer chains. This process is catalyzed through the addition of cross-linker. Several different cross-linking methods are used, including condensation curing, platinum catalyzed hydrosilylation, or peroxide induced curing [112]. Thus, there are many options available for synthesizing silicone polymers with different properties.

A silicone based elastomer that has been often used to create soft or wearable devices is poly(dimethylsiloxane) (PDMS). It is moderately compliant (Table I), [113], inexpensive, and amenable to facile processing using established tools and methods. It can be used to create structures or substrates for functional devices that are stretchable, transparent, permeable to air, nontoxic, and biocompatible. As with other silicone polymers, the material properties of PDMS are tunable. For example, a cured pristine PDMS surface is hydrophobic, but can be modified to be hydrophilic through oxygen plasma activation or ultra-violet radiation. As with many silicone polymers, commercially available PDMS reagents, such as Sylgard 184 (Dow Corning), consist of two-part liquid compounds. The two parts are combined in ratios that may be adjusted in order to vary the elasticity that is achieved after curing. Typical values for the Young's modulus of PDMS are reported in Table I.

Other commercially available silicone elastomers include platinum-catalyzed silicones, such as the commercial products Ecoflex and Dragon Skin (Smooth-On, Inc), which are low-viscosity, two-component reagents that have been widely used in soft robotics. These silicones are available with a large range of elasticity, pot life, and cure time. The tensile strain of Ecoflex ranges from 800% to above 1000%. [114] The Young's modulus varies in the range of 0.05 MPa to 1 MPa [115]. Commercial Ecoflex is a platinum catalyzed silicone elastomer with low viscosity and is also available as a compound (with two components, which are typically mixed in a 1A:1B ratio by their volume) that can be cured either at near room temperatures, or at elevated temperatures to facilitate rapid cross-linking [114], [116]. Among other polymers polyurethane (PU), nitrile butadiene rubber, acrylic elastomer, poly(isobutylene-co-isoprene) (IIR), polyolefin (POE), poly(styrene-block-butadiene-block-styrene) (SBS) are also being used as soft materials for applications in soft and wearable robots [117].

Hydrogel materials are networks of polymer chains that have attracted great attention among researchers. They have been used to realize functional devices for soft robotics and wearable applications. Hydrogel polymers occur in natural form in the bodies of animals. As a result, many hydrogel materials are biocompatible [118]. Hydrogels typically contain between 10% and 95% water. The quantity of water can be altered through heat activation in order to tune their elasticity. This has, for example, been used to create stiffness-tunable wearable devices, such as protective pads worn on the skin (Figure 3A) [70]. The mechanical properties of hydrogels vary greatly. While they can be made elastic, in terms of strength, many hydrogels are brittle. Thus, while there are a number of hydrogels that can achieve a maximum strain of 200% to 2000%, their tensile fracture strength is typically in the range from 100 kPa to 10000 kPa. For example, (PBMA-b-PMAAc-b-PBMA)/PAAm (PBMA: Poly(butyl methacrylate), PMAAc: Polymethacrylic acid, PAAm: Polyacrylamide) contains 42% water and has a fracture strain of 10000 kPa, with a maximum tensile strain of 600% [119].

Many other polymer materials have been used in soft robotics. They include thermoplastic polyurethane (TPU) [20], polyurethane (PU) [120], nitrile butadiene rubber [121], and acrylic elastomers. Several recent review articles survey these materials in greater detail than can be included here [109], [122]–[124].

b) Liquid alloys: are metals that are in liquid phase at room temperatures. They have attracted great attention in recent years for applications in soft electronics and robotics. Several metal alloys remain liquid at room temperature. Mercury is the most familiar such alloy, but is toxic. Today, Gallium (Ga) alloys are more popular. Gallium has a melting temperature of 30°C. This temperature can be decreased via addition of Indium (In) or Tin (Sn). For example, eutectic gallium-indium (EGaIn) and eutectic gallium-indium-tin (Galinstan) have melting temperatures of 15.7°C and -19°C, respectively. Both of these alloys possess high electrical and thermal conductivity [125]. Such liquid metals must often be encapsulated within soft substrates for applications. This is often achieved via microfluidic channels. Such liquid alloys do not store mechanical energy under tensile strain. Encapsulated liquid alloys conform to Poisson's law, which states that the total volume of incompressible liquid remains constant. Thus, the elongation of encapsulated liquid alloys yields a decrease in cross-section area [111].

c) Textiles, fabrics,: and their products are a familiar part of many garments and products that we interact with in close proximity to our body. Wearable garments made of textiles can readily be made flexible, deformable, deployable, durable, soft, and stretchable. These attributes make them ideal for wearable devices. Most textiles are made from fibers or yarns that have woven, knit, or other composite structures.

The stretchability of textile and fabrics typically falls in one of three categories: non-stretchable, two-way stretchable, or four-way stretchable. Non-stretchable fabrics are often conformable but are inextensible in each planar direction. In contrast, two-way or four-way stretchable fabrics are stretchable in one or both in-plane orthogonal directions. The anisotropic arrangement and mechanical properties of many fabrics are useful in many applications. Such anisotropies arise through variations in stitching [126] or fiber reinforcement [127].

The physical properties of fabrics can be modified, often dramatically so, through post-processing, such as coating, or through their composition with similar or dissimilar materials. Such modifications often also affect other properties of the fabrics, such as breathability, that may affect their suitability for some wearable applications.

d) Smart materials and composites: possess properties that provide additional functionality, such as electronic actuation or sensing [128], [129]. They include functional materials or composites overlapping with the categories described in the foregoing. Piezoelectric materials provide functionalities through conversion between electrical and mechanical energy [25], [130]. Many polymers or polymer structures have been designed to provide similar functionalities [59], [131]. Such materials have been used to realize sensors and actuators, as further discussed below. Another smart material category includes phase change materials. Shape memory alloys are one important category. Application or removal of heat, such as via electric current, causes such materials to transition between an martensite phase and the austenite phase, yielding bulk elongation or contraction that can perform mechanical work [71], [132].

In many cases, smart materials or composites can be chemically or structurally engineered to achieve desired performance characteristics. For example, PDMS is electrically insulating ($\rho = 4 \times 10^{13} \Omega - m$) with a very low dielectric constant (ϵ = 2.3 - 2.8). Both properties can be tuned by combining the PDMS bulk matrix material with suspended additives (e.g., conductive carbon powders or silver nanowires, AgNWs) [133].

This example illustrates how components of composite smart materials contribute different attributes, for example, by acting as a bulk substrate or a functional additive. The mechanical softness of such thin films or membranes is largely dominated by their carrier substrate [134].

Many combinations are possible, and many methods have been described for tuning such materials. Thus, a large variety of smart materials have been created and used in wearable devices. To describe one integrated example, Gerratt et al. realized a wearable tactile sensing glove for prosthetics [135]. It integrated resistive and capacitive sensors for capturing finger motion and contact pressure, respectively (Figure 5A). The materials include elastomers, silicone foam, liquid metals, and thin-metal gold films (Figure 5A ii, iii). The metal films embedded in PDMS substrate, with liquid metal wire interconnects, acted as resistive strain sensors (Figure 5A ii). Capacitive pressure sensors were formed from layers of silicone foam dielectric material encapsulated between conductive film layers (Figure 5A iii), which were then integrated in the textile glove (Figure 5A iv). The similar compliance of all of the materials ensured that, when combined, the wearable device retained significant compliance. We discuss functional applications of smart materials in a later section.

In summary, there are many compliant materials or composites that may be used in wearable robotics. Table-III lists an array of representative examples that have been used in such applications.

F. Fabrication

The diverse materials used in soft, wearable robotics require a variety of manufacturing methods that are often different from those employed for conventional mechanical or electronic systems. A key distinction can be drawn between small-scale fabrication for research or prototyping, which may employ manual or improvised processes that do not translate to mass production, and fabrication methods that utilize, are compatible with, or may be readily translated to, large-scale manufacturing.

Key features that must be considered include the materials to be used and design requirements, including dimensions and resolution. For example, if a device requires patterning with resolution on the microscale over a large area, a microprinting method might be preferred to a 3D lithography method. On the other hand, the materials involved often dictate the fabrication methods that can be used. For example, a microprinting method is not compatible with all materials. Here, we review some of the most used fabrication methods. A comprehensive account of the continuously growing array of fabrication methods that could be used for such devices is beyond the scope of this article.

a) Soft lithography and molding: Soft lithography processes are extremely useful when a quasi-planar compliant substrate must be patterned over a large area with a resolution no finer than the microscale. Such processes have been widely used in manufacturing soft robotics and wearable devices [120], [130], [139]. Soft lithography processes involve creating a “master” form, on which the negative patterns are realized. An elastomer is cast and cured on this master to replicate the patterns. After curing, the elastomer replica is removed from the master, exhibiting the designed patterns. Such a master can be produced using conventional microfabrication methods, such as SU-8 photolithography, micromachining, or 3D printing.

Molding is a similar approach where liquid elastomers are patterned or shaped using a rigid frame or mold. A large variety of 3D shapes can be produced using molding techniques. Molding may or may not require thermal treatment of the liquid resins that catalyze to produce the polymer elastomer. There are different molding techniques available depending on the requirements of the device and processed materials. Examples include compression molding, replica molding, micro-transfer molding, solvent-assisted molding, and injection molding [16], [17], [40], [140]–[143]. Numerous publications, online training videos, instructions, curricular materials, and classes provide instruction on such molding techniques, making them easy for the un-initiated to learn to use.

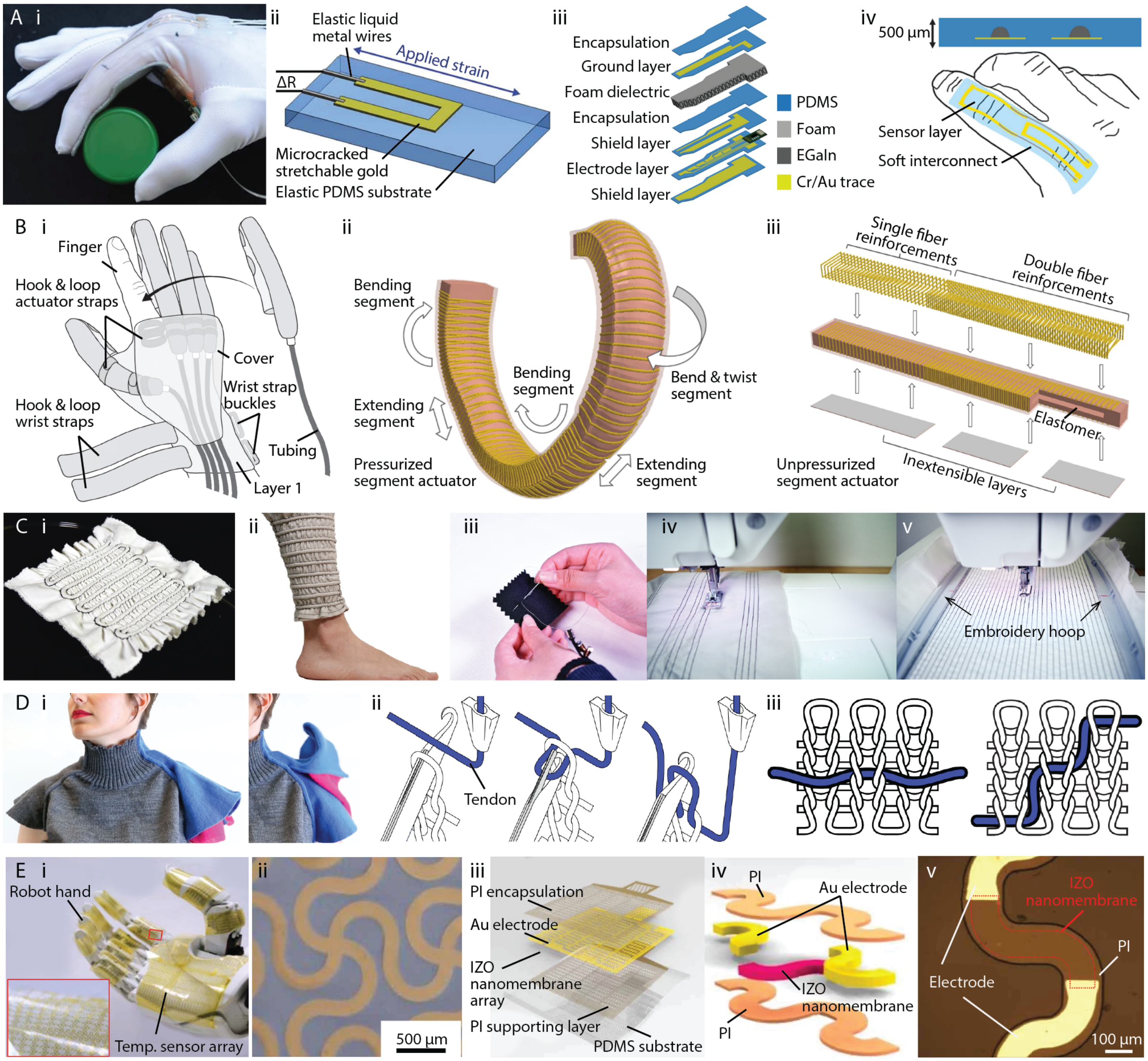

Fig. 5. A few examples of functional soft and wearable robotic devices realized using various materials and relevant fabrication methods. A. Wearable prosthetic tactile gloves with integrated resistive and capacitive sensors for monitoring finger articulation and pressure [135]. B. Fiber reinforced soft robotic glove with pressurized actuator manufactured using 3D printing and soft lithography techniques for rehabilitation and training [136]. C. Fluid driven soft wearable actuators realized using fabrics and stitching [126]. D. Machine knitted wearables with tendon-based actuation [137]. E. A prosthetic skin with temperature sensor array on a robot hand was made using micro-/nano-fabrication techniques including photolithography, wet etching, reactive ion etching and deposition [138].

b) 3D printing: 3D printing technologies have greatly developed in recent years, and have been extensively used in soft and wearable devices including robotics [12], [16], [144]–[150]. Such technologies are often used to print rigid 3D molds for soft lithography processes. The feasible resolution is often limited by the 3D printing process. In addition to molding techniques, emerging methods of additive manufacturing allow direct printing of soft materials [151]. Currently, several commercial 3D printers can print soft materials such as hydrogels or rubbers [152]. Additionally, research has produced 3D printers that can print silicone polymers and liquid alloys in order to manufacture largely functional devices in a unitary process. Such 3D printers use computer-aided 3D design. Thus, the design of an object can comprise any shape within support or other printing process limitations [153]. Limitations include minimum feature sizes, speed, scaling, and surface roughnesses.

A widely used method of 3D printing is based on additive deposition. It involves the expulsion of liquid or glassy-phase materials through a nozzle to construct 3D structures layer by layer. Another popular category of methods, photopolymer based printing, cures solid structures from liquid polymer baths via optical catalysis/curing. The list of 3D printing technologies is growing, and includes: direct ink writing (DIW), stereo lithography (SLA), selective laser sintering (SLS), photo-curable ink-jet printing, fused deposition modeling (FDM), and shape deposition modeling (SDM). For example, Zhao et al. realized a fiber-reinforced soft prosthetic hand, which was composed of pneumatically actuated fingers and a 3D printed rigid palm with integrated optical waveguides [120]. The waveguides were composed of elastomers and were fabricated using four-step soft lithography. A 3D printed mold replicated the waveguides with high precision. In another example, Nguyen et al. developed fluid-driven soft robotic limbs that were fabricated from silicone elastomer [30]. It consists of three-chambered actuators which were made of bundles of ring-reinforced actuators (RRA). Different materials and fabrication methods were used to realize the RRA parts, primarily including a 3D printed mold and soft lithography techniques.

3D printing and molding techniques make it possible to realize complex 3D structures with a variety of soft materials and also allow the integration of different materials to generate unique functionality and material properties. For example, Polygerinos et al. realized a soft robotic glove for rehabilitation and training (Figure 5B i). They used fiber reinforced rubber to create a pressurized bending actuator (Figure 5B ii) [136], which was composed of an molded elastomer main body, and strain limiting layers (Figure 5B iii).

c) Apparel engineering: Apparel engineering methods involve the engineering of wearable structures from fabric or other materials. Textile construction transforms fibers into textiles via knitting or weaving. Textiles are cut and recombined to form garments that are specified as patterns. Non-textile sheets, such as polymer layers, are sometimes also employed. Textiles are combined, joined, or layered via sewing, heat sealing, ultrasonic fusing, or chemical adhesives. Sewing methods include hand sewing, machine sewing, and machine embroidery; each requires different levels of machine automation or manual work [126]. Sewing introduces holes, since fibers are threaded through the textile via a needle. In some applications, such as fluidic actuator design, even small holes present problems. In such cases, heat sealing or ultrasonic welding may be used, or holes may be sealed via post processing. Heat sealing involves the application of heat to fuse layers of materials together in order to form closed, airtight seams. This requires special materials, such as TPUs (described above). Such methods are challenging to apply in thick or multi-layered structures. Ultrasonic fusion or welding is a related method that is used to form sealed fabric connections or closures in industry. This process is compatible with a wider range of materials than can be used with heat sealing.

d) Micro- and nano-fabrication: Micro- and nano-fabrication are terms that refer to an array of methods that are widely used in semiconductor manufacturing, MEMS, and related areas of industry and research. These methods are highly mature, and make it possible to produce devices with the fine resolution and accuracy needed in miniature devices. They can facilitate high resolution patterning and accurate geometric registration. Microfabrication methods involve a number of variable processing steps including patterning, thin film deposition, chemical processing, plasma processing, micro-assembly, among others. The use of such methods use has conventionally been limited to high modulus materials. Recent advances, including results from our lab [154], show how these methods can be used in the fabrication of soft devices. This can be achieved through careful selection of materials for compatibility with the required processing steps, including high-temperature or chemical processing, and through the use of rigid carrier substrates that constrain and control the geometry and registration of the soft materials during fabrication.

Two approaches for realizing soft electronic devices via microfabrication techniques include direct fabrication of electronic layers on soft polymers [155] or the fabrication of such layers on rigid carriers for later transfer to soft substrates [138], [156]. For example, Sim et al. fabricated electronic sensing interfaces for prosthetics using the latter approach. They produced a thin ($\sim 2\mu m$) polyimide (PI) layer on top of a rigid glass carrier substrate that was later etched away to form a freestanding structure [138]. The device was then transferred and bonded to a thin layer of PDMS to form a prosthetic skin (Figure 5D i, ii). Electrodes in the device were formed from gold (Au) via electron beam evaporation, photolithography, and wet etching. Spin coating, annealing, photolithography, and wet etching were used to define the pattern geometry of the IZO nanomembrane array (Figure 5D iii, v) [138]. This example illustrates the many steps, selected from a standardized repertoire, that are combined to produce device via micro-fabrication or nano-fabrication. When applied to soft materials, these methods may meet the needs of future soft, wearable robotic and haptic systems.

In addition to the techniques described above, several other methods have been used to realize soft, wearable robotics. Examples include machining [18], [22], [121], [157], laser processing [30], [78], [158], [159], and transfer printing [130], [139], [160]. Often, several fabrication methods are combined. In summary, fabrication techniques for soft wearable robotics diverge from those used in traditional manufacturing processes for rigid materials, but recent advances illustrate the advantages of adapting such traditional methods for use with soft materials. The materials involved constrain the methods that can be used to create functioning systems and devices.

G. Actuation

Among the most intensively investigated technologies for soft robotics are actuators, which convert supplied energy into mechanical work or other responses (for example, electrical or thermal responses). In robotics and haptics, actuators are often tasked with converting orders of magnitude more energy to produce substantial displacements, forces, thermal or other changes.

(Sensors, which are discussed below, are also energy transducers, but the converted energies are often very small.) Today, few soft robotic actuators can match the performance of conventional devices. This disparity has motivated ample research activity in this area. Actuators that produce forces or displacements also produces mechanical stresses and heat that must be carefully considered in relation to ergonomic requirements, safety, and operating performance. Soft materials are intrinsically insulating, which can result in more severe thermal management challenges than are encountered in many conventional mechatronic systems, further amplifying the challenge of designing actuators for many soft robotic systems.

A large variety of actuator types have been used in wearable systems. They include rigid devices such as electromagnetic motors and piezoelectric actuators. Integrating rigid actuators within soft structures involves several drawbacks that can impair system functionality, including reduced compliance and large stress gradients. Here, we focus attention on soft and flexible actuation methods, which are often well suited for use in soft, wearable robotics.

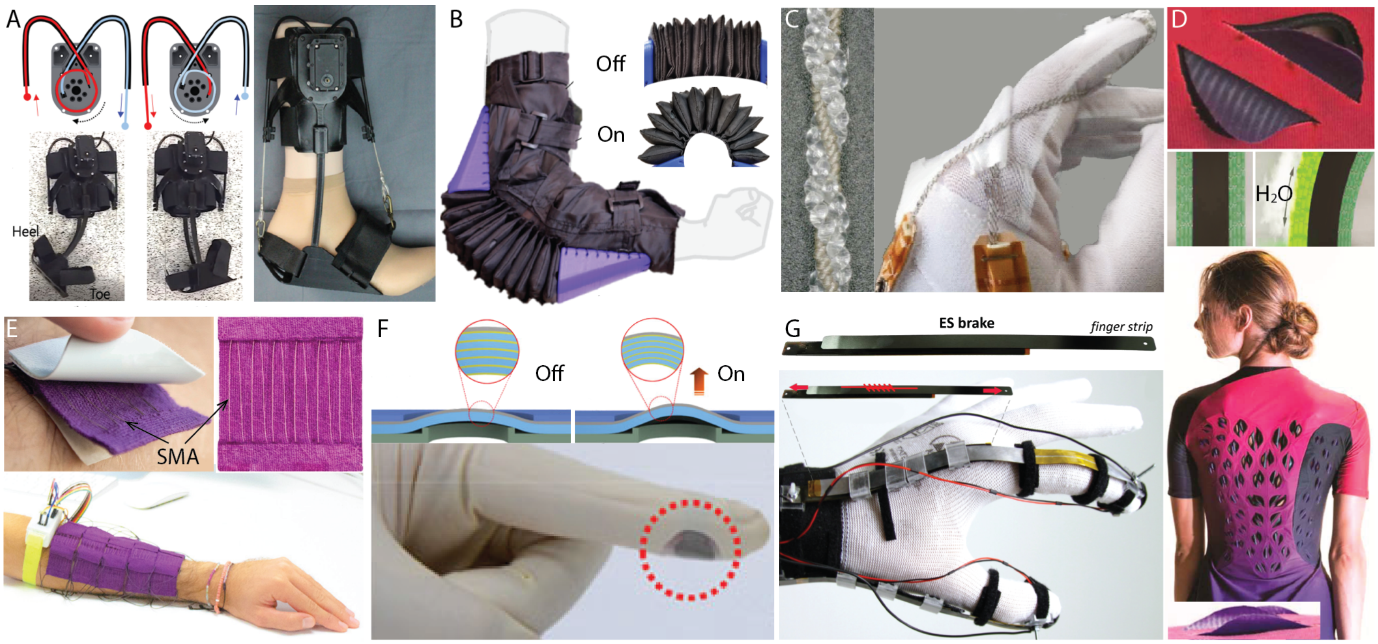

Fig. 6. Examples of soft and flexible actuation methods for wearable applications. A. Bidirectional cable-driven actuation for an ankle-foot-orthosis [161]. B. Fluidic actuation for bicep lifting assistance [162]. C. Twisted and super-coiled fibre actuators assist with finger bending [163]. D. Biohybrid actuation with microbial cells that adjusts the humidity of clothing microenvironment [164]. E. Shape memory alloy actuator patches that create shear forces on skin for haptic feedback [165]. F. Electro-active polymer actuation that generates vibrotactile feedback [133]. G. Electrostatic actuation for joint arresting haptic feedback [78].

a) Cable-driven actuation: Cable-driven actuation utilizes cables – filaments, wires, or tendons – to supply forces or displacements, often via remotely positioned motors. Cables can often be selected to be thin and flexible and are thus suitable for integration in many soft, wearable devices. The forces and displacements, or mechanical work, that can be produced using such actuation schemes depend on the motor characteristics and routing details, but are often large when compared with other soft actuator technologies. Because of their capabilities, and their use of standard electromagnetic motors, such actuation methods have been used in many wearable robotic systems, including devices for rehabilitation, haptics, or other applications. In these applications, they may supply mechanical work needed for haptic force feedback, force assistance, tactile cues such as compression or skin stretch, or for driving a supernumary limb. To list just a few of many examples: Elor et al. designed a cable-driven soft exosuit on the upper arm for upper-extremity rehabilitation in VR [150]. Kwon et al. developed an ankle-foot-orthosis with a bi-directional tendon-driven actuator for assisting both dorsiflexion and plantarflexion (Figure 6A) [161]. Pezent et al. designed a wrist-wearable device that supplies haptic squeezing cues via a cable-driven mechanism [166]. In addition to their capabilities, cable-driven actuation methods possess important drawbacks. When such cables are used to route large forces through conduits, control and actuation problems often arise due to friction. In wearable applications, thin cables may produce high stress concentrations on the skin, yielding discomfort or even pain. To avoid these drawbacks (while possibly amplifying frictional problems), some researchers have instead used fabric bands for the delivery of haptic cues [167], or have encapsulated cables within polymers [16].

b) Fluidic actuators: Fluidic actuators use encapsulated gaseous or liquid fluid media to supply mechanical forces or displacements. Such actuators have been among the most widely used in soft robotics. One reason for this is that fluid volumes or channels can often be integrated within soft polymer materials that can be efficiently fabricated, yielding intrinsically compliant actuated structures.

Fluidic actuators can produce forces, displacements, or work densities that span a large range, depending on their design and operating range of fluid volumetric displacement or fluid pressure. Indeed, conventional fluidic actuators include high-force industrial hydraulics and miniature devices for displacing biological fluids. Forces that can be produced depend on the device geometry and configuration, but typically increase monotonically with operating pressures and with the characteristic cross-section area of the fluid channel.

Soft, fluidic actuators have used fluids in liquid or gaseous phases, respectively used in hydraulic or pneumatic actuators [168]. Common fluids include air, water, oils, or other hydraulic liquids. Hydraulic actuation can be advantageous due to its incompressibility, which can provide greater efficiency, smaller fluid volumes, or simplified control, since little energy is stored in fluid compression. For similar reasons, at low to moderate pressures (for example, 0.1 to 10 MPa) – such as are typically used in soft robotics applications – hydraulic actuators can mitigate failure-related hazards, such as bursting, that are often observed in pneumatic devices, because fluid pressures drop extremely rapidly when leaks occur. Pneumatic actuation is advantageous because of the convenient availability of compressed air sources, lower mass, and the absence of liquids that could affect other device components. Fluidic actuator bandwidth depends on the operating pressure and displacement range, the actuator design, and other design details such as channel length between the power source and actuator.

Fluidic actuators can be powered (driven) via fluid flow and pressure delivered in different ways [169]. Mechanical pumps, pistons, and compressors generate fluid energy from electricity or other sources. Other sources use stored potential energy, such as compressed air reservoirs. Industrial pneumatic and hydraulic sources are often bulky, and, in the latter case, may not operate in regimes that are useful for soft robotics. Many compact pneumatic sources are readily available today [170], [171], while fewer hydraulic micropumps exist that are appropriate for most soft robotics applications. Many common fluidic power sources, such as compressed air supplies, are not directly amenable to electric (digital or analog) control such as is normally required in integrated robotic or haptic systems. Instead, many fluidic systems use electrically controlled valves, regulators, or other devices to modulate fluid flow rates, flow directions, or pressures.

Conventional fluidic sources can increase system size or mass, or require them to be tethered to infrastructure. To avoid this, emerging research in soft robotics has been directed at identifying other methods for powering fluidic actuators. Diverse methods are described in recent literature, including the use of compressed fluid (liquid CO2) [19], explosive combustion [172], liquid propellant [173], and low boiling point liquids [174]–[176], the use of inductive heating to boil liquids, generating vapor, and photothermal techniques [177]. Stretchable pumps have also been demonstrated based on charge-injection electrohydrodynamics [178].

Many fluidically-actuated soft, wearable robotic devices have been developed. Examples include an elbow flexion assistive device based on pleated fabric pneumatic actuators (Figure 6B) [162], a haptic glove based on pneumatic pockets [179], or devices that use fluidic actuation for particle or layer jamming to constrain or support limb movements or actions for rehabilitation, assistance, or injury prevention [180], [181].

TABLE II
COMPARISON OF DIFFERENT ACTUATION METHODS FOR WEARABLE APPLICATIONS[1]

Actuation	Ref.	Compliance	Safety Hazards	Portability	Force	Stress	Displacement	Strain	Frequency
Pneumatic skin	[60]	Stretchable	Burst	Tethered	1 N	NA	NA	10%	0-100 Hz
Pneumatic sleeve	[55]	Stretchable	Burst	Tethered	4 N	200 kPa	16 mm	-33%	1-50 Hz
Hydraulic muscle	[126]	Stretchable	Burst	Tethered	13 N	500 kPa	122 mm	-50%	0.2-5 Hz
Cable-driven orthosis	[161]	Flexible	Concentrated force	Portable	70 N	NA	100 mm	NA	NA
SMA glove	[132]	Stretchable	Heat and electric current	Portable	10 N	260 kPa	50 mm	-40%	0.5 Hz
SMA stickers	[71]	Stretchable	Heat and electric current	Portable	3 N	600 kPa	20 mm	-44%	0.1-0.33 Hz
Coiled fibre glove	[163]	Stretchable	Heat and electric current	NA	2 N	69 MPa	2.3 mm	-23%	NA
DEA thimble	[59]	Flexible	High voltage (3.5 kV)	Tethered	14 mN	NA	450 um	NA	0-100 Hz
DEA tactile interface	[133]	Flexible	High voltage (4 kV)	Tethered	255 mN	NA	650 um	NA	0-500 Hz
Electrostatic brake	[78]	Flexible	High voltage (1 kV)	Tethered	20 N	NA	NA	NA	NA
Biohybrid suit	[164]	Flexible	Biohazards	Portable	NA	8 Mpa	NA	8%	NA

The data are collected from manuscripts, graphs, and supplementary materials of each reference with approximation. NA is used where no corresponding information is found. Positive values for strain indicate elongation, while negative values indicate contraction. [1]

c) Shape memory alloys: Shape memory alloy (SMA) actuators have been used in many robotic systems, including soft, wearable devices. SMA actuators are engineered alloys, such as NiTi, that undergo thermally-controlled phase changes between two different atomic ordered (crystalline) structures. These changes produce macroscopic actuation in the form of displacement, shape, or force. Because actuation is achieved without any need for motors, mechanical actuators, or fluidic sources, SMA actuation systems can be designed to be compact, quiet, and light weight.

The phase changes that produce SMA actuation are generated via active heating and, less often, through active cooling. Because these materials are conductors, electrical power, from infrastructure or batteries, provides a convenient method for dynamic heat delivery, although other heat sources are also used. These advantages also imply performance drawbacks that affect SMA actuation, and that also affect other thermally-dependent actuation methods (such as nylon filament actuators, for example). While SMA actuators can be rapidly driven to their contracted phase, the speed at which these transitions can be reversed is limited by heat transport out of the SMA structure, typically via convection, radiation (when surrounded by air) or conduction (if encapsulated in another liquid or solid medium). The rate at which cooling can be achieved depends on the temperature of the ambient medium, and the size and geometry of the SMA actuators. Because SMA structures must often be massive enough to produce sufficient force, in many cases, this reversal of contraction requires more than one second. Thus, it is challenging to employ SMA actuation in applications that require high mechanical power to be produced, such as in force assistance or force feedback applications. In addition, due to the thermal mode of actuation, care must be taken in using SMA actuators close to the skin.

A variety of different behaviors can be generated through the design and arrangement of structures integrating SMA and other materials. Jeong et al. embedded helical SMA coils within stretchable polymer tubing to augment wrist motions [132]. This system produced forces of 10 N and relative displacements of 40%. SMA have been also applied in sewed patterns on fabric patches to produce tactile feedback in social haptics (Figure 6E) [165]. Other researchers have coated SMA with shape memory polymer (SMP) to achieve variable stiffnesses upon direct joule heating of the embedded SMA wire [182]. Hamdan et al. designed skin-wearable tactile devices based on SMA coils for tactile feedback (Figure 3B) [71].

d) Electroactive polymers: Electroactive polymers actuators (EAPs) change size or shape in response to applied electric fields. EAP actuators are most commonly used in tactile devices that apply localized mechanical stimuli to the skin. These actuators produce low forces (on the order of mN) and low displacements (on the order of μm), but may be actuated at high frequencies (approaching 100 Hz). The term EAP has been applied to many different actuators and materials, including dielectric elastomer EAPs, which are electrostatically actuated, and ionic actuators, which involve ion transport in conductive polymers [183]. Piezoelectric polymer EAPs, which have been used in wearable applications, produce relative displacements when an electric field is applied. This occurs due to molecular dipole alignment. Ying Gao used a piezoelectric polymer material, polyvinylidene difluoride (PVDF), to realize responsive, organically-moving garments (Figure 1I) [25].

Dielectric elastomer actuators (DEAs) are a class of EAPs that can be designed to be rapidly actuated through electrostatically generated Coulomb forces between electrodes separated by elastic dielectric materials. Voltage requirements are often on the order of several kilovolts (kV) or more. This can create design challenges, since electrical discharge through air or other materials is possible at distances of a few millimeters. For the same reason, safety requirements, such as current limiting, insulator design, and suitable grounding strategies, are often required. Risks are higher if the electrically active regions of such devices could, through failure or misuse, produce current paths that traverse the torso, since even electrical currents less than one milliampere (mA) across the heart create risks of cardiac fibrillation. This can be avoided by confining the electrically active region of a device to a single limb, for example, and avoiding potential current paths to ground through other body regions.

DEA actuators can also be designed to be soft, thus have been used as soft replacements for vibration motors that are used in conventional devices. Koo et al. developed a soft tactile display on the fingertip using an array of EAP actuators [59] (Figure 2N), including 20 actuated elements 2 mm in diameter. Mun et al. integrated multilayer DEAs in a glove and sleeve for haptic feedback (Figure 6F) [133]. Boys et al. used hydrostatically-coupled DEA for providing haptic feedback with tunable forces and displacements [184].

e) Other actuation methods: Many other actuation methods have been investigated for use in soft robotics. They include electrostatic brakes, electrotactile (charge- or current-based) stimulation, humidification (including moisture absorbtion by bacteria), and super-coiled fibre actuators, among others. Several authors have designed electrostatic brakes or clutches for arresting motion. Such clutches can produce substantial forces, as in the wearable device of Hichet et al., which generated arresting forces of 20 N for haptic feedback using voltages of 1 kV, in tandem with piezo actuators capable of providing cutaneous vibrotactile feedback (Figure 6G) [78]. Thus, the forces that can be produced by such devices far exceed those produced with DEA actuators operating at higher voltages. Twisted string actuators generate linear motion via the twisting of fiber strands or filaments via compact, fast rotating, low-torque motors [147]. Coiled fibre actuators are composed of polymers that produce muscle-like actuation in response to electrically-supplied Joule heating. Such actuators have been applied in wearable applications [163].

A more unusual actuation method that has been investigated for wearable technologies consists of moisture-activated microbial cells. This actuation method was used to produce a self-ventilating garment possessing pores that opened, cooling the wearer, in response to increased moisture [164].

Table II presents several actuation methods, and reports aspects related to their wearability and functionality, including their mechanical compliance, safety considerations, portability, feasible force magnitudes, mechanical stress, absolute or relative displacement, and actuation frequency bandwidth.

H. Sensing

Sensors are critical to the functionality of robotic systems, enabling them to detect or perceive environmental stimuli, perform controlled movements, and manipulate their environments. Common sensing tasks include tracking the kinematic configuration and movements of the robot, sensing contact forces, and collecting environmental information, such as the geometry and configuration of nearby objects. Such sensing tasks mirror many of those that are performed by the sensory organs of the bodies of humans or other animals, which possesses multitudes of sensors for transducing visual, auditory, and mechanical information into neural information. Such a comparison is also interesting because biology has often informed or inspired soft robotic design. However useful this analogy may be, there are gross disparities between the complexity and capabilities of biological and soft robotic systems. For example, human abilities of tactile sensing, which are important for myriad activities of touch perception, grasping, manipulation, and interaction, are enabled by numerous mechanoreceptors – end organs of the peripheral tactile sensory nervous system. A single hand possesses on the order of 10^5 such receptors, greatly exceeding the sensing density and capabilities of even the most advanced electronic skins, as further discussed in recent review articles [72], [185].

In conventional rigid robotic systems, sensing needs and solutions are heterogeneous. Kinematic and force sensors are among the most frequently used. A hallmark of conventional robotic systems is the integration of kinematic and force sensors within, or close to, the actuators, in configurations that form servomotors or related mechatronic drives. In contrast, in most soft robotic systems, reduced integration between sensors and actuators is common. In soft robotics, this has contributed to a large diversity of sensing methods, designs, placements, and modalities. Recent reviews include [80], [186], [187].

In the last few decades, a large number of soft, wearable, and conformable sensors to detect strain, pressure, gesture, light, temperature, motion, and many other variables have been developed for wearable robotics applications. Data collected from these sensors can be used to control the behavior of the robotic system in a physical environment, through actuation-integrated feedback control, motion or task planning, or to provide application-dependent information, including the affordance of interactivity, as in the sensing of motion or kinesthetic inputs from a user in relation to objects in a virtual environment. Sensing requirements often depend greatly on the task and application domain involved (Section 2), which include healthcare, prostheses, diagnostics, movement, haptics and many others [188].

Several of the most significant sensing tasks in wearable, soft robotics concern mechanical sensing. This can include the sensing of parameters such as mechanical strain, pressure, displacement, or force. These parameters may be required for the control of a robotic system, such as a supernumary limb, or to facilitate user-action-dependent behavior or interactivity. A great diversity of mechanical sensing methods have been used in soft robotics. An immense variety of rigid sensors have been integrated in soft and wearable devices, far more than could be profitably reviewed here. Instead, we describe prominent sensing methods based on soft or compliant materials.

One category of such sensors leverage electrical principles. These include including capacitive and resistive sensors. Soft capacitive and resistive sensors have been enabled through the use of electronic or ionic (conductive or resistive) soft materials, or the integration of compliant electronic or ionic materials within soft polymers or other compliant structures.

a) Resistance sensing: Resistive sensors are based on changes in electrical resistance of a current path in response to mechanical stimuli. A simple example of such a device involves changes in the electrical resistance of a soft, conductive channel or wire in response to strain, or changes in length. In a conductive channel, the resistance R increases with length, l, and decreases with cross-section area, A, i.e.. $R = \rho l/A$, where ρ is volumetric resistivity, a material parameter.

Many soft, wearable robotic systems have employed strain sensors based on resistance. For example, Do et al. described strain-sensitive stretchable devices based on helically twisted hollow polymer fibers filled with a liquid metal, eutectic Gallium Indium [193]. Through twisting, the change in restance in response to mechanical strain could be tuned to application requirements. Many other skin-wearable examples using resistive sensing have been used (e.g., Figure 7B i, ii [142]).

b) Capacitive sensing: Capacitive sensing is based on capacitive coupling, which is the transfer of electrical energy by means of charged surfaces coupled through electric fields. A simple example of a capacitive sensor is a parallel capacitor with a soft dielectric material whose softness enables the device geometry, and thus capacitance, to change in response to applied mechanical displacements, stresses, forces, or strains. The capacitance of such a device is the ratio of change in electric charge to electric potential, depends on the device geometry and the dielectric constant of the materials. In simple devices, capacitance sensing is performed via charge or current sensing, while in more refined approaches, the capacitive device forms part of an oscillating circuit whose resonant frequency is sensed electronically in order to measure capacitance.

Atalay et al. employed capacitive sensors for strain sensing in a glove [158], while Cooper et al. produced capacitive sensors based on helically twisted fibers filled with liquid metal, similar to the resistive fibers reported by Do et al citedo2017twisted. Yao and Zhu developed multimodal wearable capacitive sensors for pressure, strain, temperature, and touch contact in several application areas [194]. Figure 7A illustrates several more examples.

When compared with resistive sensors, capacitive sensors can be more easily integrated in two-dimensional sensing arrays, because current does not directly flow between pairs of electrodes [195], [196]. This can facilitate tactile sensing via 2D soft, skin-like devices [197], [198]. This is more challenging to achieve using arrays of resistive devices, which often involve multiple current pathways between the electrodes that are used to read out the signals. However, Sundaram et al. applied an active grounding method in order to realize a pressure sensing glove with 548 resistive sensing elements (Figure 7B iii, iv) [159].

Both capacitive and resistive sensors can be designed to achieve high sensitivities. Capacitive sensors involve additional design considerations because their capacitance is affected by the dielectric properties governing electric fields in their nearby environment, and not merely by their geometric and mechanical state. To reject signals produced via nearby objects that are not in contact with the sensing device, the passive design or active control of the configuration of grounded surfaces in the device can be used [199].

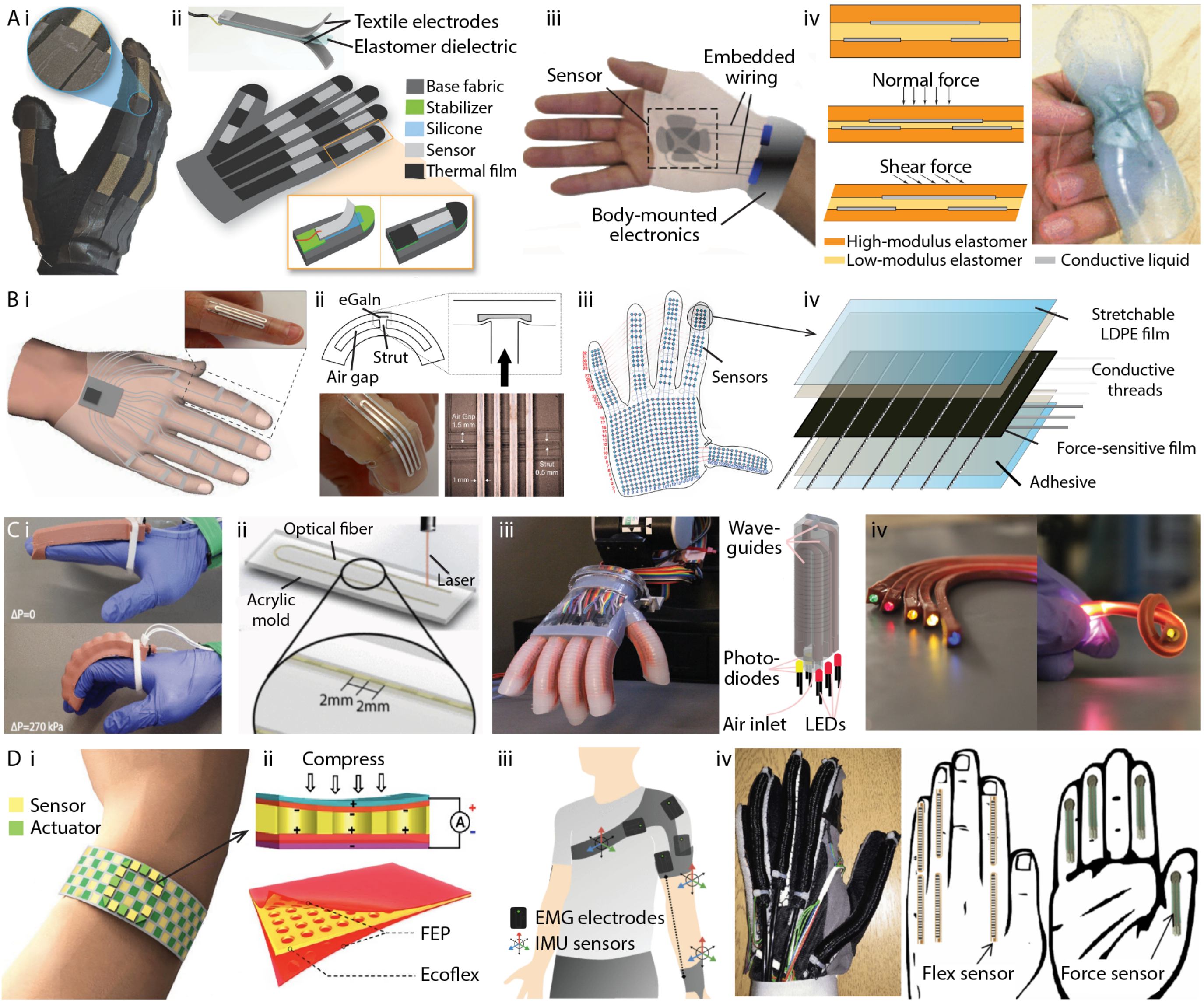

Fig. 7. Examples of sensing methods for soft wearable robotic applications. A. Examples using capacitive sensors. i-ii. Sensing glove for human body articulation using a customizable, stretchable textile-silicone composite capacitive strain sensor [158]. iii-iv. Soft-matter sensor measuring elastic pressure and shear deformation [189]. B. Examples using resistive sensing. i-ii. Curvature sensor for monitoring human or robotic motion [142]. iii-iv. Array of 548 resistive sensors on a soft tactile glove for normal force readings to identify tactile information when interacting with objects [159]. C. Examples with optical sensing designs. i-ii. A soft orthotic with curvature control enabled via embedded optical fiber [190]. iii-iv. Soft prosthetic hand for shape, texture, and softness detection using stretchable optical sensing techniques [120]. D. Examples of other sensing technologies. i-ii. Stretchable and flexible piezoelectric sensor for detecting force and pressure [191]. iii. An upper limb soft wearable assistive exosuit using IMU for joint angle sensing and EMG for muscle activity sensing [192]. iv. The Exo-Glove, a soft wearable hand robot for grasping assistance using commercially available flex and force sensors [157].

c) Optical sensors: Optical sensors are widely used in wearable applications, including health monitoring [200], [201]. Such sensors have attracted interest for wearable soft robotics due to their robustness and sensitivity. Optical sensors leverage the transmission, reflection, or refraction of light to sense physical properties or changes, such as mechanical deformation. Several methods for optical sensing via soft, stretchable, compliant, or flexible materials have been investigated. Optical fibers have been used in several such investigations. Precise strain sensing can be performed via patterned optical fibers that function as Bragg gratings. Other techniques for optical sensing utilize materials that vary in refraction or luminescence, such as photonic crystals, liquid crystal materials, or mechanochromic materials [188]. Remote optical sensing via the skin or other sensors can be used to measure light transmitted through materials or tissues. SUch sensing methods have been used curvature control of soft actuators (Figure 7C i, ii) [190], as well as shape, texture, and softness detection on a soft prosthetic hand (Figure 7C iii, iv) [120].

d) Piezoelectric sensors: As described in Section III-E, piezoelectric materials, including piezoelectric polymers, have been applied for several sensing tasks in soft robotics, including strain, force, or pressure sensing. Examples of piezoelectric sensing applications include self-powered, multifunctional pressure and shear sensors [202] as well as those developed to be used as e-skins or skin patches [185], [191]. Other uses of piezoelectric sensing combine them withwith other sensing methods to form hybrid sensing systems. One example is pyroelectric sensing, where a charge is generated in response to temperature changes and is thus primarily used for thermal detection, while another example is triboelectric sensing, where contact electrification generates a change in charge [188].

e) Magnetic sensors: Several magnetic sensing methods have been used in soft and wearable robotic applications. In one common configuration, miniature magnets are embedded in an elastomer. Changes in the resulting magnetic field are captured via Hall effect or other inductive sensors to measure strain, deformation, shape change, or other attributes [203], [204]. Such sensing methods are relatively noise robust and resistant to hysteresis [205].

f) Multimodal sensing: The sensing principles highlighted here represent a selection of those that have been used in soft and wearable robotics. Other methods include physiological sensing techniques such as electromyography and inertial sensing methods. These methods were combined in the exosuit created by Little et al. (Figure 7D iii) [192]. This example illustrates how sensing techniques are often combined synergistically. For example, Gerratt et al. developed a wearable tactile glove combining capacitive and resistive sensors [135], while Lacour et al. created a skin-wearable device using piezoelectric sensors combined with thin film transistors to detect pressure and strain [206].

IV. Conclusion: Frontiers, Challenges, and Future Prospects

In this review, we surveyed many aspects of soft, wearable robotics in order to provide the reader with an overview of the state-of-the-art, recent trends, design considerations, and engineering knowledge and methods that are contributing to the evolution of this active, evolving domain of research.

Engineering research in soft, wearable robotics and haptics is advancing rapidly due to the promise that such technologies hold for diverse applications, in areas ranging from healthcare, to augmented and virtual technology, fashion, and industry. Advancements in soft, wearable robotics have been enabled through the development of new materials and technologies, including compliant and soft materials and systems that are able to meet the often unique design and fabrication requirements that arise in this area, and that provide sensing, actuation, and other capabilities supporting their functionality. The promising potential of soft, wearable robotics is also associated with the ability of such systems to intimately complement the capabilities of the human body, enhancing human abilities of movement, sensing, furnishing capabilities that expand performance, providing protection to the body, or supplementing human perception and cognition.

Despite the exciting nature of these developments and advancements, there are several important challenges that must be overcome in order for soft, wearable robotic and haptic systems to attain their potential. One of the most important challenges is that of engineering new actuation methods that are compatible with the compliance of these systems, and with the softness of the materials that comprise these systems and the areas of the body with which they interface. In conventional robotic systems, established technologies including electromagnetic actuators or motors, pneumatic actuators, and hydraulic actuators, together with their accompanying mechanisms or transmissions, serve the great majority of motion control needs. While many soft analogs of each of these technologies have been developed, their capabilities often remain orders of magnitude more limited than their conventional counterparts. Advancements are needed in order for soft robotics to attain the high performance (for example, precision, speed, or operating range of forces) of conventional robotic systems. Such improvements may also require advances in methods of control engineering for soft robotic systems, which often comprise continuum systems with infinitely many degrees-of-freedom.

While sensing technologies are in some respects more advanced than those for actuation, here too there are opportunities for advancement. For example, as we described in the foregoing, electronic sensors cannot yet match several of the remarkable characteristics of the human skin, which is innervated with on the order of 10,000 mechanically sensitive neurons in each hand, and also provides impressive multi-modal sensing capabilities for mechanical, thermal, chemical, and noxious stimuli via a common substrate.

Control for soft, wearable robotics presents further challenges and opportunities for research. Recent research highlights the importance of human-in-the-loop considerations in control design. Further developments of these methods for soft, wearable robotics could enable such systems to perform robustly and meet the needs of myriad users.

Additional challenges arise from wearability. Many soft, wearable robotic systems are designed to be portable. New methods for powering such systems are needed in order to facilitate this, and to avoid encumbering their wearers. Energy requirements may also be reduced through the advancement of low-power technologies for sensing, actuation, and computation.

Other challenges arise from goals of interfacing or acting upon the body. For example, emerging soft robotic systems provide assistive forces or apply forces to the environment that are reflected to their wearer, as in supernumary limbs or prosthetics. Providing such forces via devices that are anchored to the skin and indirectly to subcutaneous tissues greatly constrains the design and performance of wearable robotics. This is a fundamental problem affecting the use of robotic wearables by endoskeletal creatures: soft tissues mediate forces between actuators and the skeleton. New ideas may be needed in order to overcome these limitations, ideally without recourse to very invasive or irreversible methods that require surgery. Examples could include minimally invasive micro-anchors that directly couple actuator forces to the skeleton. Today, implanted devices are primarily applied in medical applications. However, research in soft robotics and electronics is enabling devices that can offer greater biocompatibility than is possible with conventional technologies. In exceptional cases, body-penetrating (e.g., piercings) or implanted structures are used for body adornment. Over time, if perspectives on similarly intimate integrations of technologies with the body evolve, there could be demand for non-medical devices that are not merely wearable, but that integrate with, or within, tissues of the body itself.

Much as in any emerging area of technology, range of potential applications of soft, wearable robotics is not yet fully understood. Past and recent history in the development of new technologies suggests that these development will yield many applications that cannot yet be envisaged today. As we have highlighted, many emerging soft robotic technologies resemble existing wearable categories of garments, clothing, or other accessories. Such wearables are omnipresent, serving functional needs, matching cultural demands, or contributing to aesthetics or expression. Thus, it is possible that advances in soft robotics could transform the way that many articles of apparel are viewed today. Such advances could yield robotic clothing that augments human abilities in ubiquitous arenas of human activity, such as workplaces, domestic environments, leisure environments, or the outdoors. Such developments could thus be transformative.

Efficiently combining advancements in each of these areas will require new methods for systems integration. The capabilities of conventional robotic and electronic systems, or even the highly integrated systems supporting biological organisms, provide inspiration for what future soft, wearable robotic systems could one day achieve. Such advancements may require major progress in methods of materials and manufacturing.

The computer age is less than a century old, which is remarkably short when compared with timescales involved in biological evolution. In what today seems like the distant future, it is possible that soft, wearable robotics could achieve levels of efficiency, functionality, integration, and complexity that naturally evolved systems have produced. Such a vision could point to a long-term frontier in soft wearable robotics, toward seamless and synergistic integrations of human-produced technologies with biological systems.

TABLE III
SELECTED SOFT-ROBOTIC MATERIALS, TECHNOLOGIES, AND APPLICATIONS[2]

Materials	Actuation/Sensing Methods	Processing	Devices	Applications	Ref.
Silicone	Cable-driven actuation	3D printing, machining	Glove	Grasping assistance	[16]
Silicone	Pneumatic actuation, EMG sensing	Soft lithography	Rings	Grasping assistance	[17]
Silicone, foam, Au	Resistive and capacitive sensing	Soft lithography, microprocessing	E-skin	Prosthetic tactile sensation	[135]
Silicone, FEP, Au, Al	Vibrotactile actuation, piezoelectric sensing	Spin coating, deposition	Flexible patch	Vibrotactile feedback, pressure detection	[191]
Silicone, fabrics, PU rubber	Optical sensor, pneumatic actuator	Soft lithography, 3D printing	Strain sensors	prosthetic hand	[120]
Silicone, fabrics	Pneumatic actuation, EMG and IMU sensing	Soft lithography, 3D printing	Supernumerary limb	Tasks assistance	[30]
Silicone, fabrics	Capacitive sensing	Soft lithography, laser cutting	Glove	Monitoring finger motions	[158]
Silicone, fabrics, fiber	Hydraulic actuation	Soft lithography, 3D printing	Glove	Grasping rehabilitation	[13]
Silicone, fabrics, fiber	Pneumatic actuation, IMU sensing	Soft lithography	Glove	Haptic feedback on wrist	[40]
Silicone, fabrics, liquid alloy	Pneumatic actuation, IMU and resistive sensing	Soft lithography, apparel engineering	Soft orthotic boots	Ankle–foot rehabilitation	[19]
Silicone, liquid alloy, fabrics	Resistive sensing	Soft lithography, apparel engineering	Sensing suit	Track joint angles and gait phase	[143], [141]
Silicone, liquid alloy	Resistive sensing	Soft lithography	Glove	Joint angle measurement	[142]
Silicone, liquid alloy	Capacitive sensing	Soft lithography	Glove	Shear and pressure sensing	[189]
Fabrics	Cable-driven actuation, IMU sensing	Apparel engineering	Exosuit	Walk assistive	[10]
Fabrics	Cable-driven actuation, load cells and gyroscope sensing	Apparel engineering	Exosuit	Walk assistive	[207], [9]
Fabrics	Pneumatic actuation	Apparel engineering	Skirt	Expressive fashion	[68]
Fabrics, Teflon tube	Cable-driven actuation, resistive sensing	Apparel engineering	Glove	Grasping assistance	[157]
Fabrics, tapes	SMA actuation	Layer construction	Skin stickers	Tactile interfaces	[71]
Fabrics, latex	Pneumatic actuation, Resistive sensing	Apparel engineering	Glove	Hand rehabilitation	[208]
Fabrics, PVDF	Piezoelectric actuation, facial expression sensing	Apparel engineering	Garment	Interactive garment	[25]
Fabrics, PEDOT/PSS	Fiber bundle actuation	Wet spinning with chemical treatment	Heating glove, artificial muscle	Wearable heaters and electromechanical actuators	[209]
Fabrics, TPU	Pneumatic actuation	Apparel engineering	Knee sleeve exosuit	Knee rehabilitation	[20]
LDPE thermoplastic	Pneumatic actuation	Heat-sealing	Wristband	Haptic guidance	[39]
TPU-coated fabrics	Pneumatic actuation	Laser cutting, CNC heat-sealing, 3D printing	Supernumerary limb	Assistive device	[11]
ABS, thermoplastic PU	Cable-driven actuation	3D printing	Supernumerary finger	Grasping assistance	[12]
Silicone, AgNWs	EAP actuation	Soft lithography	Sleeve, glove	Tactile interfaces	[133]
Silicone, AgNWs	Capacitive sensing	Soft lithography	E-skin	Muscle motion sensing	[139]
Silicone, CNTs	EAP actuation	Soft lithography	Forearm band	Haptic communicator	[131]
Silicone, CNTs	Capacitive sensing	Transfer printing	E-skin	Motion sensing	[160]
Silicone, CNTs	Resistive sensing	Dry-spinning	E-skin	Motion sensing	[210]
Silicone, graphite, CNTs	Resistive sensing	Soft lithography, bar coating	E-skin	Motion, acoustic, and biosignal sensing	[211]
Silicone, carbon powder	EAP actuation	Micro-fabrication, hot pressing	Thimbles	Vibrotactile display	[59]
Silicone, graphene, P(VDF-TrFE), Au, Ion gel	Piezoelectric sensing	Micro-/nano-fabrication	E-skin	Bending motion sensing	[130]
Silicone, rGO-on-PVDF-nanofibers	Resistive sensing	Electrospinning, spin coating	E-skin	Pressure sensing, photodetector	[212]
Silicone, rGO nanofibers, PVDF	Piezoresistive sensing	Electrospinning	E-skin	Biosignal sensing	[213]
Steel cables, Velcro	Cable-driven	Laser cutting, 3D printing	Finger caps	Haptics for VR	[22]

Materials: Au = gold, FEP = fluorinated ethylene propylene, Al = aluminum, PU = polyurethane, PVDF = polyvinylidene difluoride, PEDOT/PSS = poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate), LDPE = low-density polyethylene, TPU = thermoplastic polyurethane, ABS = acrylonitrile butadiene styrene, AgNWs = silver nanowires, CNTs = carbon nanotubes, P(VDF-TrFE) = Poly(vinylidenefluoride-co-trifluoroethylene), rGO-on-PVDF-nanofibers = reduced graphene oxide (rGO) encapsulated poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] (PVDF) nanofibers. Actuation/sensing methods: EMG = electromyography, IMU = inertial measurement unit, SMA = shape memory alloy, EAP = electroactive polymer. [2]

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