Review of Robot Skin: A Potential Enabler for Safe Collaboration, Immersive Teleoperation, and Affective Interaction of Future Collaborative Robots

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***Abstract*—The emerging applications of collaborative robots (cobots) are spilling out from product manufactories to service industries for human care, such as patient care for combating the coronavirus disease 2019 (COVID-19) pandemic and in-home care for coping with the aging society. There are urgent demands on equipping cobots with safe collaboration, immersive teleoperation, affective interaction, and other features (e.g., energy autonomy and self-learning) to make cobots capable of these application scenarios. Robot skin, as a potential enabler, is able to boost the development of cobots to address these distinguishing features from the perspective of multimodal sensing and self-contained actuation. This review introduces the potential applications of cobots for human care together with those demanded features. In addition, the explicit roles of robot skin in satisfying the escalating demands of those features on inherent safety, sensory feedback, natural interaction, and energy autonomy are analyzed. Furthermore, a comprehensive review of the recent progress in functionalized robot skin in components level, including proximity, pressure, temperature, sensory feedback, and stiffness tuning, is presented. Results show that the codesign of these sensing and actuation functionalities may enable robot skin to provide improved safety, intuitive feedback, and natural interfaces for future cobots in human care applications. Finally, open challenges and future directions in the real implementation of robot skin and its system synthesis are presented and discussed.**

***Index Terms*—Collaborative robots, safe collaboration, immersive teleoperation, affective interaction, robot skin.**

I. INTRODUCTION

REMOVING the isolated fence, collaborative robots (cobots) can collaborate or interact with humans closely, especially when human operators need a robotic system to augment their abilities. The expansion of research in collaborative robotics produces a variety of cobots with varying mechanical design, price, and safety features [1]. As an existing system with general-purpose, portable, and ready-to-deploy hardware modules, cobots can address fluctuations of application scenarios in demand on whether the cobot is collaborative, teleoperated, or autonomous, i.e., the three operating modalities of cobots. This distinguishing feature is extending their applications from the conventional production line to a more diverse range of human-centered scenarios [2], [3].

This review starts from the promising application domain of, how collaborative robotics complements and supports healthcare delivery and the healthcare staff, in combating the coronavirus disease 2019 (COVID-19) pandemic and in home care for coping with the aging society. There are many challenges to be considered on its implementation in human care, which are discussed according to the original results of a field investigation [see more details in Section II-A]. The findings so far are more "open questions" rather than "solutions" given the challenges are still big. For example, the safety assurance of uses/patients during human-robot interaction (HRI) is one of them [4]. These challenges are putting forward the development of demanded features for future cobots, including safe collaboration, immersive teleoperation, affective interaction, and other emerging features (e.g., energy autonomy and self-learning).

The fast development of electronic skin offers the feasibility to address the demanded features. The pioneering work in this area is more focusing on soft robots [5]–[7], health engineering [8]–[10], human/robot fingertips [11]–[13], and human-robot interfaces on human body [14]–[16]. Apart

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Clinical Research Ethics Committee of the First Affiliated Hospital of Zhejiang University under Application No. IIT20200048A-R1, and performed in line with the full, informed consent of the volunteers, in accordance with all local laws.

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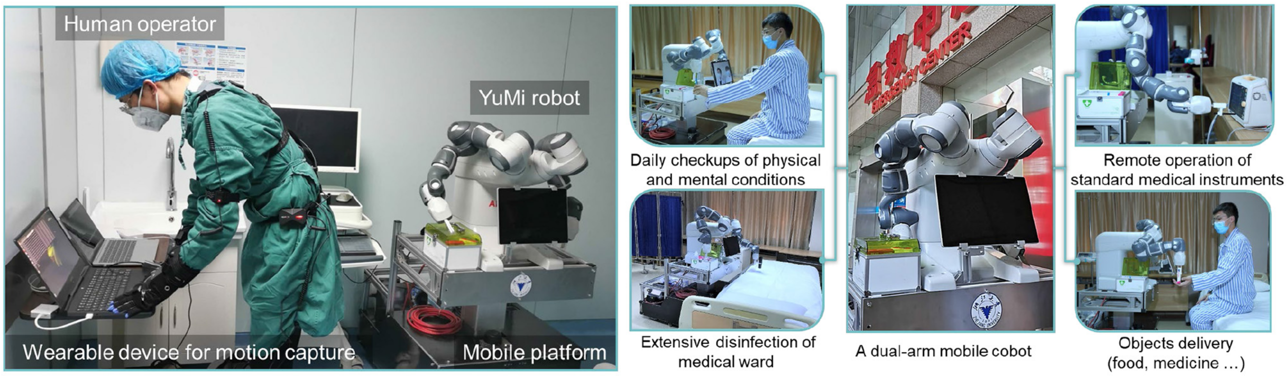


(a) (b)

Fig. 1. The ongoing field tests of a dual-arm mobile cobot for patient-care applications at the Emergency Department of the First Affiliated Hospital of Zhejiang University, Hangzhou, China: (a) The teleoperation system consists of a mobile platform, a dual-arm cobot (YuMi, IRB14000), and a wearable motion capture device including a pair of data gloves to capture the finger motions for the teleoperation of grippers; (b) By leveraging the motion capture device, motion data collected from the upper limb of the healthcare worker can be obtained, processed, and used to wirelessly control the robot arm remotely for delivering healthcare services. Ethical approval has been granted to the research team for the related research, which covers the human-subject related aspects and test of devices in hospital environment, where ethical principles are fully followed.

from the above focuses, some significant efforts also have been devoted to developing electronic skin for large-area and rigid cobot body (i.e., robot skin) [17]–[19]. However, it still has large room to be improved, and the motivation of developing such skin for cobots is still not discussed enough. This review makes a more comprehensive investigation into how demanded features can be addressed by the new paradigm of robot skin that incorporates multimodal sensing and self-contained actuation. To well blend into human living environments, future skin-covered cobots are coupled robotic systems composed of rigid, flexible, and soft components [20]. Cobots will inherently provide the rigid part to ensure necessary force, power, and responsiveness of actuation, while robot skin will offer the soft part for the requirements of demanded features. This review aims to attract more industry-academia research/collaborations on those open questions and in the recommended directions of the potential enabler, that is, robot skin.

The goal of this review is quadripartite: 1) to identify the promising applications of cobots in human care and their demanded features, which motivate the development of robot skin [Section II]; 2) to bridge the gap between the robot skin, as a potential enabler, and the demanded features of cobots by explicating their relationship [Section III]; 3) to exploit a comprehensive investigation into the state-of-the-art research of robot skin with the expected functionalities [Section IV]; 4) to envision the scientific challenges of robot skin and its directions for future research to empower future cobots with the demanded features for human care [Section V].

II. FEATURES OF COBOTS TO BE ADDRESSED BY ROBOT SKIN

A. The Promising Applications of Cobots

1) The Role of Cobots in Combating the COVID-19: One of the emerging applications for human care is combating infectious diseases, such as the COVID-19 pandemic. The effective and efficient deployment of cobots speeds up the medical test and treatment process, reduces the risk of cross-infection, and frees up staff from time-consuming and repetitive manual operations to other important tasks, providing an effective solution for the mitigation and suppression intervention of the COVID-19 pandemic [21], [22]. The potential benefit of deploying cobots for combating the COVID-19 pandemic is in four aspects [1], [23]: 1) Emergency medical resource supply, such as ramping up existing medical device production and repurposing existing non-medical device production to medical device production; 2) Disease prevention, e.g., autonomous and extensive disinfection of contaminated surfaces; 3) Diagnosis and screening, such as automated or remotely robot-assisted use of standard instruments for vital signs measurement and oropharyngeal swabbing for the medical test; and 4) Patient care delivery, e.g., providing social interaction with patients, changing position for critically ill cases and teleoperating medical machines. As the above roles are mapped to technical requirements, there is an emerging research area – teleoperation of cobot (telecobot) – where the robot needs to be not only collaborative with patients and caregivers (cobot) but also remotely operated for the life-critical patient-contact tasks (telerobot). For example, a cobot has been experimentally used to verify the potential application useful to combat the coronavirus disease outbreak during the COVID-19 pandemic. As demonstrated in Figure 1(a), in this field investigation, a cobot was installed on a mobile platform in an isolation ward and wirelessly controlled by a human operator through a wearable device in a remote control center. Simple tasks that the telecobot can complete were validated, as shown in Figure 1(b), including the daily checkups of physical and mental conditions, remote operation of standard medical instruments, extensive disinfection of medical ward, and objects delivery for care recipients.

2) The Role of Cobots in Coping With the Aging Society: In addition, collaborative robotics is also a potentially powerful tool for in-home care. Powered by the fourth revolution of healthcare, i.e., Healthcare 4.0 [24], the transformation of elderly care from human-dominated and hospital-centered

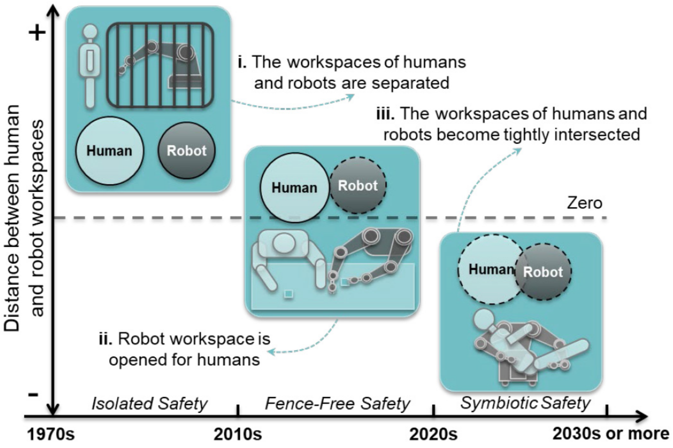


Fig. 2. Illustration of the continuous evolution of the design paradigm of robotic safety from isolated safety to fence-free safety and towards symbiotic safety by distinguishing the distance between human and robot workspaces and the extent of HRC.

care to robot-assisted home-based care is taking place [25]. Collaborative robotics is a promising solution for addressing the lack of professional caregivers, which is induced by the ever-increasing aging population. On the one hand, cobots have the potential to reduce the elderly's dependence on caregivers by assisting them directly. On the other hand, cobots can improve the ability of single professional caregivers, allowing them to take care of more elderly people as needed. The potential role of employed cobots in such application is threefold [25]: 1) Autonomous accomplishment of the relatively easy assistive operations, e.g., autonomous cleaning and automated use of standard home appliance; 2) Instant support for the independent living of the half-disabled elderly who are partially incapacitated, where the cobot is teleoperated by using their remaining capabilities, such as robot-assisted bathing and robotic interventional rehabilitation; and 3) On-site professional operation of the skilled people, e.g., the professional caregivers employed in the remote healthcare institutions can teleoperate a cobot to give first aid to seniors suffering a sudden illness or injury at home, or to assist timely and accurate medication for seniors with dementia. However, there are challenges in advanced materials and biomachines, artificial intelligence (AI), fog computing, cloud computing and communication, regarding the real implantation of cobots for delivering home care services remotely [25]. A well-established home care system can be rapidly repurposed for delivering healthcare services to potential patients who are under stay-at-home orders during the COVID-19.

B. Limitations of Current Cobots

The environments of the aforementioned human care applications of cobots are highly dynamic and unstructured, compared to settled industrial environments. To handle such generally unknown and human-dominated environments challenges the capabilities of cobots, especially of sensing, actuation, and learning. The current features of cobots, such as flexible mechanical design, varying price, and safety features [1], are still lagging behind in the effectiveness of deployment for human care, where the requirements of cobots are stringent. For instance, during the field investigation of the cobot at a COVID-19 specific hospital in Figure 1, there are many issues limiting the real implementation of cobots: 1) High-performance wireless communications; 2) Temperature and haptics sensing at the robot fingers and body parts; 3) Perception of patient's responses and affective state; 4) Usability and accuracy of the remote operation; 5) Robot self-disinfection; and 6) Self-learning for new tasks. Another urgent need is regulations on functional safety, privacy, and ethical issues because the existing ones are originated from traditional robot applications, and ward-care is not well addressed. Some explorations are moving on new materials and mechanical design for safety, dexterity, and self-disinfection, and teleoperation for life-critical operations combined with machine learning for less critical tasks, but still in the research phase. Specifically, the safety solution of most existing off-the-shelf cobots may rely on lightweight design, soft padding, limited power, and constrained speed, or external sensors and software to improve safety behavior [26]. Although these methods improve safety to some extent, they may affect the performance of cobots or not effective in some particular conditions, which are gaining more and more attention [26], [27]. Applications in human care call for considerable improvements of it, expecting cobots are absolute safe while offering better performance in delivering care services [25]. On the other hand, the lack of sensors and sensing modalities on body parts may make current cobots unable to fully understand the environment or humans they are interacting with. The insufficient intelligence also imposes challenges to current cobots to interpret much useful information from the limited sensing function, while simple motor actuation of cobots makes it difficult to express themselves in a natural and intuitive manner. All of these limitations are motivating the ongoing research of advanced technologies for improving the performance of cobots [3].

C. Demanded Features of Future Cobots

The ever-increasing demands and technological challenges of applying collaborative robotics in human care are putting forward the development of three key features for future cobots, including: 1) the basic feature – *Safe Collaboration* – gives a top priority to address the safety issue when considering the closer collaboration or interaction when cobots and their human peers work or living together to share the work-load; 2) the advanced feature – *Immersive Teleoperation* – enables cobots to function as the augmented second body of human operators to interpret the multimodal sensory information and perform collaborative tasks remotely and accurately; and 3) the top feature – *Affective Interaction* – endows cobots with natural communication channels between robots and humans to anticipate command changes by observing affective state of humans, allowing cobots to automatically estimate their performance and effectively provide care services, particularly emotional support. In addition, other emerging features for general-purpose cobots and long-term operation are also discussed in this section.

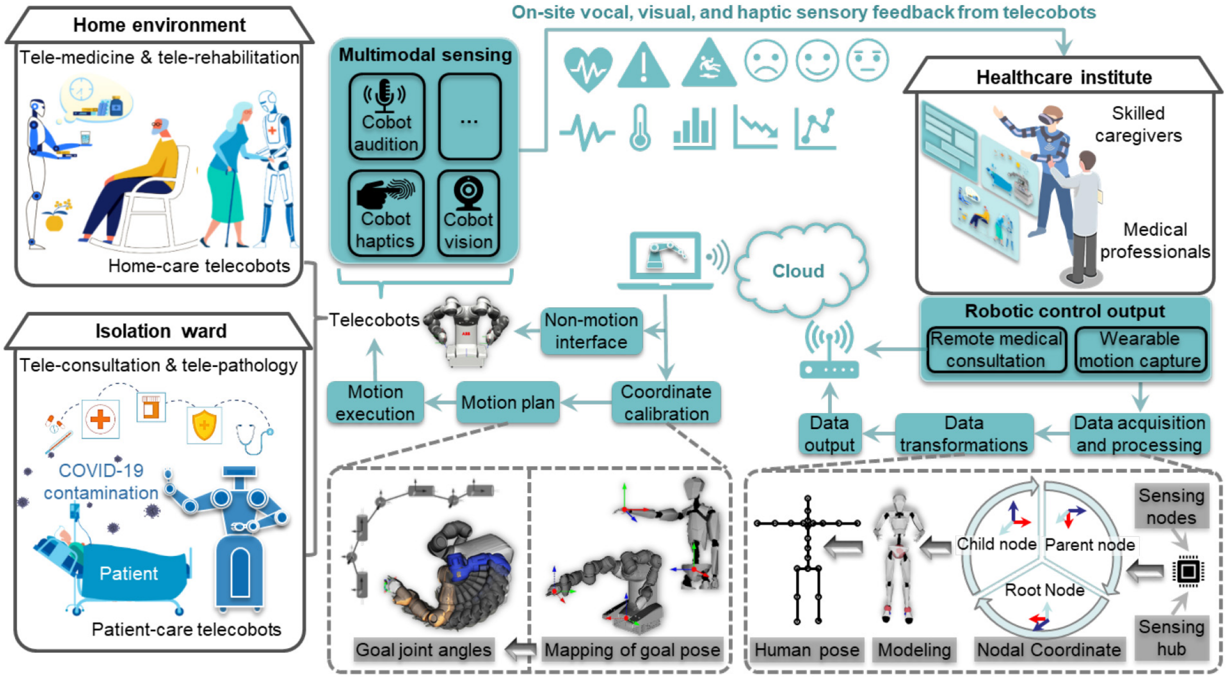


Fig. 3. Telecobot system composed of wearable devices on human operators and cobot in remote environments. Adapted from [25], [30]. Wearable devices are used for capturing the intention of human operators and mapping to robotic motor control. Telecobots are employed to conduct tele-medicine and tele-rehabilitation during home care for the elderly or perform tele-consultation and tele-pathology in isolation ward. Multimodal sensing data of telecobots in remote environments are transferred to skilled caregivers or medical professionals in healthcare institute by leveraging cobot audition, vision, and haptics.

1) Safe Collaboration: The deployment of robots in a shared environment with humans poses many challenges, of which the most direct and basic one is safety. Along with the continuous revolution of industry and the gradual expansion of robot families, such as industrial robots and cobots, the safety system of robots experienced several transformations, starting from isolated safety to fence-free safety and towards symbiotic safety, as illustrated in Figure 2. The main consideration of this evolution is the distance between human and robot workspaces.

Conventional industrial robots work independently at a fixed position with physical barriers that are used to separate human-robot workspace to guarantee isolated safety [28]. In contrast, cobots operate in the same workspace as humans, therefore sparking the new working mode now addressed as human-robot collaboration (HRC). Working with humans means that the isolation fence is removed while still guaranteeing the safety of the operators, a modality called fence-free safety. With rapid advances in collaborative robotic technology, a variety of cobots will blend into human living spaces to operate side by side with humans or assist humans with specific tasks, such as healthcare cobots [24]. The workspaces of humans and robots become tightly intersected. In this foreseeable future, human-robot-symbiosis systems that emphasize symbiotic safety due to the ever-closing collaboration will come into being.

How to ensure the security of advanced cobots in these systems to satisfy symbiotic safety requirements when performing collaborative tasks is, therefore, an emerging research topic. In this regard, technological advances of cobots in collision avoidance and minimizing injury of human-robot collisions will address the security issues of collaboration [27].

2) Immersive Teleoperation: Robotic teleoperation, i.e., telerobotics, refers to a system where human operators remotely control semi-autonomous robots to accomplish specific tasks, conceptually lying between traditional teleoperations and fully autonomous robots [29]. Driven by the advanced technologies of Healthcare 4.0, the shift of healthcare from hospital to improvised hospital, community, and home is happening through remote monitoring of health status and remote delivery of interventions and treatment [23], [24]. Under this shift, telerobotics can be potentially used to undertake human care, especially the home care of the elderly [30], [31] and the patient care of an infectious disease pandemic [32], as shown in Figure 3. This is the explicit system architecture of telerobotics, which is illustrated by the field investigation mentioned in Section II-A, indicating the exchanged information in the closed-loop remote control. Robots in these human care scenarios will interact or collaborate with humans frequently and closely, resulting in a high requirement for the safety assurance capability of telerobotics. Collaborative robotics, as a typical example of semi-automatic robotics and a representative of the ongoing development phase of human-robot-symbiosis, is capable of enhancing safety performance and serving for these fields, paving the way to a major research trend of telecobots for human care.

To ensure the control stability and maneuverability of telecobots in remote unstructured and dynamic environments, great efforts should be paid to research and develop immersive teleoperation, especially in the case of unstable networks with asynchronous time delays. Aiming to improve the ability of physical interaction between telecobots and remote environments, it is expected to enlarge the modality of systematic sensors and actuators for exchanging the vocal, visual, and haptic information via high-speed networks connecting human operators and remote telecobots [33]. With enhanced robotic manipulability and multimodal realistic high-fidelity feedback, immersive teleoperation allows telecobots to truly function as an augmented second body of a human operator to extend the capabilities of human operators in the telepresence context [34].

3) Affective Interaction: Differing widely from the human-robot-environment interaction of immersive teleoperation, affective interaction solely concentrates on how to enable cobots to interpret and respond to the implicit communication message in emotional states from the human object [35]. Emotions, as an essential part of human behavior, play an important role in human-to-human communication and decision making [36]. For a human-robot coexisting system, it would be desirable to develop a deep understanding of affective interaction to improve human-to-machine interaction, especially for human care [37]. In robot-assisted human care, the affective interaction will positively and bidirectionally impact cobots and care recipients, allowing cobots to convey affective expressions, thereby establishing a deeper and closer partnership with care recipients.

On one hand, affective interaction expects to deepen the technological progress of collaborative robotics in recognition of human affective cues for improving the adaptive performance of cobots to respond effectively without requiring the user to continuously issue explicit feedback [38]. On the other hand, affective interaction desires to empower cobots to generate emotional assistive behaviors for care recipients, making them less lonely and more socially engaged [22]. For example, cobots can provide emotional support for dealing with the mental health and wellbeing of lonely elders or patients in quarantine who are generally required for long-term isolation [39]. Therefore, the technological breakthrough in immersive teleoperation and affective interaction will constitute a significant step toward creating real-world avatars and cobots to precisely deliver a diverse range of sophisticated remote human care services in a more natural way and safer manner.

4) Other Emerging Features:

Energy Autonomy: Cobots are typically composed of isolated power supply, embedded sensors, mechanical actuators, and control center, which are varied and optimized for specific tasks [40]. Typically, an isolated power source serves a single function as a storage battery of a cobot, resulting in sub-linear scaling of overall system energy density with total energy to power a wide variety of electronics [40]. Increased battery packs with large weight and volume necessitate additional modifications of the overall robotic system to maintain performance [40]. In the application of human care where environments are unstructured and highly dynamic, energy storage is one of the major barriers to achieving long-duration autonomy of cobots to cope with various tasks. Thus, an energy-autonomous system for the uninterrupted operation of future cobots in human care will attract more efforts from the academic or even industrial domain.

Self-Learning: Enormous breakthroughs have been made in machine learning or AI in the recent ten years, resulting in game-changing applications in computer vision and language processing. It is hoped that the field of intelligent robots can be constructed with robots that can perform a diverse range of tasks in various environments with general human-level intelligence [41]. However, this revolution has not yet occurred with breakthroughs in machine learning [41]. Specifically, in human care, general-purpose cobots are being designed to help with domestic tasks or professional healthcare actions. These cobots would be accompanied by a large amount of prior knowledge and abilities, and they need to be able to learn on the job, understand and predict with respect to the situation. However, developing the learning applications for allowing cobots to undertake even simple tasks remains extremely challenging [41].

III. ROBOT SKIN AS A POTENTIAL ENABLER

A. New Paradigm of Robot Skin Coupled With Actuators

Sensors and actuators equipped on the cobot body are the most important components to address the aforementioned features of future cobots [42]. As illustrated in Figure 4, on the analogy of human skin, robot skin, which is built of flexible or soft materials and covers the cobot body, is a new physical barrier between the cobot and the external environment [43]. It is generally used as sensors, enabling host cobots to extract much information by converting multiple stimuli from the environment into electrical signals which can be received by the cobot brain for generating safe and effective instructions [12]. Mimicking the mechanical properties of human skin, the advanced robot skin can be applied to various complex contours of cobots by deforming itself while maintaining its sensing performance [8], [44]. In addition to the sensibilities, the powerful robot skin can also integrate with actuation function enabled by biological muscles to obtain specific functionalities, for example, the variable stiffness [45]. Future skin-covered cobots are coupled robotic systems composed of rigid, flexible, and soft sensing components and actuation mechanisms [20]. For example, rigid parts, such as robot links, function as the skeleton to ensure necessary force, power, and responsiveness of actuation for collaborative tasks, while the flexible and soft robot skin consisting of the sensitive skin and the actuated muscle facilitates safe and natural interactions with humans and enhances the capability of adaptation, sensitivity, and agility.

B. Desired Contributions to the Demanded Features

1) Improved Safety for Safe Collaboration: The inherent flexibility and softness of robot skin may increase the safety level of host cobots in collaborations by absorbing collision energy through deformation, while rigid materials and structures cause serious injuries to humans upon physical collisions [46]. Several external stimuli, such as proximity and contact force, perceived by robot skin are the fundamental data to analyze hazards and assess risks, thereby fast triggering safety reaction strategies for avoiding unexpected collisions and keeping the injury risk within safe levels during HRC [47].

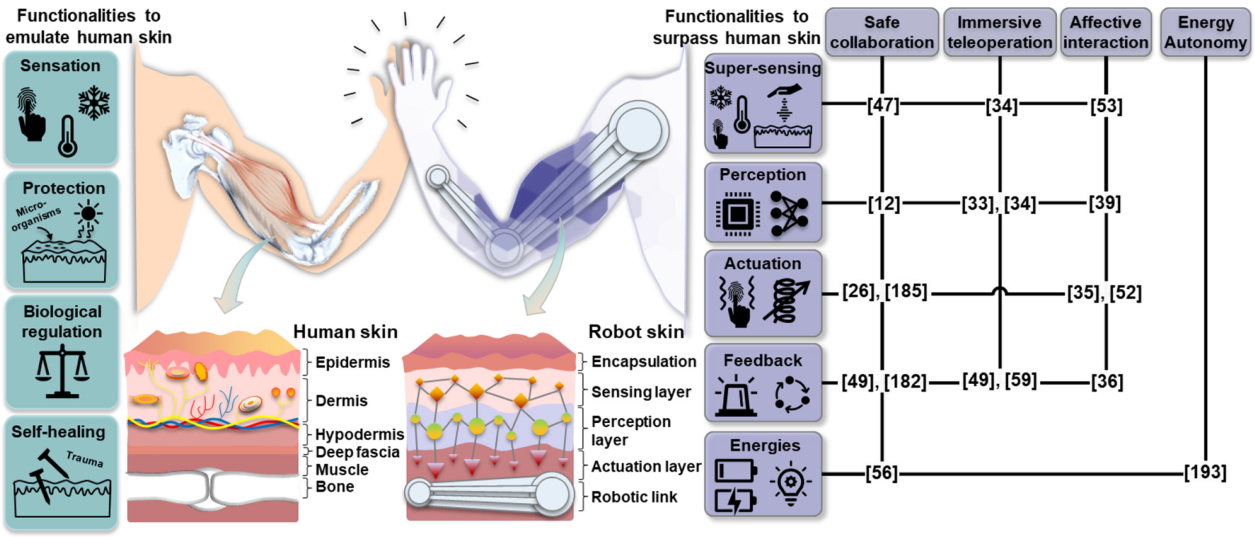


Fig. 4. Robot skin functionalities inspired by the biological structure of the human body and their relations to the demanded features: Robot skin not only executes the human skin functionalities such as self-healing, sensation, protection, and regulation, but surpasses the human skin with the capabilities of super-sensing, localized perception, self-contained actuation, active feedback, and power supply.

Robot skin embedded with actuators to control its stiffness can reduce the peak collision force by altering its stiffness according to the proximity parameters from the approaching human peers in dynamic environments, thereby limiting the injury once a collision occurs [26]. This process is similar to the natural responsive action of the human body to tighten muscles when defending against external shocks.

2) Intuitive Feedback for Immersive Teleoperation: The successful establishment of immersive teleoperation systems of cobots is based on the coupled communication of vocal, visual, and haptic signals [48]. Robot skin is the typical necessary hardware to endow the host cobots with the ability to perceive and process multimodal information, such as proximity, force, and temperature, providing the fundamental to the success of any physical extension of immersive teleoperation systems [34]. The sensory information perceived by robot skin can be reflected in different forms, e.g., visual and haptic signals, to give human operators complete immersion. For example, robot skin integrated with visual feedback functions, such as color-changing and light-emitting, can convert the sensory information into visual signals on-site, which can be further intuitively transmitted to a human operator [49]. The tactile information interpreted by robot skin, on the other hand, can be directly processed, transferred, and then represented as haptic signals by the haptic actuators interacting with a human operator [50].

3) Natural Interfaces for Affective Interaction: First of all, the softer tactility of robot skin can provide host cobots with a better physical interface in affective HRI, compared with traditional rigid components [51]. Tactile information detected by robot skin can not only increase immersion and sense of presence but also convey various pro-social emotions [52]. For example, a stroke, a poke, or a soft push may convey comfort, anger, or calmness, respectively [51], [53]. In addition to enabling cobots to recognize human emotions by touch sensing, robot skin can help host cobots directly producing realistic touch to convey their emotions that would be perceived and interpreted by humans, enriching the affective experience [52]. On top of that, the incorporation of various actuators into robot skin, such as thermal, vibrotactile, and stiffness-modulation actuators, provides cobots with the advanced functionality of affective tactile stimulation [35]. Several application scenarios could benefit from this functionality, including therapeutic interventions, affective disorder assistance, and emotional care for empty nesters [39].

4) Power Supply for Energy Autonomy: Traditionally, energy autonomy is a key to wearable systems for real long-term applications [54]. One of the new trends of wearable systems in the application domain is from human body to robot body, i.e., from electronic skin to robot skin [10]. Similar to the wearable system, self-powered or energy-autonomous robot skin is being designed to deal with the high density of heterogenous and networked electronic components (e.g., sensors, actuators, and controllers) required in robot skin system without adding heavy batteries [55]. Such robot skin systems may consist of energy harvesters, energy storage devices, and efficient/wireless power transferrer. They are expected to extend the applications of cobots, in particular, human care. On the other hand, replacing traditional stand-alone batteries with robot skin that functionalizes as conformal multifunctional structural batteries can enhance cobots through the simultaneous extension of their operational time and reduction in total weight [56].

C. Expected Functionalities of Robot Skin

As a potential enabler, robot skin with advanced functionalities, such as proximity sensing, pressure sensing, temperature sensing, sensory feedback, and stiffness tuning, can be deployed onto the cobot body to directly power the required fundamentals of sensing and actuation for the emerging features. By detecting the presence of nearby humans or obstacles, cobots equipped with proximity-sensitive skin

TABLE I
COMPARISON BETWEEN HUMAN AND REPRESENTATIVE ROBOT SKIN

Sensing modalities	Characteristics	Human skin	Robot Skin							
Pressure	Lightest detectable pressure [Pa]	2000	0.9	[65]	3.3	[66]	0.2	[67]	9	[68]
	Durability [Thousand cycles]	1000000	100		1		10		10	
	Response time [ms]	30–50	8		20		30		138	
	Spatial resolution [cm^{-2}]	≈ 0.01–250	≈ 1		0.25		2.56		0.64	
	Sensitivity [kPa^{-1}]	0.02–0.09	64.3		0.33		110		147/442	
	Frequency range [Hz]	≈ 0–400	0.5–2		1		0.5–2		0.2–0.81	
Strain[a]	Stretchability [%]	≈ 30%	400%	[69]	60%	[70]	0.8%	[71]	5%	[72]
	Gauge factor[b]	–	1960		46.3		7400		85000	
	Durability [Thousand cycles]	1000000	1		5		0.5		1	
	Elastic modulus [kPa]	10–500	980–2120		1420		–		–	
	Response time[b] [ms]	–	–		–		88		–	
	Spatial resolution [cm^{-2}]	12–18[c]	≈ 4		22.2		0.08		–	
	Frequency range[b] [Hz]	–	–		0.5–3.1		–		–	
Temperature	Operation range [℃]	15–45	0–80	[73]	15–40	[74]	20–50	[75]	30–65	[76]
	Durability [Thousand cycles]	1000000	25		20		55		400	
	Response time [s]	1–5	1.4		10		–		16.5	
	Spatial resolution [cm^{-2}]	0.5–20	0.36		0.67		4		10	
	Sensitivity [℃$^{-1}$]	20%–200%	24%		2.89%		10.4%		1.23%	

[a] The characteristics of strain of natural skin (i.e., hairy skin) is more related to physical properties, since the sensing mechanism is similar to pressure (i.e., pressure sensing induced by tangential force).

[b] Strain sensing performance of natural skin is recommended to refer to pressure sensing combined with physical properties of it.

[c] The spatial resolution of strain in human hand (i.e., glabrous skin).

can make proactive decisions quickly on control strategies to actively avoid collisions and ensure safety and reliability in collaborations [57]. As in humans, tactile sensing in cobots helps in understanding the contact interaction behaviors (e.g., shape, slip, softness, and roughness-smoothness) of a real-world object, making host cobots capable of detecting pressure, force, vibration, and thermal stimuli [12], [44], [58]. In addition to the above perceptual functionalities, robot skin will integrate more and more advanced functional actuators to provide sensory feedback in various modalities, such as vibrotactile and visual feedback for enhancing the user-interactivity of cobots [49], [59], or to actively control its specific properties, e.g., extending sensitivity by altering stiffness for improving the adaptability of cobots to the dynamic environment [60]. In addition to the above sensing and actuation functionalities, robot skin is also expected to be capable of supplying energy for both skin system and cobots. It is one of the essential fundamentals for the uninterrupted operation of cobots, achieving energy-autonomous systems.

IV. THE STATE-OF-THE-ART

This section gives an overview of recent progress in robot skin with the expected sensing (e.g., proximity, pressure, strain, and temperature), actuation (e.g., sensory feedback and stiffness tuning), and power-supply function (e.g., energy harvesting and energy storage) for cobots in human care. Table I provides the quantitative value of human skin parameters [61]–[64] and its comparison with the current state of art sensors response (pressure [65]–[68], strain [69]–[72], and temperature [73]–[76]). The value of all characteristics of a particular sensing modality in a single column is taken from the same work. It should be noticed that some specific characteristics of current robot skin are outperformed natural skin to some extent. For example, Wang *et al.* [77] developed a pressure-sensitive skin that has a spatial resolution of 347 per centimeter^2. A comprehensive investigation of each sensing modality of recent advancements in robot skin is summarized in the following sections one by one. It should also be noticed that some particular characteristics of human skin may not be deterministic. For example, there are two claims on minimum detectable pressure, which are 2000 pascals and 5 pascals in [64] and [78], respectively. In addition, a claim of the frequency response of human skin may go up to 1000 Hertz [79]. Energy density and location of energy storage in the human body are recommended to refer to [80]. Robot skin for energy autonomy covers a broader range of energy technologies and applications. Here, this review mainly envisions the codesign of sensing and actuation function of robot skin for future cobots to address the challenges directly confronted with human care potentially. Thus, it is not included in this section, but the full scope of energy-autonomous skin can be comprehended by further reading the recommended existing literature [80]–[82].

A. Proximity Sensing

Superior to human skin with nature functionalities, robot skin equipped with proximity sensing function extends its capability with the sixth sense to directly detect the presence of nearby objects without contact. Table II summarizes the recent representative robot skin proximity sensing with various transduction mechanisms, including inductive [57], [83]–[85], optical [53], [86], [87], capacitive [88]–[92], and electrostatic gating types [93]–[95].

1) Inductive Sensing: Inductive sensing principle of proximity sensors relies on alternating magnetic fields to detect approaching objects that disturb the generated magnetic field. The proximity can be detected as a variation of the inductance of a coil or mutual inductance between several

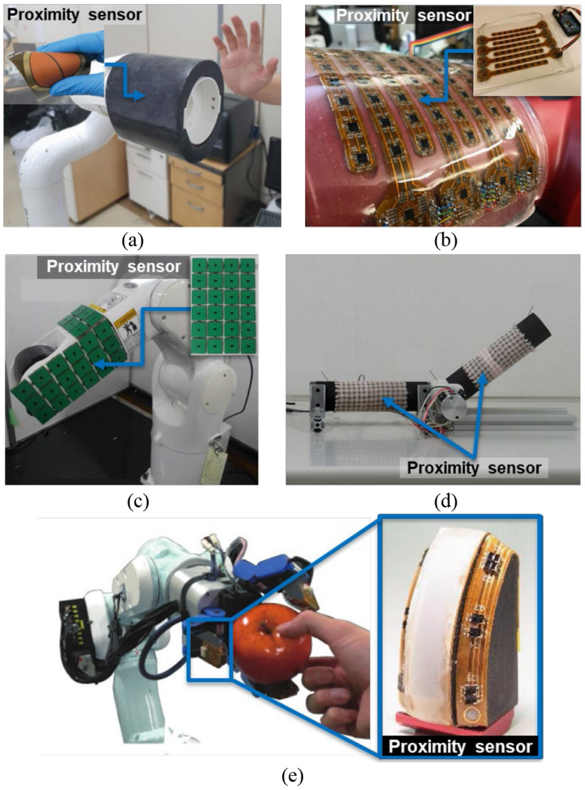
TABLE II
A SUMMARY OF RECENT REPRESENTATIVE ROBOT SKIN WITH PROXIMITY SENSING

Transductions	Functional elements	Sensing range [mm]	Sensor scale [mm]	Detectable materials	Year	Ref.
Inductive	Spiral coil electrode	0−300	100 × 100 × 2.75 (unit)	Acrylic resin, human, metals	2020	[57]
Inductive	Carbon micro-coils	0−150	32 × 32 × 0.6 (unit)	Copper, aluminum, plastic	2017	[83]
Inductive-capacitive	Planar spiral coil and electrode	0−5.6	− (unit)	Copper, aluminum, plastic	2018	[84]
Inductive-capacitive	Low temperature co-fired ceramic and electrode	0−10	17.5 × 17.5 × 0.3 (unit)	Metals	2019	[85]
Optical	VNCL4010 proximity and ambient light sensors	0−70	108 × 108 ×5 (8 × 8 array)	Human hand	2018	[53]
Optical	Photo-reflector	0–70	140 × 140 × 7 (5 × 5 array)	Bright objects	2015	[86]
Optical-capacitive	Time-of-Flight sensor and planar electrode	0−300	27 × 27 × 4 (unit)	Acrylic resin, human hand	2020	[87]
Capacitive	Conductive fabric	0−50	− (unit)	Human hand, aluminum, water, natural rubber, wood	2019	[88]
Capacitive	Planar electrode	0−120	100 × 70 × 5 (unit)	Human body, acrylic resin	2020	[89]
Capacitive	Planar electrode	0−20	146 × 146 × 0.13 (6 × 6 array)	Human hand	2021	[90]
Capacitive	Ionic materials based capacitor	0−10	50 × 50 × 0.8 (4 × 4 array)	Human hand	2020	[91]
Capacitive-resistive	Planar electrode and graphene	0−19	8 × 12 × 3.5 (unit)	Iron, plastic	2017	[92]
Electrostatic gating	Reduced graphene oxide	0−200	− (unit)	Human finger, object with positive/negative charges	2021	[93]
Electrostatic gating	Organic transistor	0−53	0.06 × 0.5 (unit)	Rubber, silicon, glass, plastic	2019	[94]
Electrostatic gating	Microsized organic crystal	0−8	− (unit)	Human finger, charged objects	2018	[95]

coils, even directly by measuring the varying magnetic field. Seung *et al.* [96] proposed a sensing system composed of capacitive force and inductive proximity sensing with a detection range of up to 150 millimeters and a spatial resolution of 3 millimeters for conductive materials. The key sensing element is carbon micro coils. Nguyen *et al.* [83] further improved the sensing system, achieving a higher spatial resolution of 2 millimeters. As shown in Figure 5(a), Nguyen *et al.* [57] developed a skin-type dual proximity sensor and applied it to a cobot body with a softcover. Combining the inductive and capacitive proximity sensing principle, their device with the dimensions of 100 × 100 × 2.75 millimeters^3 can detect an approaching human body up to 300 millimeters away. Multiple sensor modules can be easily fabricated with various dimensions and shapes so as to cover different contours of a cobot body.

2) Optical Sensing: Proximity sensors based on optical sensing principle are based on the reflected light intensity, return time interval of reflected light, or reflected light incident position, respectively. As shown in Figure 5(b), Hughes *et al.* [53] presented a flexible robotic skin that can detect proximity, which has the dimensions of 108 × 108 ×5 millimeters^3 and contains an 8 × 8 array of optical proximity sensors. When an object approaches within 20 centimeters, the intensity of the emitted light is reflected back to the naked sensor as a function of distance. In their design, the sensor was embedded in a layer of polydimethylsiloxane, resulting in reliable detection at distances up 70 millimeters. As shown in Figure 5(c), Tsuji *et al.* [87] developed a skin module with a dimension of 27 × 27 × 4 millimeters^3. Thanks to the combination of Time-of-Flight sensor and self-capacitance sensor, it is possible to obtain efficient measurements for distances ranging from 0 to 300 millimeters.

3) Capacitive Sensing: The proximity detection based on capacitive sensing principle uses conductive electrodes to generate and measure electric fields that would be interfered with approaching objects. The observed changes of the electric fields reflect the approaching distance and physical properties (e.g., materials type) of the object. As shown in Figure 5(d), Matsuno *et al.* [88] proposed a robotic skin



(a) (b)
(c) (d)
(e)

Fig. 5. Robot skin with proximity sensing function. (a) A skin-type dual proximity sensor with the inductive and capacitive proximity sensing principle by Nguyen *et al.* Reprinted with permission from [83]. Copyright 2021, IEEE. (b) A flexible robotic skin that can detect proximity by Hughes *et al.* Reprinted with permission from [53]. Copyright 2018, IEEE. (c) A proximity sensing array by Tsuji *et al.* Reprinted with permission from [87]. Copyright 2020, IEEE. (d) A skin-like proximity sensor based on conductive fabric by Matsuno *et al.* Reprinted with permission from [88]. Copyright 2019, IEEE. (e) Finger-covered proximity skin for secured grasping by Koyama *et al.* Reprinted with permission from [99]. Copyright 2019, Springer Nature.

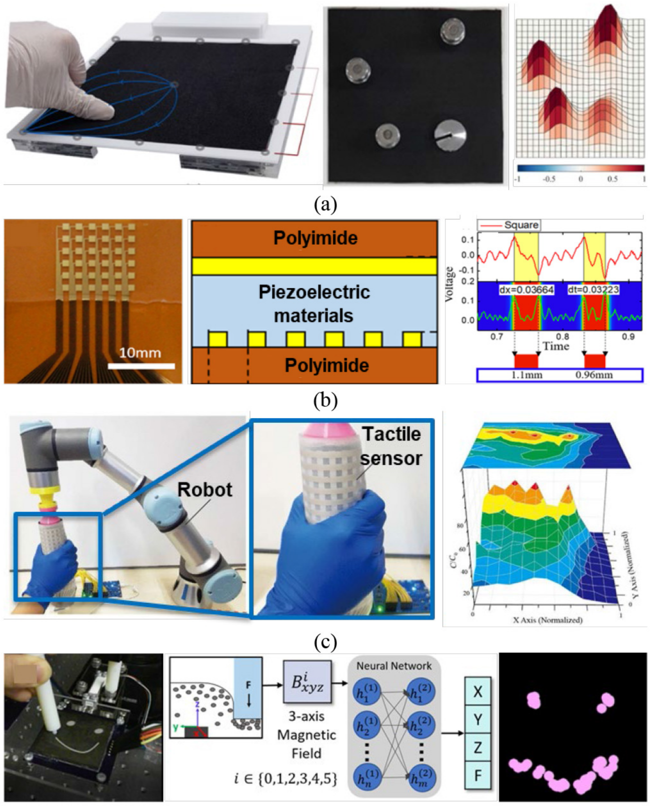


Fig. 6. Functional materials enabled methods for force- or pressure-sensitive robot skin. (a) Sensitive skin based on piezoresistive materials by Park *et al.* Reprinted with permission from [158]. Copyright 2021, IEEE. (b) Sensitive skin based on piezoelectric materials by Shin *et al.* Reprinted with permission from [111]. Copyright 2018, IEEE. (c) Sensitive skin based on ionic materials by Liu *et al.* Reprinted with permission from [124]. Copyright 2020, Authors. (d) Sensitive skin based on magnetic materials by Hellebrekers *et al.* Reprinted with permission from [129]. Copyright 2019, IEEE.

based on conductive fabric that can detect proximity by measuring electrostatic capacity. By continuously updating the reference capacitance, their device attached to a 2-link robotic arm can eliminate the influence of the environment, thereby ensuring stable and robust proximity measurements. Tsuji and Kohama [89] developed a skin sensor integrated with a self-capacitance proximity sensing module and a shock-absorbing structure, which has the dimensions of 100 × 70 ×5 millimeters^3. For a conducive object with an area of 100 × 70 millimeters^2, the sensor could detect it from a distance of 120 millimeters. In addition to the above body-covered proximity skin for human safety, finger-covered proximity skin can be used for secured grasping [97], [98]. As shown in Figure 5(e), Koyama *et al.* [99] developed a high-speed proximity sensor for the robotic fingertips to control the positions and postures of robot hand without contact before grasping, which means there is no fear of damaging the end-effector or the object.

4) Other Sensing Principles: In addition to the above transductions (i.e., inductive, optical, and capacitive sensing), proximity sensing can also be achieved by using the thermal field near the skin surface [92] and electrostatic gating [100]. Huang *et al.* [92] developed a flexible capacitive-resistive proximity sensor. In the thermal-resistive proximity sensing mode, the proximity sensor detected approaching objects with a certain temperature (e.g., plastic at 65 degrees Celsius and iron at 40 degrees Celsius) in the distance from 0 to 24 millimeters. Kedambaimoole *et al.* [93] developed a wearable proximity sensor based on reduced graphene oxide (rGO), employing the principle of electrostatic gating. The detected object functions as a gate controlling the flow of current in rGO, depending on the distance between the charged object and sensor. In such transduction, human finger has positive static charges on its surface, thereby inducing the resistance of the sensor to decrease when approaching.

5) Brief Summary: A longer detectable distance generally requires sensors based on inductive and capacitive transductions with a larger active area of functional elements. Optical proximity sensors are mostly based on commercially available sensing components and have a longer detection range. Compared to capacitive or inductive ones, optical-based sensors generally have limited detectable materials, and sensing performance varies with the surface condition of target objects. Since the functional elements of the above three transductions are coils, electrodes, and silicon-based electronic components, the proximity sensors based on them are easy to fabricate and integrate through a flexible printed circuit board, and easy to be incorporated to robot body. It is possible to improve the sensing performance (e.g., detection range and detectable materials) by leveraging the combination of several transductions in a single sensing device. Electrostatic gating principle provides a new way to sense proximity. The functional elements of it can be intrinsically flexible or stretchable with the proper material design. But the fabrication is relatively sophisticated and is complex than the other three principles. It also has limitations on the detectable objects that generally need to be charged.

B. Pressure Sensing

In past years, considerable efforts have been devoted to the development of robot skin with tactile sensing function to help cobots understanding the sense of touch. In this regard, force- or pressure-sensitive skin help host cobots locate the contact point or area and measure the interactive force or pressure, providing a computational basis for impairment estimation in an unintended collision [46], follow-up actions in a cooperation task [101], profile detection for surface topography measurements [102], and recognition of touch modalities in an affective interaction [51]. Generally, there are two strategies to achieve force- or pressure-sensitive skin: Functional materials enabled method and vision-based computation method.

1) Functional Materials: As shown in Figure 6, many functional materials are being used in force- or pressure-sensitive skin, such as piezoresistive materials [103]–[107], piezoelectric materials [108]–[111], piezocapacitive materials [112]–[115], triboelectric materials [116]–[119], iontronic materials [120]–[125], magnetic materials [126]–[129], biomimetic materials [130]–[133], and fiber-optic materials [134]–[136]. Table III summarizes the pressure-sensitive robot skin based on the above functional materials. Inspired by the interlocked dermis-epidermis interface in human skin, Boutry *et al.* [133] developed a soft electronic skin with

TABLE III
A SUMMARY OF RECENT REPRESENTATIVE ROBOT SKIN WITH PRESSURE SENSING BASED ON FUNCTIONAL MATERIALS

Transductions	Detection range	Durability [Cycles]	Response time [ms]	Spatial resolution [cm^{-2}]	Sensitivity [kPa^{-1}]	Frequency range [Hz]	Year	Ref.
Piezoresistive	3.7 Pa−75 kPa	8000	20	16	134	0.2−1	2020	[103]
Piezoresistive	0.425 Pa−2 kPa	20000	0.44	−	11668.6	0.25−1.5	2020	[104]
Piezoresistive	10 Pa−100 kPa	5000	3	−	39.4	1−4	2020	[105]
Piezoresistive	7.4 Pa−1000 kPa	10000	23	1.78	20.9	1	2020	[106]
Piezoresistive	50 Pa−600 kPa	33000	60	64	5.61	0.5−2	2021	[107]
Piezoelectric	2 Pa−10 kPa	12000	−	0.056	0.8 V	1−5	2020	[108]
Piezoelectric	15.4 kPa−27.6 kPa	−	240	0.38	0.044 V	2	2019	[109]
Piezoelectric	≤ 800 kPa	80000	10	4.94	0.0077 V	2.5−30	2021	[110]
Piezocapacitive	0.5 Pa−80 kPa	10000	27.3	0.36	8.31	1−4	2021	[112]
Piezocapacitive	2 Pa−200 kPa	500	100	1.23	0.28	0.2	2019	[113]
Piezocapacitive	1.9 Pa−145 kPa	9000	50	0.16	0.159	1	2020	[114]
Piezocapacitive	3.4 Pa−50 kPa	1000	33	16	0.43	−	2021	[115]
Triboelectric	16.4 Pa−45 kPa	2500	−	0.54	367 V	2−4	2021	[116]
Triboelectric	19 Pa−100 kPa	5000	180−200	1	650 V	−	2020	[117]
Triboelectric	19 Pa−32 kPa	7200	−	0.11	1.67 V	2−3.5	2019	[118]
Triboelectric	≤ 400 kPa	500	−	1.85	0.16 V	0.83−5	2021	[119]
Iontronic	300 Pa−2500 kPa	10000	8	4	0.55	−	2021	[120]
Iontronic	1.12 Pa−32.35 kPa	7000	43	1	131.5	1	2019	[121]
Iontronic	13 Pa−3063 kPa	5000	5	1	9.17	0.25−1	2021	[122]
Iontronic	7.5 Pa−200 kPa	5000	30	4	13.5	1−1.5	2020	[123]
Iontronic	0.08 Pa−340 kPa	5000	9	6400	220	1	2020	[124]
Magnetic	≤ 230 kPa	30000	15	2500	0.27	0.17	2021	[126]
Magnetic	70 Pa−330 kPa	1000	90	0.23	0.055	0.01−5	2021	[127]
Magnetic	46.67 kPa−800 kPa	−	−	33.33	−	−	2019	[128]
Biomimetic	0.5 Pa−10 kPa	28000	90	0.25	83.9	0.5−2	2019	[130]
Biomimetic	20 Pa−30 kPa	4000	8	0.25	1000	1	2020	[131]
Biomimetic	4.4 Pa−15 kPa	10000	130	0.083	151.4	0.21−1.41	2020	[132]
Fiber-optic	≤ 292 kPa	200	−	−	0.021	−	2020	[134]
Fiber-optic	7 mPa−10 kPa	10000	0.01	1.78	1870	1000−20000	2020	[135]
Fiber-optic	0.45 kPa−10 kPa	1000	−	−	1220	0.4−1	2020	[136]

TABLE IV
A SUMMARY OF RECENT REPRESENTATIVE ROBOT SKIN WITH PRESSURE SENSING BASED ON VISUAL COMPUTING

Sensors	Size[a] [mm]	Weight [g]	Sensing field [mm^2]	Image resolution	Image FPS[b]	Component cost [$]	Year	Ref.
GelSlim 3.0	37 × 80 × 20	45	675	640 × 480	90	25[c]	2021	[140]
GelSlim 2.0	50 × 172 × 25	222	1200	640 × 480	90	–	2018	[141]
GelSight (prototype)	40 × 80 × 40	–	252	640 × 480	30	30	2017	[142]
GelSight (product)	129.1 × 35.4 × 81.5	340	737.1	2048 × 1536	122	–	2021	[143]
Digit	20 × 27 × 18	20	304	640 × 480	60	15[c]	2020	[144]
Ominitact	30 × 30 × 33	–	3110	400 × 400	30	600	2020	[145]
TacLINK	80 × 280	–	49763	640 × 480	30	150	2020	[146]
VTacArm	58 × 175	–	15700	1640 × 1232	40	–	2020	[147]

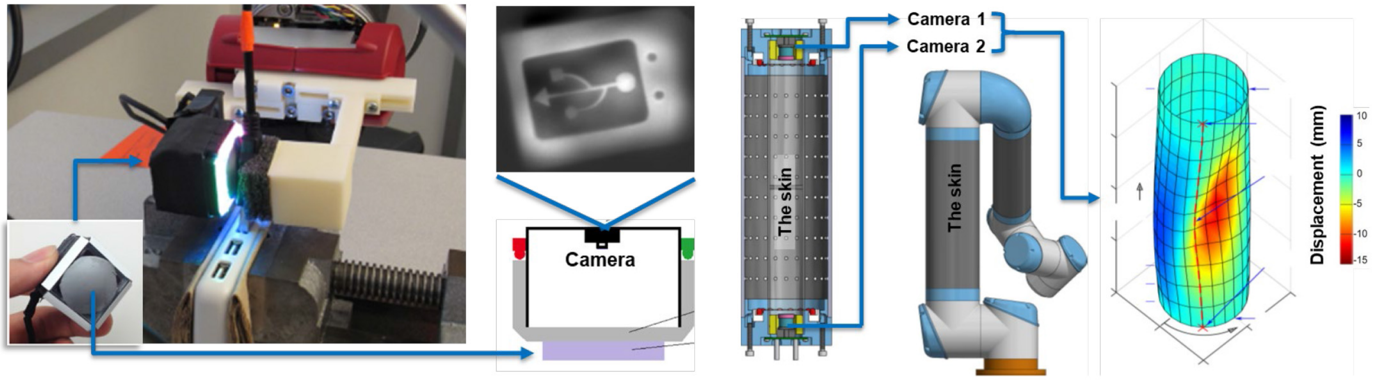
[a] The size is with dimension of Length × Width × Hight or Diameter × Hight.

[b] FPS denotes frames per second.

[c] Considering the manufacturing of 1000 pieces.

a three-dimensional structure that mimics the hills and mechanoreceptors to detect normal and tangential forces. Their device was fixed on the gripper of a cobot and capable of detecting the slip for the cobot to interact with fragile objects, such as raspberries and ping-pong balls. By using the new detection principle, the dependence of the sensor on functional materials to improve sensing performance can be reduced. Yoshimoto *et al.* [137] proposed a novel, low-cost, and universal tactile sensing system for imaging pressure distribution by leveraging a tomographic approach with conductors rather than piezoresistive materials in traditional electrical impedance tomography, which successfully estimates the pressure distribution in sheet- and finger- shaped sensing areas. The contact location has an error rate of 5.68 ± 2.78%, while the local pressure has an error in the range 0.0269 −0.0509 megapascals for a maximum pressure of 0.50 megapascals. Wu *et al.* [138] reported a tactile sensor integrated with an inductance-capacitance oscillation circuit. The circuit enables the direct transduction of force stimuli into digital-frequency signals that are similar to human stimuli responses. Their sensor exhibits a high sensitivity of 4.4 kilopascal^{-1} and a very low detection limit of 0.3 pascals, which is less than the sensing threshold value of human skin.

2) Vision-Based Computation: The vision-based computation method is an effective way to improve the robotic touch by using visual data [139]. The characteristics of some recent prototypes of vision-based sensors [140]–[147], are summarized in Table IV. A typical example is GelSight fingertip-style tactile sensor [148], [149], as shown in Figure 7(a). Calandra *et al.* [150] proposed a learning model to enable a robot to learn regrasping policies from raw visuotactile data of the GelSight tactile sensor, allowing the robot to



(a) (b)

Fig. 7. Vision based methods of force- or pressure-sensitive robot skin. (a) Fingertip-style vision based tactile sensor by Li *et al.* Reprinted with permission from [149]. Copyright 2014, IEEE. (b) Whole body vision based tactile sensor by Duong *et al.* Reprinted with permission from [146]. Copyright 2021, Authors.

"gently" grasp an object with significantly reduced force. To further reduce the form factor and enhance mechanical reliability, Lambeta *et al.* [144] demonstrated a vision-based tactile sensor that is open-sourced. The sensor is capable of manipulating glass marbles in-hand with a multi-finger robotic hand by training deep neural network model-based controllers. The vision-based tactile sensing method is able to be further scaled up for large-area sensing with acceptable wiring issues [147]. As shown in Figure 7(b), Duong and Ho [146] developed a large-scale vision-based tactile sensing system for a robotic link, which is able to form a whole-body tactile sensing robot arm. The sensor not only provides tactile force feedback but can modulate stiffness by alter inflation pressure level, which could be helpful to reduce collision force between human and robot [26]. Although considerable efforts have been devoted to developing vision-based tactile sensors [151], [152], they cannot detect a thermal stimulus and high-frequency vibration due to inherent limitations of the working principle. An effective way to overcome the above limitations is to 'active' the deformable components of the sensor. For example, Shi *et al.* [153] developed a vision-based tactile sensor for the detection of temperature by monitoring color changes of the deformable components with temperature.

3) Machine Learning Assisted Sensing: Machine learning methods have also been regarded as an effective and powerful tool for analyzing sensing signals, enabling sensors to interpret much useful information behind the detected signals [5]. Some powerful learning algorithms make the robot hand be capable of sorting objects [154], manipulating objects [144], and classify interactions [15]. In addition to these general-purpose applications, there are some exciting advancements in applying machine learning for improving sensing performance. These advancements are mainly emerging in pressure sensors which can provide richer data (i.e., high spatial resolution, large sensing nodes, or multiple directions in a sensing node) and useful information behind the data (e.g., translational and rotational torque, shear force for slippage detection, contact geometry, etc.) than other types of sensors. Existing machine learning methods can be utilized in the sensor calibration for: 1) extending spatial resolution of limited sensing elements [126], [155]; 2) improving the adaptability of mass production long-term usage [156]; compensating hysteresis induced by the viscoelastic property of the polymeric substrate materials [157]; 4) decoupling multimode deformations [134]; and 5) enhancing measurement reliability of large-area sensor array [15], [158] or some specific transductions [159], [160].

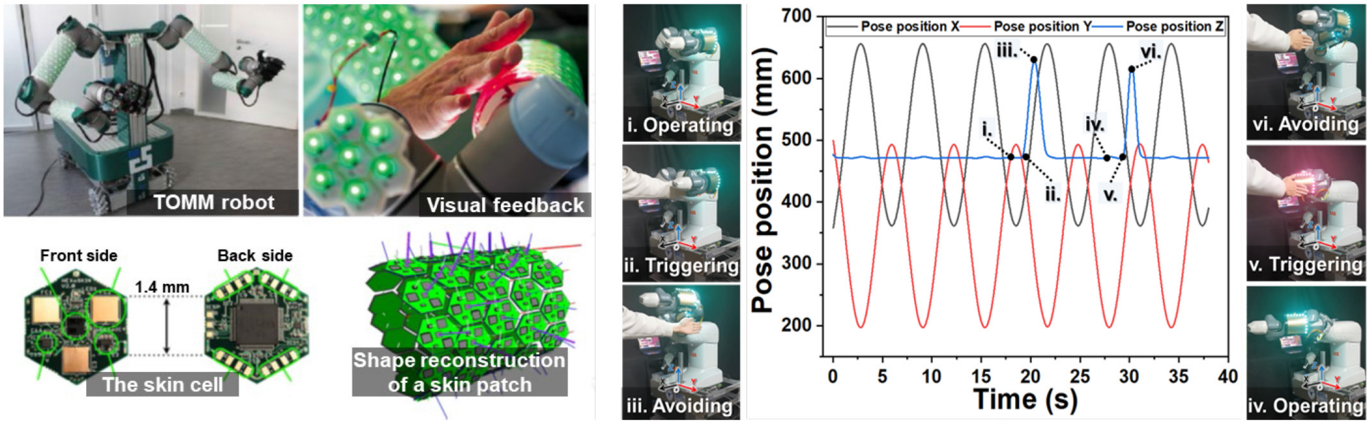
4) Brief Summary: Numerous efforts have been devoted to developing novel functional materials and transduction mechanisms for pressure-sensitive skin. Some of them have been comprehensively studied, accompanied by an in-depth comparison [161], exclusively of magnetic and fiber-optic materials. As shown in Table III, the emerging studies of robot skin based on these two materials show an explicitly outperformed performance than both human skin and other types of robot skin in spatial resolution and frequency response, respectively. Particularly, some high-impact studies of fiber-optic materials have validated the promising application in robotics [162]–[165]. In addition, a combination of different transduction mechanisms and various functional materials may improve pressure sensing performance [166]. Another interesting ongoing technology for pressure sensing is vision-based sensors, which have been scaled up to a robot arm. Thanks to the camera embedded into the sensor, cobots could directly obtain rich contact information, such as geometry, contact force, and rotational or translational slip. Since the raw data is in the form of images, machine learning algorithms can be directly deployed to obtain high-dimensional information of contact, such as softness and surface texture.

C. Temperature Sensing

Despite the above advancements in proximity and pressure sensing, temperature gradient detection capability is also required for material identification and object manipulation [154], [167]. Similar to pressure sensing, the transduction mechanism of temperature sensors is based on resistive materials [74], [168]–[173], capacitive materials [75], thermoelectric materials [174]–[176], iontronic materials [73], [76], [177], biomimetic materials [178], [179], and fiber-optic materials [180]. The key characteristics of recent representative

TABLE V
A SUMMARY OF RECENT REPRESENTATIVE TEMPERATURE SENSORS

Transductions	Sensitivity [°C^{-1}]	Detection range [°C]	Durability [Cycles]	Response time [s]	Recovery time [s]	Susceptible to hysteresis	Spatial resolution [cm^{-2}]	Year	Ref.
Resistive	0.31%	18–53.5	8	6.4	44	Yes	5.5	2021	[168]
Resistive	2.89%	15–40	20	10	–	No	0.67	2021	[74]
Resistive	9.2%	25–70	3	0.05	–	No	1	2019	[169]
Resistive	0.83%	22–70	–	0.1	–	–	1	2018	[170]
Resistive	1.64%	40–110	6	19.5	1.16	No	–	2019	[171]
Resistive	0.284%	30–110	4	–	–	–	0.7	2020	[172]
Resistive	0.69%	≤120	1000	0.106	0.281	–	0.36	2020	[173]
Capacitive	10.4%	20–50	55	–	–	No	4	2021	[75]
Thermoelectric	109.4 μV	28–58	7	0.37	0.93	–	0.28	2020	[174]
Thermoelectric	25 μV	25–85	10	1	–	–	2.12	2020	[175]
Thermoelectric	10.2 mV	15–65	5	22	–	No	0.1	2019	[176]
Iontronic	24%	30–80	–	1.4	–	–	0.36	2020	[73]
Iontronic	1.9%	0–80	25	–	–	Yes	0.53	2020	[177]
Iontronic	1.23%	30–65	400	16.5	–	No	10	2019	[76]
Biomimetic	0.8%	20–130	–	10	–	–	1	2019	[178]
Biomimetic	6.6%	0–45	215	1	9	No	0.6	2017	[179]
Fiber-optic	1.8%	25–70	3	4.5	12.5	No	–	2019	[180]



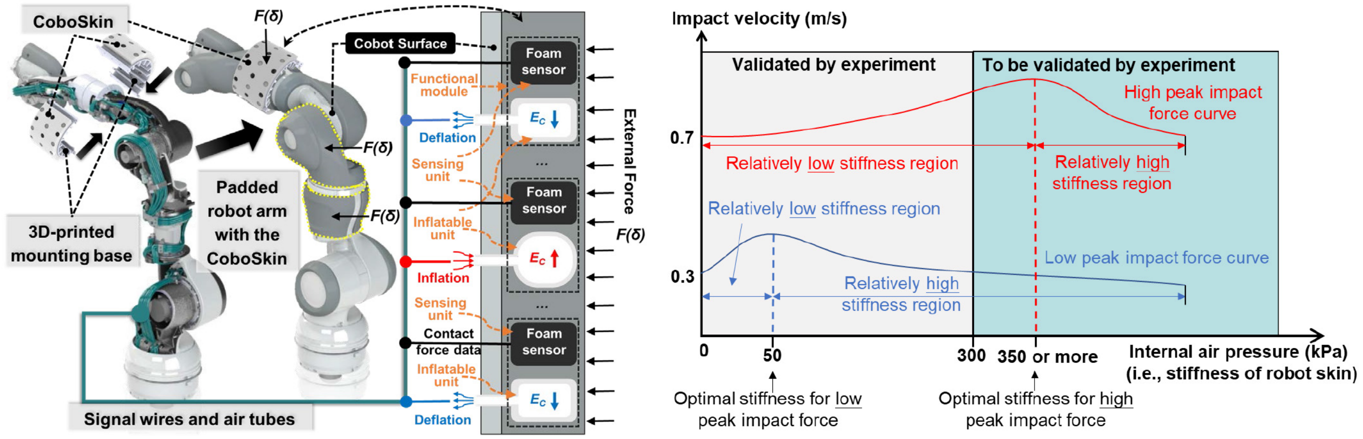
(a) (b)

Fig. 8. Robot skin with visual feedback. (a) A robot platform is partially covered with user-interactive robot skin by Leboutet *et al.* Reprinted with permission from [17]. Copyright 2018, IEEE. (b) The safety mode of robot skin with visual warning from green light to red light by Gbouna *et al.* Reprinted with permission from [90]. Copyright 2021, IEEE.

temperature sensors based on the above materials are summarized in Table V. Soni *et al.* [181] demonstrated a skin-like printed temperature sensor, of which the distinguishing feature is the highly temperature-sensitive layer. The sensor has a thermal response range from 25 to 100 degrees Celsius and a sensitivity of 1.09% per degree Celsius. Inspired by the pit membrane that has the highest sensitivity in nature and is leveraged to locate warm-blooded prey at a distance, Di Giacomo *et al.* [179] reported a biomimetic temperature-sensing layer – pectin film – for artificial skin. By mimicking the sensing mechanism of pit membranes, their method could successfully parallel the record performances of pit membranes, showing a sensitivity of at least 10 millikelvins in a wide temperature-sensing range (45 kelvins). Overall, resistive temperature sensors are still dominated this research domain and few studies focus on the fiber-optic materials. Research trends in temperature sensors based on brand-new iontronic materials shows a promising solution to improve the sensitivity and spatial resolution as well as decouple the mechanical deformation and sensing response. In addition, appropriated codesign of advanced sensing and actuation mechanisms may endow robots with unprecedented functionalities, empowering them in challenging applications. For example, thermal regulation has been validated as a useful way to improving temperature sensing, enabling robots to sort objects [154].

D. Sensory Feedback

1) Sensory to Visual Feedback: User-interactive robot skin with rapid and direct visualization feedback of sensing signals can intuitively reflect the contact position [17] and issue injury warning timely for human operators, as shown in Figure 8(a). Inspired by a bioluminescent jellyfish, Zhang *et al.* [182] proposed an electronic skin with dual-mode response characteristics to the applied pressure: electrical response and optical response. The electronic skin can detect notable changes in electrical signals in the low-pressure region (below 60 kilopascals) and emit bright luminescence in the high-pressure region (above 60 kilopascals), which, respectively, imitates the functions of the mechanoreceptors (i.e., tactile



(a)

(b)

Fig. 9. Robot skin with the ability of stiffness tuning. (a) Illustration of the working principle of safety improvement by altering the stiffness of robot skin according to the predicted impact velocity or the limited peak impact force by Pang *et al.* Reprinted with permission from [26]. Copyright 2021, The Authors. *Ec* is the elastic modulus of covering materials. (b) When the limited peak impact force is below 30 newtons, or the impact velocity is below 0.3 meters per second, the optimal stiffness is obtained by altering internal air pressure below 50 kilopascals by Pang *et al.* Adapted from [26].

sensing) and nociceptors (i.e., pain warning) in the biological skin. Wang *et al.* [49] also reported an electronic skin with tactile sensing and visual warning for detecting robot safety. The electronic skin was applied to a cobot body and could simultaneously issue the colors varying from light green to dark blue according to the applied external force. Gbouna *et al.* [90] proposed a scalable user-interactive robot skin. The skin can perform in safety mode for active collision avoidance [Figure 8(b)] or in interaction modes for HRI by recognizing gestures. Visual feedback of this skin can be employed for potential collision warning or for gesture trace indexing.

2) Sensory to Vibrotactile Feedback: With the continuous advancements in codesign of sensors and mechanical actuators, robot skin is undertaking a transformation to a sensing-to-actuation coupled robotic device for augmenting HRI [183]. Vibrotactile feedback has attracted more and more attention in developing such robotic devices. In teleoperation, it can provide high-fidelity feedback of cobots interacting with remote environments. It can also be applied to prosthetics for restoration of feeling to amputees or even for remote communication between deaf-blind people and cobot [184]. Yun *et al.* [59] proposed an integrated visual-haptic interface. By leveraging a dielectric elastomer microactuators array, their device can produce programmable vibrotactile response up to about 30 times of human-perceivable thresholds at a localized area. Ozioko *et al.* [184] developed a tactile sensor with the integrated flexible actuator, providing pressure sensing with wireless vibrotactile feedback in a prosthetic hand. Their sensor is capable of self-controlled simultaneous sensing and actuation, illustrating a promising application in future tunable robot skin to extract richer information.

3) Brief Summary: Most actuation schemes based on advanced materials are functionally validated in a unit prototype. This is similar to the research in sensing function, because most interesting materials have relatively sophisticated fabrication, codesign process, and actuation power source, limiting the scalability. On the other hand, some studies presented scalable or large-area robot skin based on commercially available electronic components but with simple actuation of visual feedback.

E. Stiffness Tuning

Endowing robot skin with the stiffness-tuning capability by coupling sensors and actuators is an emerging research topic. A pilot study by Kim *et al.* [185] demonstrated a soft inflatable skin with self-contained tactile sensing for safe HRI, which illustrated the reduction of peak collision force could benefit from stiffness-tuning capability. In their experimental results, as the air pressure inflated into the skin increased, the peak impact force tended to decrease. However, if the internal air pressure was higher than 13 kilopascals in the peak force increased again, since the skin became too stiff to absorb impact energy as much as possible at high air pressure levels. Despite the above advancements in their methods, the initial impedance of their device is affected by the inflation process. Furthermore, the volume of their skin becomes large when the skin is inflated, which may interfere with the robot motion. By integrating inflatable actuators and force sensing units, Pang *et al.* [26] proposed a soft robot skin with variable stiffness for safer HRC. As shown in Figure 9, the skin can alter its stiffness without affecting the initial impedance of sensing units and the robotic motion of host robots. Thanks to the capability of stiffness modulation, their skin is capable of not only reducing the peak collision force but also extending the sensitivity of sensing units. They further generalized the design of the skin to an off-the-shelf cobot body [60]. The stiffness-tuning capabilities of the above robot skin are actuated by the pneumatic power source and cannot cover the entire cobot body. The sensing function is also supplely narrowed down to contact force with limited spatial resolution. They are inherently limited by the original application-orientated codesign of sensing and actuation. Stiffness tuning has gained much attention with the development of soft robots and continuum robots, resulting in a diverse range of methods to achieve it.

Thus, exploring other stiffness-tuning mechanisms with the constraints of sensing or the application requirements may further improve sensing capability, interactivity, and safety.

V. OPEN CHALLENGES AND DIRECTIONS

Despite the aforementioned significant progress in the development of advanced functionalities, there are several open challenges and directions towards the real implementation of robot skin.

A. *Seamless Coverage and Uneven Distribution*

An important characteristic of robot skin is the distribution throughout the body of the cobot, which is still a big challenge. Human skin, as the largest organ in the human body and houses a huge nerve network composed of a variety of sensory receptors that are widely distributed with different-sized receptive fields [186]. Muscles and human skin are tightly coupled by the deep fascia which is similar to connective tissue, enabling the advanced function of variable stiffness. Similarly, the sensors and actuators of the ideal robot skin should also readily scale to thousands in number and be unevenly distributed on the whole body with variable spatial densities depending on the sensing and actuation requirements [187]. In the special case of sophisticated tasks, some body parts may need to be covered with high spatial resolution robot skin. On the other hand, by covering some body parts with a low-resolution robot skin, it is possible to address simple stimuli detection, actuation, and motor control [44]. For example, robotic hands, especially fingers, should have higher spatial resolutions in tactile sensing than other parts for dexterous and stable manipulation. However, only a few studies have embarked upon developing a full-body skin system for cobots and there is still a large room for improvements and relevant contributions to address this challenge [188]. In the future, whole-body robot skin may have only a few gaps with a certain width between adjacent robotic links to ensure the rotation of cobot joint, which may be the only way to make a distinction between humans and future cobots. Future cobots may even be covered with stretchable robot skin on their joints (e.g., knuckle, elbow, knee) for exploration [42].

B. *Dense Connectivity of Whole-Body Robot Skin*

Processing complex sensory information from whole-body robot skin requires efficient signaling, sampling, and transmitting methods. Increasing density and quantity of sensors and actuators while scaling up robot skin into a whole-body coverage normally calls for a larger number of interconnecting wires to support new components, i.e., skin units. The increasing number of wires imposes burdens on dexterity and the time required to scan a set of skin units. To mitigate this burden, skin units are normally designed in a matrix form [5]. However, simply scaling down a passive matrix architecture to increase the density will increase cross-talk between interconnects [189]. These problems can be addressed with an active matrix that pairs each sensor with a transistor to provide local signal amplification and allows sensors to take turns transmitting information, thereby reducing the power consumption compared to passive matrices [77]. However, the matrix design has the disadvantage of low robustness due to the susceptibility to row-/column-wise failures [190].

Except for the matrix form, net-structured connection schemes based on traditional cables or flexible/stretchable interconnections provide alternative solutions to wiring complexity [188]. For example, in a whole-body net-structured robot skin system, the skin unit with a self-contained microcontroller for local computing connects multiple neighboring skin units to form one entity called a skin patch. Several skin patches are connected to a distributed processing unit. All distributed processing units are connected to a high-performance centralized processing end. Because the transmission bandwidth and power supply of the serial bus are limited, as the number of sensors increases substantially, a large number of addressing lines will be difficult to manage no matter in a matrix or net structure form. Although cable is common practice in the industry and some progress has been made on flexible/stretchable interconnects, it is still insufficient for whole-body skin, which may interfere with the sensors embedded into robot skin or the motor control of the host cobot [188]. To complement this promising method, wireless data transmission would be an ideal solution to largely reduce the wiring complexity, including traditional cables and flexible/stretchable interconnects [191]. However, the interference among a large number of closely placed skin units and patches poses a big hindrance and questions its reliability over the wired data transfer. A large amount of power consumption also issues with wireless transmission, which may be addressed by wireless power transmission and energy-autonomous design of skin units [192], [193].

C. *Long-Term Durability and Inherent Harmlessness*

Human living environments have a variety of practical factors that may influence the long-term durability and stability of robot skin, e.g., splashed with water when cobots frequently assist seniors taking a shower or clean house furnishings, and spray of chemical disinfectant or exposure of ultraviolet light when cobots employed in combating infectious diseases in an isolation ward for taking care of patients. These factors should be carefully considered in the initial material design of robot skin, since they will influence the sensing performance if robot skin is not waterproof or not resistant to ultraviolet light. Furthermore, as human skin can repair itself when experienced physical trauma, an ideal robot skin should equip with a similar capability of repeatable self-healing or wound-healing, which can significantly increase the lifetime of devices when they are damaged [194]. In order for practical applications, robot skin is required to unconsciously repair damage at room temperature, especially repeated damage at the same location [195]. In addition, robot skin should remain functional while being subject to physical harm to guarantee continuous sensory feedback for safe robotic motor outputs and instant decision making, which is also an important capability of human skin [187]. On top of that, robot skin will not be purely biological devices but a hybrid integration that combines the best features of polymer chemistry and bioengineering [196], [197]. However, advanced materials technologies have the potential to be harmful and bio-incompatible. As a result, badly designed robot skin could be devastating to users' health. How to control the misuse of harmful materials in robot skin will therefore be a real challenge.

D. Other Enabling Technologies of System Synthesis

There is no unique technology that can satisfy all requirements of future cobots. Apart from the abovementioned promising technologies in the component aspect (i.e., robot skin), a combination of different technologies should be pursued to achieve a system synthesis for fully addressing the emerging features of cobots. The demanded features remain constant challenges, and joint efforts are needed to evolve standards to integrate cobots as companions. For instance, synchronous efforts should be devoted to robotic system architecture (e.g., inner compliant mechanisms and deformable components of cobots as well as outer computer vision and motion capture system) and motor control algorithms (e.g., power and force limitation control) for enhancing safety assurance capability [26]. Haptic signals in immersive teleoperation systems are bidirectionally exchanged over the network [33]. It involves human operators and a closed global control loop between the human operators and cobots. Significant efforts should therefore dedicate to develop ultra-fast and high reliable communication technologies for ensuring systemic stability and teleoperation quality since they are very sensitive to communication delay [23]. Affective interaction highly depends on the intelligent feature extraction and pattern recognition, i.e., affective computing of tactile information collected by robot skin. The enormous distributed tactile signals desire to be processed locally at first to identify and estimate the affective state from touch, followed by the transmission to cobot brain for actuation or motor control [39]. Augmented by other advanced technologies in Healthcare 4.0, such as edge computing and fog computing, Internet of Things, AI, big-data analytics, and blockchain, the robot skin system will truly make cobots capable of offering the demanded features [24], [25].

VI. CONCLUSION

In conclusion, the application scenarios of cobots are extending from traditional manufacturing to the services sector. Cobots have the potential to deliver human care services in the future while equipping with demanded features, including safe collaboration, immersive teleoperation, and affective interaction. Robot skin tightly coupled with multimodal sensing and self-contained actuation may play an important role in addressing these features by improving cobot safety, giving intuitive feedback, providing natural interfaces. As a potential enabler, robot skin is expected to be capable of proximity sensing, pressure sensing, temperature sensing, sensory feedback, and stiffness tuning, which are required for directly powering fundamentals of sensing and actuation desired in demanded features.

Despite the existing experimental advancements in expected functionalities of robot skin, several pivotal issues still line in the real implementation of robot skin to cobots. Future research on large-area and eco-friendly robot skin prototypes for cobots should focus on advanced design, fabrication, and transmission technologies: 1) to enhance the physical scalability and adaptability of robot skin in multiscale and arbitrary shape for full-body and seamless coverage; 2) to enable the efficient transmitting of a tremendous volume of data from multimodal sensors of robot skin to processing units and back to self-contained actuators or robotic motors; and 3) to improve the long-term stability and ensure harmlessness to human health. In addition to the above points of the component level, significant synchronous efforts should also be devoted to robotic system architecture, motor control algorithms, affective computing, and other advanced technologies in Healthcare 4.0 to augment robot skin at the system level and constitute standards for guiding systemic design, since every demanded feature is valid by a system synthesis.

Some possible solutions to the above three questions may be: 1) Highly integrated multiple sensing modalities and actuation functionalities in a modular skin unit [188], [198], [199]; 2) Ultra-low latency and highly reliable wireless networked sensing/control system [200] with AI-based model-free optimal design [201], edge computing for localized intelligence to largely reduce the dimensions of transmitted data [202], or encoding the data in spike form [139]; and 3) Development of advanced biocompatible and self-healing materials that can withstand extreme or field environments [8], respectively.

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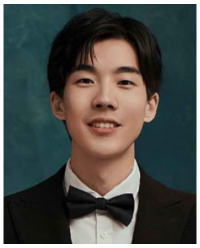

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