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Smart Stretchable Electronics for Advanced Human–Machine Interface

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The recent development of human–machine interface (HMI) involves advances in wearable devices that safely interact with the human body while providing high mechanical compliance. Various cutting-edge technologies such as highly stretchable electronics, multiple sensor fusion, and wearable exoskeletons have enabled a higher level of interactivity. Notably, recent developments using machine intelligence have achieved unprecedented performance and solved various challenges. Herein, the recent progresses in stretchable HMI including stretchable sensors, stretchable actuating systems, and machine intelligence-aided stretchable devices are presented, and their principles and working mechanisms are discussed.

1. Introduction

The human–machine interface (HMI) provides a direct pathway between humans and machines. They have many roles in industries, healthcare, and entertainment. Recent advancements in soft sensors and actuators have unleashed the higher potential of HMI devices for its mechanical compliance, which provides a comfortable environment to the user.[1–5]

An HMI is a bidirectional communication interface that is divided into human-to-machine (H2M) systems and machine-to-human (M2H) systems. H2M devices include sensors for measuring command signals such as touch,[6–8] voice,[9,10] and gesture,[11–14] which allow for better system control, and measurement systems for measuring electrophysiological signals such as electromyography (EMG), electrocardiography (ECG), and electrooculography (EOG).[15–19] M2H devices provide electrical, thermal, visual, or mechanical feedbacks that simulate various sensations.[20–22]

H2M control systems use sensors with various mechanisms. These include strain sensors that directly measure deformations due to human motions or stretchable electrodes, which indirectly measure electric signals of the muscle. The performance of these sensors has been greatly improved in recent years through the integration of multiple functions, logic circuitry, and multidimensional detecting ability.

Although majority of soft HMI devices concentrate on H2M systems, M2H system with a stretchy form is on the rise due to increased demand for wearable virtual and augmented reality (VR and AR) devices. These technologies include tactile feedback, thermal sensations, and wearable assistive devices. As these system fabrications into stretchable forms require sophisticated technologies, only few reports of fully stretchable M2H devices exist.[23–26]

Recently, HMI device performances have been improved with the assistance of machine intelligence.[27–34] These sophisticated electronic systems allow for the prediction of body motions with few sensors,[35,36] detection of objects,[37,38] and decoding neural command signals.[39]

In this article, we review the recent advancements in stretchable electronics for HMI devices in three parts: 1) stretchable sensors, 2) stretchable actuating systems, and 3) intelligence-aided systems. A systematic diagram of these main parts is shown in **Figure 1**.

Three main categories of stretchable sensors are presented to discuss their recent developments. Mechanical sensors play an important role in HMI through the development of motion tracking strain sensors and tactile sensors (pressure and temperature) that mimic the human sensory system. Electrical sensors extract motion and user intention by measuring electrical signals generated from the muscle and brain. Moreover, recent developments in integrated systems of logic circuits and wireless platforms will be further reviewed.

Stretchable actuating systems are a great alternative to rigid exoskeletons and various human assistive devices. This system has recently attracted considerable interest due to the tactile

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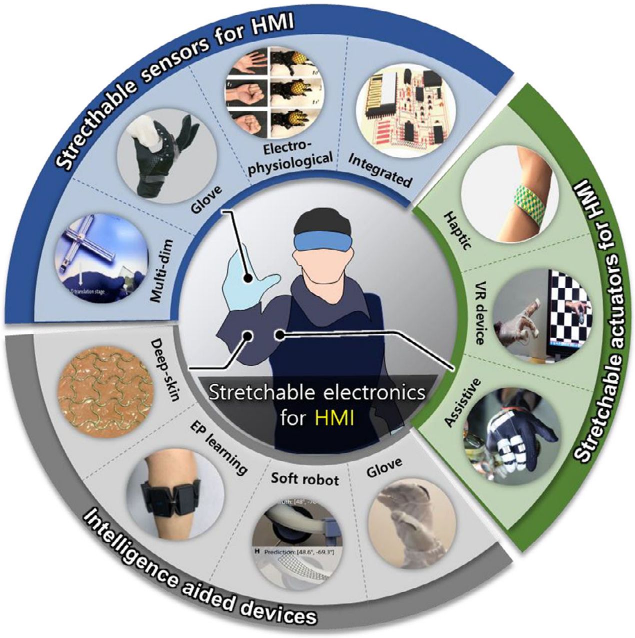

Figure 1. Compositions of stretchable HMI devices. Multidimensional sensor: Reproduced with permission.[40] Copyright 2015, American Chemical Society. Glove-type sensory system: Reproduced with permission.[41] Copyright 2015, Wiley-VCH. Electrophysiological signal measuring sensors: Reproduced with permission.[42] Copyright 2020, Springer Nature. Integrated system with wireless sensor module: Reproduced with permission.[43] Copyright 2020, AAAS. Wearable haptic device: Reproduced with permission.[44] Copyright 2019, American Chemical Society. Wearable haptic device for VR applications: Reproduced with permission.[45] Copyright 2019, Springer Nature. Wearable assistive device: Reproduced with permission.[46] Copyright 2015, IEEE. Deep-learned skin decoding finger motions: Reproduced with permission.[36] Copyright 2020, Springer Nature. Learning platform of electrophysiological (EP) signals: Reproduced with permission.[33] Copyright 2018, IOP Publishing Ltd. Soft robotic proprioception: Reproduced with permission.[47] Copyright 2018, AAAS. Gesture recognition machine learned glove: Reproduced with permission.[38] Copyright 2020, Wiley-VCH.

feedback information for the user. Moreover, recent developments in intelligence-aided stretchable electronic devices will be covered. They provided key advancements in sensor detection capabilities, overcoming sensor hysteresis, and controlling soft robotic proprioception.

2. Stretchable Sensors for HMI

Stretchable sensors are necessary for intimate HMI. Stretchable mechanical (strain, temperature, and pressure), and electrical sensors are typically studied to better the degrees of freedom in controlling robots and mimic human senses.[40–42,48–58] Various materials such as grapheme,[49,56] Ag nanowires,[40,48,49,57,59] carbon nanotubes[60,61] (CNTs), hydrogel composites,[62] and liquid metals,[63,64] have been proposed for stretchable sensors. In addition, to increase stretchability, structures such as serpentine that are robust to external deformations have been implemented in circuit designs.[49,51,52,55,59,65,66] Recent studies have paved the way for actual applications by solving hysteresis,[53,63,67] conformability,[42,51,52,55,56,59,62,64,68–70] sensitivity issues,[40,48,62] and so on. Examples of stretchable sensors are briefly shown in **Table 1** and **2**.

2.1. Mechanical Sensors

Studies on stretchable mechanical sensors show that they outperform traditional rigid board sensors in terms of performance (conformability, stretchability, and sensitivity). Sensors such as stretchable strain,[40,48,49,60,61] pressure,[70,73] temperature sensors,[66,69,74] and integrated devices[41,50,54] with several stretchable mechanical sensors have been introduced, thereby making HMI possible.

Attaching stretchable strain sensors to finger joints is a simple way to measure finger movements,[48] and using stretchable pressure sensors simultaneously enables the analysis of precise grasping action due to the mapped contact pressure distribution.[41,70,73] One group demonstrated a stretchable strain–pressure sensor that is mounted on a wearable glove, which feeds back the pressure signals to the wearer as visual information.[41] Therefore, the wearer was able to adjust to the target grasping force by controlling the response signal (**Figure 2**a).[41] For a single-axis joint, a single-axis strain sensor is sufficient.[76] However, due to the multidimensional behavior of the skin, limitations of traditional single-axis strain sensors require a multidimensional stretchable strain sensors for precise analysis. Sensing a multidimensional strain on skin is important for H2Ms. Several groups have used silver nanowires (AgNWs) in flexible and stretchable electronics due to their excellent electrical and mechanical properties.[40,48,49] Despite these advantages, multidimensional strain measurement is difficult due to the coupling between the major strain axis and its perpendicular axis.[40] To solve this difficulty, Kim et al. have introduced a sensitive multidimensional stretchable strain sensor using AgNWs and demonstrated a virtual 2D translation stage movement as a practical use example (Figure 2b).[40]

Tactile sensing is essential to mimic human hand sensory technology, which would benefit amputees in daily activities. However, many stretchable sensors have problems such as hysteresis, complex fabrication process, and material incompatibility, making it difficult to embed in robot bodies.[67] A study using stretchable optical waveguide sensors in a soft prosthetic hand has solved most of these issues.[67] Three waveguides were implemented in each prosthetic finger, which performed well in scanning surface textures and shapes (Figure 2c).[67] Rather than using a specific sensor, integrating stretchable strain, temperature, moisture, and pressure sensors into one tactile sensing glove can provide skin-like signals in response to external stimuli.[50] A recent study reported a human hand-like warm prosthetic hand with an embedded heater and skin layer with stretchable strain, temperature, and moisture sensors.[54] Another study demonstrated an ultrathin imperceptible stretchable multifunctional HMI device with applications in wearable sensors or prosthetic skin.[71] This device uses a sol–gel-on-polymer-processed indium zinc oxide semiconductor nanomembrane, and can be used as temperature, strain, and ultraviolet (UV) sensors that operate stably up to 30% strain (Figure 2d).[71]

Table 1. Summary of stretchable mechanical sensors.

Design principle		Materials	Function	Stretchability [%]	Sensitivity	Detection range	Response time	Thickness	Ref.
Stretchable mechanical sensor	Multi dimension	AgNW/PDMS	Strain	35	GF: 20	0–35%	–	–	[40]
	Sensitive, stretchable sensor	AgNW/PDMS	Strain	70	GF: 2–14	0–70%	≈200 ms	–	[48]
		SWCNTs, PU-PEDOT:PSS	Strain	100	GF: 62	0–30%	–	–	[60]
		SWCNT/PDMS	Strain	50	GF: 10^7 (at 50% strain)	0–20%	300 ms	–	[61]
	Skin prosthesis (multifunction)	EGaIn, Cr/Au, PDMS	Strain, pressure	>30	0.001–0.01 kPa^{-1}	0–20% 5–405 kPa	–	–	[41]
		Ag-epoxy adhesive-nitrile/ PDMS	Pressure, moisture, temperature	40	≈10 µA/kPa ≈1 pF/20 µL ≈0.6 mV/°C	0–200 kPa 0–100% 20–50 °C	–	–	[54]
		PI/SiNR/PI	Strain, pressure, temperature, humidity	30	GF: ≈2000.41%kPa^{-1}	0–30%	–	–	[50]
		Au, PI, IZO nanomembrane, PDMS	Strain, temperature, UV	30	GF: ≈2.11	0–30% −50–100 °C	–	≈300 µm	[71]
	Hydrogel	MXene hydrogel	Strain	>3400	GF: 25 (tensile) GF: 80 (compressive)	–	–	–	[62]
	Liquid metal	GaInSn/PDMS	Strain, pressure	30	GF: ≈2	0–30% <100 kPa	–	–	[64]
	Temperature	SWCNT TFT	Temperature	60	−20.2 to −41.7 mV/°C	15–55 °C	–	–	[69]
	Optical waveguide	ELASTOSILM 4601	Strain	85	0.02 dBm/cm^{-1}	–	–	–	[67]

Table 2. Summary of stretchable electrical sensors.

Design principle		Materials	Function	Stretchability [%]	Sensitivity	Detection range	Response time	Thickness	Ref.
Stretchable electrical sensor	EMG sensor	Cr, Au, PI	EMG	30	–	–	–	800 nm	[51]
		Cr, Au, PI, PVA	EMG, strain, temperature	21	GF: 2.6 0.02 °C	–	–	20 µm	[52]
		Ag-Au nanocomposite	EMG, ECG	840	–	–	–	–	[59]
	EOG sensor	Graphene/ PMMA	EOG	50	Eye movement 4° (angular resolution)	0–70° (vertical) 0–50° (horizontal)	–	350 nm	[56]
	Multifunction	CNT, silicone, Cu	EMG, strain, temperature, angular velocity, acceleration	35	0.014° s^{-1} 300 µg	–	275 ms	≈1 mm	[55]
	Self-healable	AgF, SHP	EMG	3500	–	–	–	–	[72]
	Kirigami structure	AgNW, cPI	EMG, EOG, ECG, EEG	400	–	–	–	–	[57]
	Signal coupling	Ionic hydrogel, metallic nanofilm	EMG, strain	>100	GF: ≈34	–	–	–	[42]

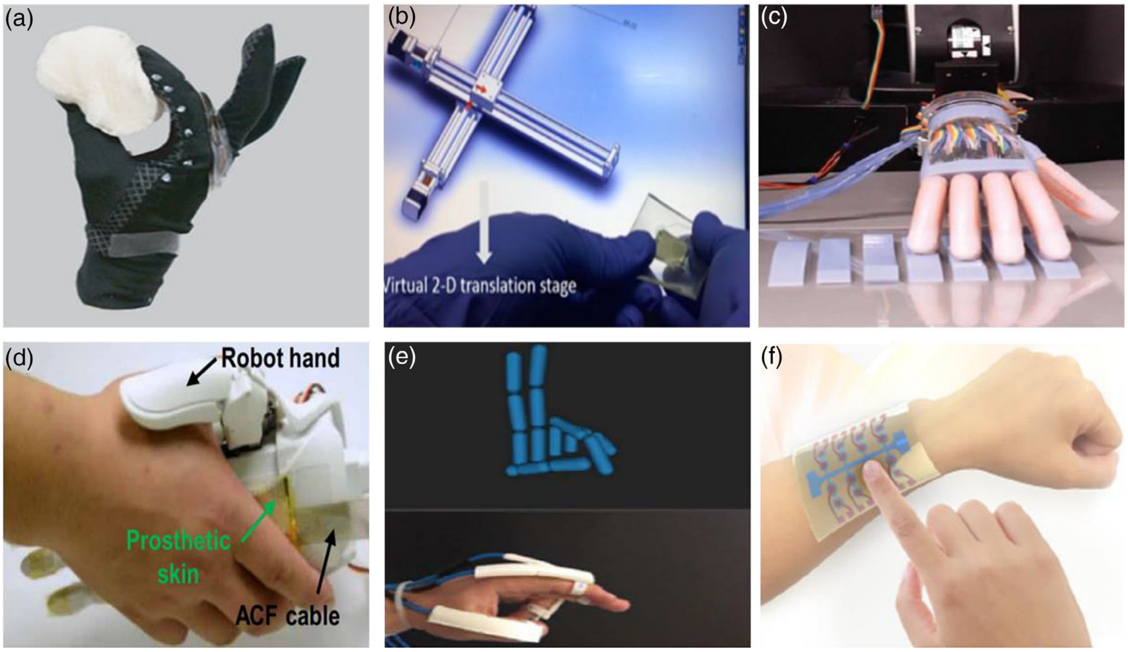

Figure 2. HMI with stretchable mechanical sensors. a) Wearable glove system using stretchable strain, pressure sensors. Reproduced with permission.[41] Copyright 2015, Wiley-VCH. b) Stretchable multidimensional strain sensor. Reproduced with permission.[40] Copyright 2015, American Chemical Society. c) Stretchable optical waveguide detecting surface roughness and shape. Reproduced with permission.[67] Copyright 2016, AAAS. d) Ultrathin imperceptible multifunctional HMI device used as prosthetic skin. Reproduced with permission.[71] Copyright 2019, AAAS. e) Soft pneumatic sensing chamber analyzing finger motions. Reproduced with permission.[53] Copyright 2019, Wiley-VCH. f) Transparent and stretchable touch panel. Reproduced with permission.[75] Copyright 2019, Springer Nature.

Although prosthetic technology enables robots to deliver skin-like sensory signals to humans, stretchable mechanical sensors could also detect human inputs that enable an intuitive control of robots.[49,53,65] For practical applications, a reliable sensor that retains repeatability, stability, and negligible hysteresis is necessary. Recently, a novel reliable soft pneumatic sensing chamber (SPSC) that possesses linearity, stability, and fast response was developed.[53] The soft wearable SPSC glove enables the control of soft gripper to grasp various objects and process finger motions in 3D simulations (Figure 2e).[53]

Touch panels also provide an intuitive method to interact with machines. Various touch panels have been developed in wearable forms using highly stretchable ionic hydrogels[77,78] and hierarchal metal structures.[79] Recently, researchers have developed a transparent stretchable touch panel that detects the pressure signals (Figure 2f).[75] They used a piezoelectric conducting polymer as the sensing area and encapsulated it with a 3D micropatterned substrate to enhance sensitivity. The sensor system, attached to the forearm, successfully controlled a homemade toy car.

2.2. Electrical Sensors

Another way to advance H2M is to utilize electrical signals from the human body. The EOG sensor records corneoretinal potential signals.[56,57] The EMG sensor measures electrical signals from muscle nerve stimulations.[42,51,52,55,57,72] Skin-mounted stretchable sensors enable the detection of subtle electrical signals transmitted through the body. Because electrical signals are detectable, machines can be controlled by human gestures with predetermined actuation modes.

There have been studies on sensitive stretchable electrical sensors that are expected to advance H2M.[42,51,52,55–57,72] Xu et al. have developed a multifunctional platform that uses several sensors and stimulator with a stretchable EMG sensor.[52] This study used Au serpentine traces for an EMG sensor and has demonstrated the possibility of controlling a grasping robot with stretchable electrical sensors (**Figure** 3a).[52]

In addition, a new approach using self-healing materials for stretchable electronics has been developed, due to its reliability under mechanical damage.[58,72] Kim et al. developed a self-healable nanocomposite conductor that recovers electrically percolative pathway and demonstrated the control of a robotic arm through sensing human forearm EMG signals, even after a complete cut (Figure 3b).[72]

Adhering a stretchable electrical sensor near the eye enables the measurement of EOG signals.[80] EOG signals can also be used to interact with machines. For example, leading a quadrotor to move toward the direction of the eye by measuring EOG signals may be possible.[56] As EOG sensors are placed in easily recognizable areas, high transparency and conformal sensors are needed. Moreover, all sensors (EMG, ECG) that measure skin surface electromyograms may be more practical if they are imperceptible. Several groups are focused on stretchable electrical sensors with high transparency and conformability.[56,57] As a result of these requirements, a recent study used ultrathin

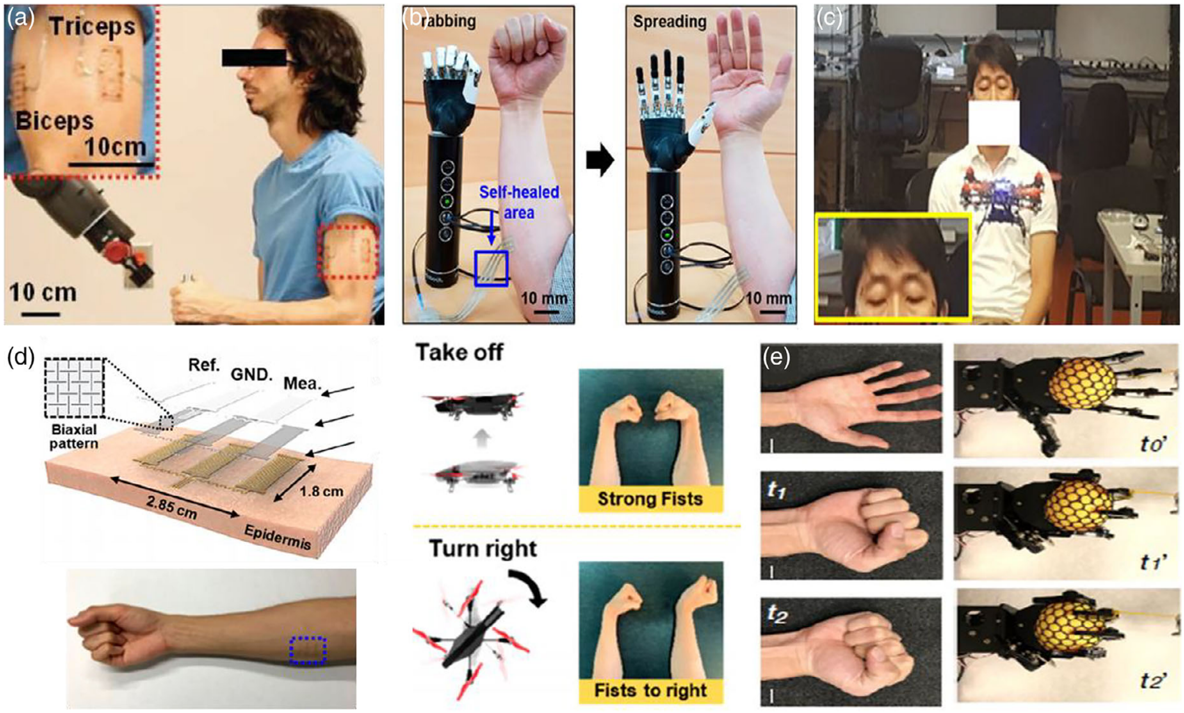

Figure 3. HMI with stretchable electrical sensors. a) Stretchable EMG sensor analyzing human intention. Reproduced with permission.[52] Copyright 2015, Wiley-VCH. b) Stretchable EMG sensor utilizing self-healable material. Reproduced with permission.[72] Copyright 2019, American Chemical Society. c) Imperceptible stretchable EOG sensor controlling quadrotor position. Reproduced with permission.[56] Copyright 2018, Springer Nature. d) Kirigami-structured stretchable electrical sensor. Reproduced with permission.[57] Copyright 2019, American Chemical Society. e) Stretchable electrical sensor coupling with mechanical signals for precise analyzation. Reproduced with permission.[42] Copyright 2020, Springer Nature.

transparent graphene electronic tattoos as an imperceptible stretchable EOG sensor.[56] The experiment controlling a quadrotor by sensing EOG signals was successfully conducted without imposing any facial movements (Figure 3c).[56] Won et al. accomplished a transparent kirigami-structured stretchable electrical sensor that is also highly conductive.[57] This sensor can measure EMG, EOG, ECG, and electroencephalography (EEG) signals. They demonstrated the control of a quadrotor with two sets of EMG signals from the forearms (Figure 3d).[57]

Recent developments in stretchable electrical sensors have allowed for intimate HMIs.[52,55–58] However, for precise analysis, coupling a mechanical signal with an electrical signal is necessary. This is because of the spatiotemporal differences between myoelectric triggers and mechanical responses.[42,81] Therefore, relying solely on mechanical signals or electrical signals can fail in determining the exact properties of human gestures. Cai et al. achieved a locally coupled electromechanical interface that analyzes the muscular excitation–contraction process.[42] Manipulation of a robotic hand with grip strength and speed recognition was conducted using the proposed stretchable sensor (Figure 3e).[42]

2.3. Integrated System

Recent developments in H2M devices sought for untethered operation and effective human monitoring through the integration of logic circuits with the sensory system. Near-field/Bluetooth communications enable rapid remote control, and devices with higher mechanical compliance enable skin-attachable wearable devices.

Researchers have developed a network of chip-less and battery-free sensors that measure human physiological signals. They separated the sensing part and the rigid reading circuit, thereby enabling conformal attachment and wireless operation of the sensors in multiple skin locations (**Figure 4**a).[52] A carbon nanotube network is used for the internal sensor and is integrated with the inductor and capacitor component in the reading circuit. Simulation results provide a suitable specification for the components (L, C, and R) to maximize the response of the voltage when the sensor resistance changes. Sensors are attached to five parts of the body and the heart rate, breath rate, arm movements, and leg movements are measured.

As an effective power supply, researchers recently introduced a perspiration-powered electronic circuit that measures human motions wirelessly. They used lactate as the biofuel source and achieved high power density with the assistance of immobilized lactate oxidase bioanodes. A composite of CNT/polydimethylsiloxane (PDMS) was used as the stretchable strain sensor and was integrated with the sensing module. As shown in Figure 4b, the system successfully demonstrated wireless HMI applications through wireless robotic arm and robotic prosthesis controls.[43]

As a system that relies on NFC communications requires close proximity between the reader and the sensor device, researchers have recently developed a textile-based sensor network that

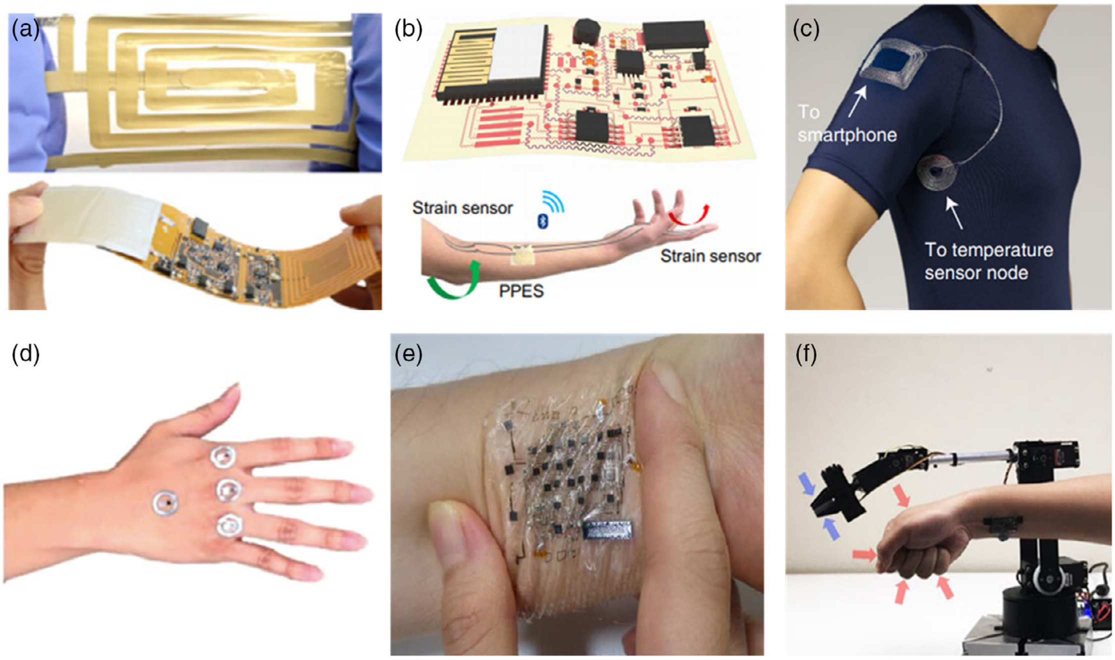

Figure 4. Integrated systems for HMI. a) Stretchable antenna and sensor system wirelessly connected with the external rigid PCB. Reproduced with permission.[82] Copyright 2019, Springer Nature. b) Perspiration-powered wireless sensor module. Reproduced with permission.[43] Copyright 2020, AAAS. c) A long-range readable textile-based near field communication (NFC) sensor system. Reproduced with permission.[83] Copyright 2020, Springer Nature. d) Liquid metal-based stretchable wireless NFC sensor device. Reproduced with permission.[84] Copyright 2017, Springer Nature. e) Stretchable circuit integration as an electronic skin device. Reproduced with permission.[65] Copyright 2018, AAAS. f) Multilayer framework stretchable electronic controlling robotic arm by EMG signals. Reproduced with permission.[55] Copyright 2018, Springer Nature.

communicate indirectly with the reader hub over the long range. As shown in Figure 4c, a single hub at the shoulder is connected to three sensors at the spine (cervical, thoracic, and lumbar) and simultaneously detect the posture in a battery-free environment.[83]

To achieve higher conformability and endurance, researchers patterned liquid metal using a selective wetting technique, as shown in Figure 4d.[84] They integrated the NFC chip with an antenna and the strain sensor made of liquid metal. Liquid metal was selectively coated above the predeposited gold (Au) patterns above the PDMS. This system can measure uniaxial strain (30%) and pressure loading (80 kPa). The sensors are attached to various parts of the body and measure the movements of wrist, swallowing motions, and fingers.

As stretchable sensors can conform to the epidermis, a manipulation component can be attached to human skin, thereby enabling direct control using human intentions.[49,53,65] A pair of electronic skin has been developed that consists of an actuating part and a controlling part.[65] This electronic skin device controls the actuator by analyzing certain pressure inputs through the stretchable circuit, and the wirelessly connected actuator performs predefined actuation states (Figure 4e).[65]

Due to the constraints of single-layer designs, previous stretchable electronics have limitations.[55] Single-layer design impedes the employment of stretchable electronics on small devices because of its sparse large scale arrangement. Furthermore, single-layer design makes it difficult to develop highly functional stretchable electronics. A recent study has introduced a multi-layer framework for stretchable electronics with the application of wirelessly controlling a robotic arm by embedding a single patch sensor such as accelerometer, gyroscope, strain sensor, temperature sensor, or EMG sensor (Figure 4f).[55]

3. Stretchable Actuators for HMI

Similar to stretchable sensors that are developed for delivering human inputs (H2M) and mimicking human senses (M2H), stretchable (soft) actuators can better M2H. They can interact with humans through intimate contact and are compact.[46] Many actuators have been proposed for assisting human gestures[46,85–90] and mechanically stimulating human senses.[44,45,91–95] For instance, wearable gloves with soft actuators such as pneumatic actuators, can assist rehabilitation by supporting the grasping force.[89] In addition, mechanically vibrating stretchable actuators interact with humans by stimulating human senses to provide certain information.[94] In this regard, we review recent advances in stretchable actuating systems, and the performance of the actuators are shown in **Table 3**.

3.1. Stretchable Human Assistive Devices

Human assistive devices improve the quality of life for injured, partially disabled people. These devices reduce the energy spent on particular motions through force assistance.[46,89] Furthermore, there are studies showing that robotic assistance significantly improved the rehabilitation of stroke patients.[85,96]

Table 3. Summary of stretchable actuators.

Actuator type		Stimulus	Material	Stretchability [%]	Actuation force/displacement	Actuation speed	Weight	Size	Ref.
Stretchable assistive device	Soft tendon	–	Soft tendon routing system	–	50 N (grasp force)	–	194 g	Maximum grasped object 76 mm	[46]
	Textile actuator	−1.0–0.5 V	Conducting polymer	220	125 mN (3 cm size)	1.4 kHz	–	Length: 20 mm	[86]
	Stretchable pump	6 kV	C, Ag, PDMS	<100	>7 kPa	2.5 Hz	1 g	Length: 75 mm Width: 19 mm Thickness: 1.3 mm	[87]
	Hydraulic actuator	9.6 W hydraulic pump	Fiber, silicon	–	7.3 N (tip force)	1–2 Hz	285 g (glove)	Width: ≈20 mm Height: ≈20 mm	[85]
	Pneumatic actuator	0–200 kPa	60 A, 85 A elastomer	400	100 N (tip force)	–	230 g	Length: 210 mm	[88]
	Pneumatic actuator	0–400 kPa	Latex balloon	50	17 N	–	100 g	Length: 140 mm Radius: 5 mm	[89]
Stretchable mechanical haptic device	TCP actuator	30–90 °C	LLDPE	–	69 MPa	–	-	–	[91]
		0–60 V	UHMWPE, NiCr	–	650 mN	15–21 mm/s	14 g (0.1 g actuator)	Length: 20 cm	[93]
	Pneumatic actuator	6 kV	Silicon rubber	–	0.13 mm	–	0.57 g	Diameter: 15 mm Height: 5 mm	[45]
	DEA	–	PUA-PEGDA	–	–	>1 Hz	–	Thickness: 0.43 mm	[95]
	Piezoelectric actuator	50 V	FEP, Ecoflex, Au, Al	–	20 mN	0–1700 Hz	–	Thickness: 150 μm	[44]
	Skin integrated haptic interface	–	PI, Cu, silicone	–	135 mN, 35 μm	100–300 Hz	130 g (total system)	–	[94]

These assistive devices with stretchability may enhance the versatility of M2H.

The human hand is essential for maneuverability. Therefore, comforting the mobility of human hands can benefit people with disabilities. Materials that are flexible and stretchable are alternatives to rigid materials in an exoskeleton due to their suitability.[46] One group proposed a compact soft wearable assistive glove, called the Exo-Glove, using a soft tendon routing system and fabric straps as pulley.[46] This device includes a slack prevention mechanism to relax the tendon friction problem, and enables the wearer to grasp various objects (plastic bottle, baseball, and spray container) without exerting significant forces.[46] Recently, a new version of the Exo-Glove using a polymer has been proposed to overcome hygiene issues (**Figure 5**a).[97] Different types of stretchable actuators have been used in assistive glove devices.[85,87,89] An assistive glove based on a stretchable pneumatic actuator showed decrements in muscular fatigue through EMG signal data.[89] Application of fluidic pressure to an actuator has also shown possibilities in stretchable actuators.[85,87,98,99]

Polygerinos et al. presented a soft robotic glove subject to hydraulic actuators that are manufactured with rubber tubes and strain-limiting layers for intentional actuations.[85] They analyzed the finger joint movements and adjusted the hydraulic actuator movements by appropriately arranging the fiber reinforcement and strain limiting layers (Figure 5b).[85] However, previous studies that utilize fluidic pressure have shown some disadvantages due to their rigidity and large external pumps.[87,100] Rigid parts can hinder the use of such devices in wearable devices and their portability. A recent study has proposed a stretchable pump, which consists of a monolithic elastomer tube with no rigid segments that behaves well in stretched conditions, enabling device miniaturization.[87] In this study, they demonstrated the fluidic muscle by adhering a soft actuator chamber to the suggested stretchable pump (Figure 5c).[87] Furthermore, a new class of soft actuators that utilize hydraulic forces called the hydraulically amplified self-healing electrostatic actuators have been proposed.[98,99] These actuators have been demonstrated as artificial muscle actuators that are expected to be applicable for stretchable assistive devices in the future.

Human assistive devices are not restricted to a glove system.[88,90,101,102] Actuator behaving as an artificial muscle can be an assistive device. However, previously introduced stretchable actuators lack the forces compared to rigid robots, which makes it challenging to be satisfiable to heavy joints, such as the elbow and shoulder.[88] Recently, a group manufactured a soft pneumatic actuator for elbow assistive use that is capable of exerting force up to 100 N (Figure 5d).[88] Furthermore, Maziz et al. showed a new concept, a textile actuator that is capable of providing large forces by combining structures such as plain weaves.[86] Textile processing (knitting, weaving) of electroactive polymers enables the fabrication of textile actuators with excellent stretchability due to its structure for designing assistive devices (Figure 5e).[86]

3.2. Stretchable Mechanical Haptic Devices

Stretchable actuators attached closely to human skin can act as external stimulation devices. An external stimulation device

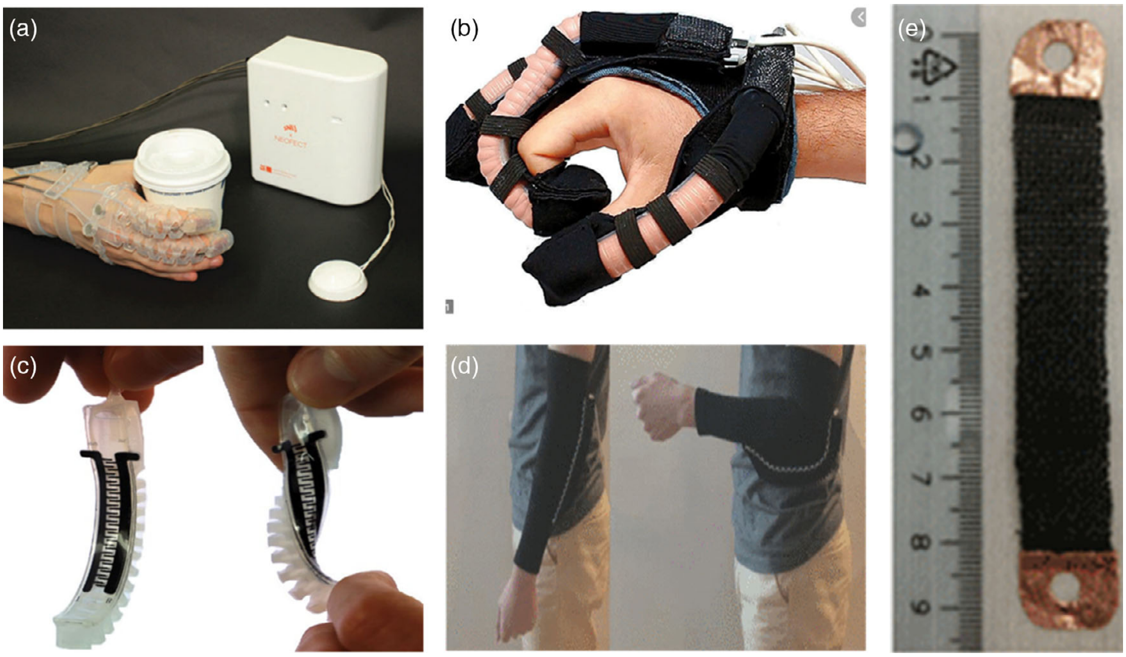

Figure 5. HMI with stretchable human assistive devices. a) Wearable hand assistive device using polymer and tendon-driven system. Reproduced with permission.[97] Copyright 2019, Mary Ann Liebert, Inc., publishers. b) Soft robotic glove with hydraulic actuators. Reproduced with permission.[85] Copyright 2014, Elsevier. c) Fluidic muscle demonstrated by soft actuator chamber and stretchable pump device. Reproduced with permission.[87] Copyright 2019, Springer Nature. d) Soft pneumatic actuator assisting elbow joint. Reproduced with permission.[88] Copyright 2020, IEEE. e) Stretchable textile actuator using textile processing. Reproduced with permission.[86] Copyright 2017, AAAS.

allows for tactile information feedback, which leads to an intimate M2H. Therefore, several studies have used stretchable actuators as mechanical haptic devices.[44,45,91–95] Stretchable electronics that provide force or strain have been developed to mechanically stimulate human senses,[91–93] and some recent studies have developed stretchable actuators that vibrate[44,94] or provide displacement.[45,95]

Fiber actuators are likely applicable to wearable haptic devices. These actuators usually contract lengthwise when heated.[93] Certain polymers designed with adequate coiled structures can strain through temperature-induced deformations.[103] However, resistance heating-driven fiber actuators exhibit the thermal degradation of the peripheral materials due to the high operating temperature. This makes thermomechanical fiber actuators work in the low performance-limited temperature scope.[103] One group proposed a new coiled-fiber actuator based on linear low-density polyethylene (LLDPE) fibers that operates at a low temperature, showing the capability of implementing a haptic device.[91] The proposed fiber actuator outperformed previous coiled-fiber actuators at the same temperature; therefore, it can be combined with common fabric materials without thermal degradation (**Figure 6**a).[91] Recently, a finger haptic device using a fiber actuator was introduced.[93] In this study, ultrahigh molecular weight polyethylene (UHMWPE) fibers were selected to overcome the mechanical weakness of LLDPE fibers. This was the first application of a fiber actuator used for haptic stimulation (Figure 6b).[93] It is also possible to utilize a robotic skin as a versatile haptic feedback actuator. In many cases, tasks are difficult to recognize ahead; therefore, devices such as robotic skins that can selectively apply force are necessary for practical applications.[92] Therefore, a robotic skin, designed to enable various manipulations using distributed force actuation, and used as a communication device with a wearer has been proposed (Figure 6c).[92]

Mechanical vibrations are used an alternative for the stimulation of human senses. Although stretchable sensors and actuators are necessary for HMI, most recent studies focused on sensing technology.[44] A device capable of both detecting and actuating may benefit HMI communication. Because of its importance, Zhong et al. composed a wearable electronic device that senses the pressure with a limit of 1.84 Pa and pulsate similar to a cell phone vibration.[44] Due to the vibrational response, this device can be a wearable haptic feedback device (Figure 6d).[44] Furthermore, producing diverse modes of vibration may extend the potential of expression. When a haptic device delivers information such as shape or size of an object, specific details are inadequate for a single monolithic vibration actuator. A recent study proposed a stretchable haptic device that provides the shape characteristics of a virtual touch and demonstrated the selective actuation through a game character interaction.[94] This device delivers valuable information through spatiotemporal patterns of vibration (Figure 6e).[94]

Some studies show the use of soft actuators as haptic devices through actuating displacements.[45,95,104] For the communication with the VR world, stimulating the human senses as real tactile senses are crucial.[105] Triggering actuators to return a certain amplitude can make subjects feel like they are touching a real object. Pneumatic actuators have been used to activate certain amplitudes that provide the virtual sense of touch.[45]

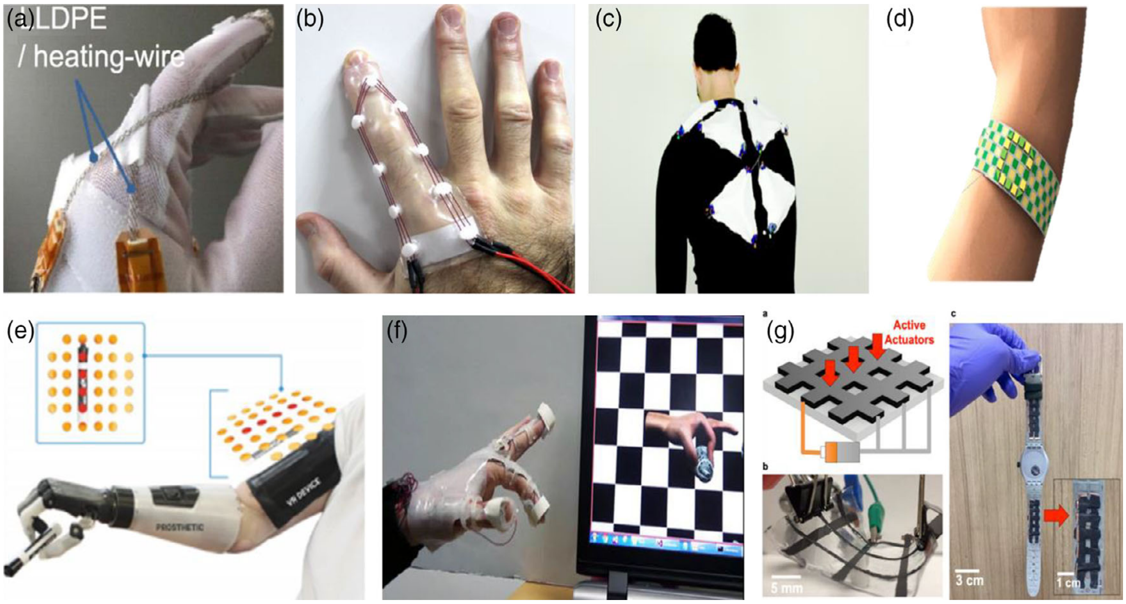

Figure 6. HMI with stretchable mechanical haptic devices. a) Fiber actuator using LLDPE fibers. Reproduced with permission.[91] Copyright 2016, Springer Nature. b) Haptic stimulation device utilizing UHMWPE fibers. Reproduced with permission.[93] Copyright 2019, IEEE. c) Robotic skin device communicating with a user. Reproduced with permission.[92] Copyright 2018, AAAS. d) Wearable haptic feedback device capable of both sensing and vibration. Reproduced with permission.[44] Copyright 2019, American Chemical Society. e) Skin-integrated haptic device that can deliver spatiotemporal vibration information. Reproduced with permission.[94] Copyright 2019, Springer Nature. f) Soft virtual reality haptic device using pneumatic actuator and flexible piezoelectric sensor. Reproduced with permission.[45] Copyright 2019, Springer Nature. g) Stretchable DEA attached to a watch strap for a stimulation device. Reproduced with permission.[95] Copyright 2019, Springer Nature.

Here, hand gestures were analyzed using piezoelectric sensors, and haptic feedback was provided through pneumatic actuators with the signals from the VR world (Figure 6f).[45] In addition, to enhance the performance of stretchable actuators, a recent study to advance a dielectric elastomer actuator (DEA) has been conducted.[95] By chemically crosslinking polyurethane acrylate (PUA) with polyethylene glycol diacrylate (PEGDA), a reduction in hysteresis loss was observed through the stress–strain curve, and utilization of DEA in watch straps to provide displacement stimulation was introduced (Figure 6g).[95]

4. Intelligence-Aided Devices

4.1. Intelligence-Aided Stretchable Sensors

Recently, there have been several advances in sensor and actuator augmentation with the aid of machine intelligence. These methods have been used to achieve higher detectability for soft sensors, coping with the chronic problem of hysteresis, decoupling unwanted stimuli, and use for soft robotic proprioception.

The human hand with the highest degree of freedom in the body, exquisitely performs a range of tasks. Typically, at least ten soft sensors are used to detect hand motions. Researchers have suggested an intelligence-aided skin-like sensor that could identify the motions with a single sensor.[36] As shown in **Figure 7**a, a crack-based highly sensitive skin-like sensor was attached to the wrist for indirectly detecting the finger motions. Cracks of the metal layer were precisely manipulated through controlled annealing with an ultraviolet laser. Combined with the long short-term memory (LSTM) network, this sensor successfully decoded the finger motions using a single sensor. In addition, transfer learning-assisted auto calibration enabled the operation in an arbitrary part of the wrist and different users. By attaching the sensor on the pelvis, the system can be extended to identify gait motions.

Tactile gloves combined with neural networks show high potential for identifying multiple objects (Figure 7b).[37] The 548 force-sensitive sensors are arranged on the knitted glove, which provides a pressure map of the grasped object. The measured pressure map represents the image data that pass through the convolutional neural network (CNN). The prototype was used to measure 26 common objects with different sizes and weights. The objects were successfully identified in 103 of 104 blindfolded tests.

Recently, a sweat resistive self-powered wearable sensor was developed to recognize various gestures using machine learning.[38] Researchers fabricated CNT-based triboelectric nanogenerators using superhydrophobic textiles, which slightly degraded the accuracy of the sensor by less than 3% from the original performance. The data generated from the sensors attached to five fingers consist of 200 samples of time series data, which were used to train the CNN network. The model successfully predicted the palm, curved, and knuckle-ball gestures, as shown in Figure 7c. Hydrophobic gloves showed better gesture recognition accuracy, whereas the performance of nontreated gloves degrades by over 7% due to the sweat generated by the wearer. Researchers have also classified 11 gestures and moved objects in the VR environment.

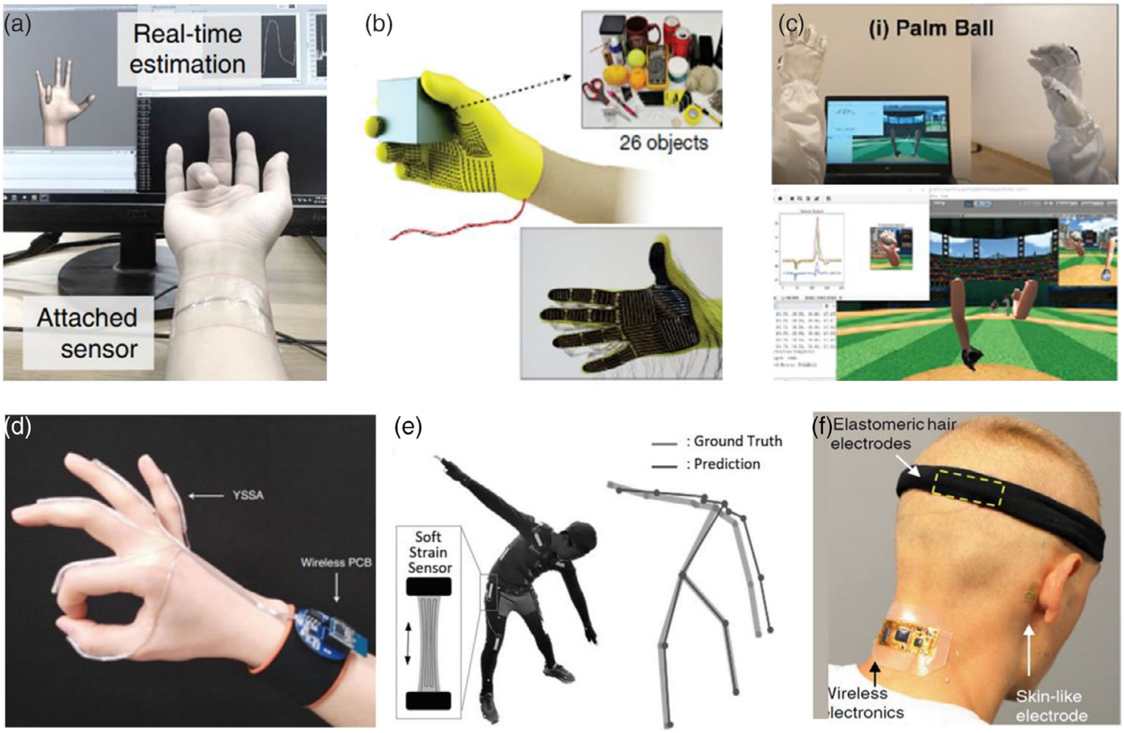

Figure 7. Intelligence aided stretchable sensors. a) Skin-like deep-learned sensor decoding the finger motions with single sensor. Reproduced with permission.[36] Copyright 2020, Springer Nature. b) Multiple tactile sensor array detecting various objects. Reproduced with permission.[37] Copyright 2019, Springer Nature. c) Sweat resistive self-powered glove predicting the hand motions. Reproduced with permission.[38] Copyright 2020, Wiley-VCH. d) Wearable sign-to-speech recognition device. Reproduced with permission.[106] Copyright 2020, Springer Nature. e) Deep full body tracking device made of liquid metal array sensors. Reproduced with permission.[35] Copyright 2018, IEEE. f) Wireless elastomeric electronic platform of measuring EEG signals. Reproduced with permission.[39] Copyright 2019, Springer Nature.

As resistive strain sensors suffer from large hysteresis, a recent study developed an algorithm containing three steps for the calibration process. First, they calibrated the stretchable sensor with the ground truth strain data produced by the webcam camera. The strain and electrical signal data were trained through the LSTM network, and then, the sensor system was embedded for wearable applications. Researchers have used three commercially available sensors of conductive fabrics and rubbers. The LSTM network successfully predicted the applied strain to between 10% and 20% errors.

A recent study proposed a machine intelligence-assisted wearable sign-to-speech device, as shown in Figure 7d.[106] They used yarn-based stretchable sensors that are integrated with an external wireless printed circuit board (PCB). For the training step, the electrical signals from the sensor were merged into the input of the principal component analysis to extract the main features of the sign gestures. Then, the networks were trained through a multiclass support vector machine (SVM) classifier. The network successfully predicted 11 classes of sign languages exceeding 99% accuracy.

Moreover, researchers have reconstructed the entire body motion by integrating several strain signals of body joints, as shown in Figure 7e.[35] A silicon (Ecoflex) channel, filled with a liquid metal compound (eutectic gallium–indium; eGaIn), acted as a highly stretchable sensor that conformably mounts on the skin. The sensor operated up to 130% strain and was attached to 20 points on the body (6 and 14 sensors on the lower and upper bodies, respectively). Vision cameras were used to capture the ground truth of body motions, and the encoding/decoding network (LSTM and fully connected layer) predicted the motions from the signals produced by the sensors. The sensor predicted various real-time motions such as squat, bend, reach, and windmill.

EEG signals create a direct communication bridge between humans and machines. Researchers developed a portable and wireless skin attachable device (Figure 7f) that tracks brain activities.[39] A deep-learning architecture classified the steady-state visually evoked potentials, which were used for the control of prosthetic systems and machines. Two layers of CNN and SVM classified five classes of EEG signals with 94% accuracy and successfully controlled a wheelchair and a wireless vehicle.

4.2. Intelligence-Aided Stretchable Actuators

Stretchable actuators can be widely applied to wearable assistive and wearable haptic devices. However, controlling actuators with hyperelasticity is a challenge due to their nonlinear properties. The machine intelligence enabled the recent progress in soft robot proprioception and better control.

For robotic proprioception, researchers embedded 30 optical fibers inside a soft actuator and identified complicated motions

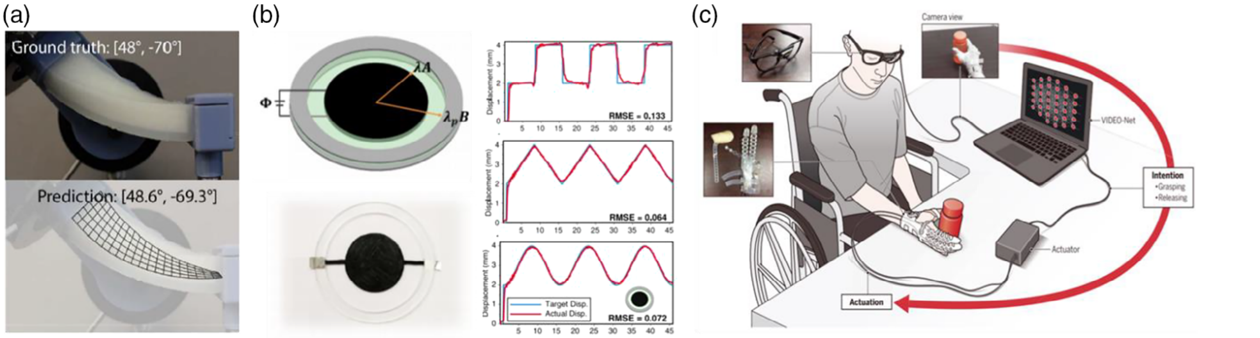

Figure 8. Intelligence aided stretchable actuators. a) Soft robotic proprioception aided by machine intelligence. Reproduced with permission.[47] Copyright 2018, AAAS. b) Control of DEA with the aid of Q-learned RL architecture. Reproduced with permission.[107] Copyright 2019, IEEE. c) Wearable soft robotic hand which outputs the user's intention through learning of vision data. Reproduced with permission.[108] Copyright 2019, AAAS.

such as bending and twisting, as shown in **Figure** 8a.[47] Researchers used two approaches to detect the deformation of the soft body: the single-output and multioutput approaches. The single-output model output whether the body is in a bent or twisting state and predicts its deformation angle. The latter uses a multioutput regression model that simultaneously predicts the bend and twist angle. The body was deformed to a known angle, and fiber terminal light intensity data were gathered for training data. The K-nearest neighbors model showed the best performance for this application.

Another study embedded soft resistive sensors and generated a model of the unknown soft actuated system using machine learning.[109] Researchers used multiwall carbon nanotube mixed PDMS for soft sensors and embedded a soft pneumatic actuator made up of Dragon Skin silicone. Recurrent neural networks simultaneously predicted the applied external force and the applied external force of the actuator. It also demonstrated an accurate kinematic model. Reference pressure and three strain sensor data were given as inputs to the network, and fingertip location from the motion capture system and force data were used for training. A proportional derivative controller was used to follow the trained model in this study.

Researchers have used the reinforcement learning (RL) method for controlling the DEA. Q-learning with multilayer perception was used for the RL architecture. To observe the current state of the actuator, a laser sensor was used to measure the radial and vertical displacements of the sensor. The agent was trained to make a voltage sequence to follow certain actuator displacement sequence. The RL method successfully controlled a circular DEA with the desired trajectories such as triangular, sine, and square waves, as shown in Figure 8b.[107]

As the augmented system introduced in Figure 5a, researchers integrated the Exoglove device with a vision-based intention detecting network (Figure 8c).[108] The spatial and temporal information of the target and human body were collected through a first-person view camera. Predicting the intention of the user through egocentric signals was verified using EMG signals captured during the grasping process. Unlike other wearable sensors for intention detection, vision-based networks are advantageous because they do not require additional person-to-person calibration.

5. Conclusion

In this report, we present the recent status of HMI stretchable sensors and stretchable actuators. Stretchable electronics had many developments in the past few years. Novel methods have been applied to improve stretchability, sensitivity, and robustness, for precise applications. Recently, implementation of machine learning techniques has increased the potential of stretchable electronics. However, few drawbacks persist. For example, stretchable optical sensors show poor dynamic performance. Currently, possessing high sensitivity, stretchability, negligible hysteresis, and linearity simultaneously is a challenge and further advancements are required. In the future, we expect stretchable electronics to be applicable for full HMI. The development of M2H such as prosthetic skin may enable amputees to sense as healthy people. In addition, improving H2M can ensure precise control of robots or grab objects naturally in a VR world. Moreover, with increasing interest in healthcare, stretchable electronics can make a breakthrough by supporting skin conformal interactions. Continued advances in system conformability, robustness, precision control, and machine learning techniques will introduce a new class of applications.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

human–machine interfaces, machine intelligences, stretchable electronics

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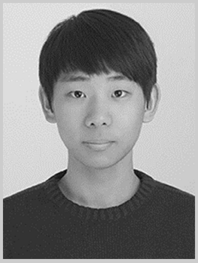

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