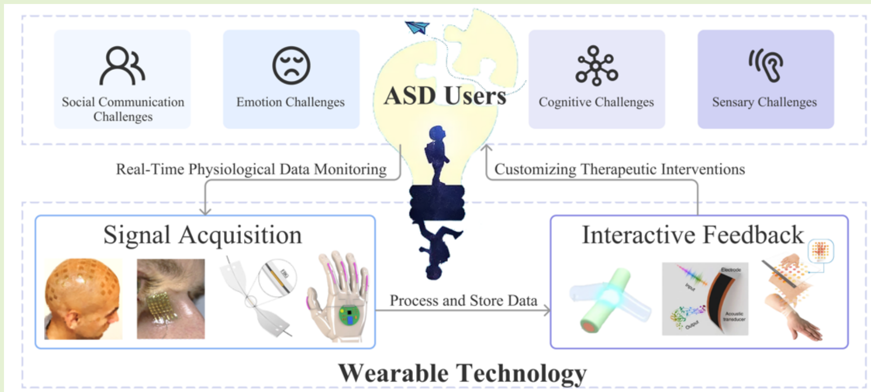
Wearable Technology for Signal Acquisition and Interactive Feedback in Autism Spectrum Disorder Intervention: A Review

Xuan Gao, Lang Yin, Suizi Tian, YongAn Huang and Qian Ji



***Abstract*—Autism Spectrum Disorder (ASD) interventions increasingly harness the capabilities of wearable technology, utilizing predictive analytics of physiological signals and personalized sensory feedback. Herein, we review the key developments in the multifaceted application of wearable technology for the ASD and highlights their potential value, covering both the state-of-the-art devices and requirements for ASD interventions. The wearable technology can be classified into two pivotal functional systems: signal acquisition and interactive feedback. The signal acquisition system employs an array of sensors for real-time physiological data monitoring in individuals with ASD, furnishing essential insights for the tailoring of customized therapeutic interventions. Additively, the interactive feedback system endeavors to ameliorate psychological and behavioral challenges, address sensory processing disorders, and enhance social and cognitive proficiencies. By facilitating diverse sensory stimulations and feedback mechanisms, wearable technology demonstrates a versatile approach to ASD intervention. Crucially, the principles and diverse applications of wearable technology in ASD are expounded upon, underscoring the emerging role of flexible electronics in this domain. Finally, the challenges and opportunities of wearable technologies are discussed, as well as the immense potential to revolutionize human-centered intervention solutions for ASD. The continued exploration of this dynamic field not only augments the quality of life and well-being of individuals with ASD but also presents an avenue for innovation at the intersection of technology and healthcare.**

***Index Terms*—Wearable sensors, flexible electronics, autism spectrum disorder, physiological monitoring**

I. INTRODUCTION

As a result of neurodevelopmental disorder, Autism Spectrum Disorder (ASD) is characterized by difficulties in social interaction and communication, repetitive and stereotyped behaviors, limited interests, and either hypersensitivity or hyposensitivity to sensory stimuli [1]. ASD has a significant prevalence worldwide, affecting approximately 1 in 100 individuals as of November 2021, with a rising trend [2].

Interventions for ASD encompass rehabilitation training, medication therapy, and psychological treatment. Notably, rehabilitation training, such as applied behavior analysis [3], sensory integration therapy [4], communication intervention [5], and Treatment and Education of Autistic and Related Communication Handicapped Children [6], are widely recognized as the most effective approach for their effectiveness in ameliorating core symptoms of ASD and enhancing overall quality of life. These approaches yield positive outcomes in enhancing patients' intelligence, adaptive behavior, motor and balance skills, as well as cognitive and expressive abilities.

However, conventional interventions for ASD individuals

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are subject to certain limitations. Firstly, the constrained access to community healthcare resources creates barriers to accessing specialized rehabilitation facilities and therapy, resulting in delays in treatment for a substantial number of individuals with ASD [7]. Secondly, individualized treatment presents challenges due to the considerable variability observed among patients in terms of the severity of their condition and the presence of comorbidities [8]. Effective intervention strategies necessitate the development and execution of tailored training programs that cater to these individual differences [9], placing considerable demands on the therapists' expertise and capabilities.

Wearable technologies enable the remote and real-time acquisition of behavioral and physiological data from individuals, transforming the landscape of ASD monitoring and treatment [10]. For instance, ASD individuals often grapple with high levels of anxiety disorders [11], emotional dysregulation, and challenging behaviors [12]. Existing wearable technologies, by quantifying pertinent biological parameters, assist ASD patients in enhancing self-awareness of anxiety levels, internal emotional states, and aggressive behaviors [13]. In conjunction with psychological and behavioral therapies, these technologies can create conditions for emotional regulation and behavioral improvement. Apart from health monitoring, wearable technologies can provide personalized assistance and intervention strategies tailored to individual differences and needs [14]. For example, using head-mounted displays and smart glasses to provide audio-visual cues or utilizing wristbands, or gloves to provide tactile feedback. These technologies facilitate superior adaptation to daily routines and social contexts. The prospect of personalized assistance and intervention holds great promise for improving functioning in clinical conditions and alleviating behavioral issues among ASD individuals [15].

Recent works reviewed wearable technologies in ASD interventions, demonstrating a diverse range of focuses and findings. Cabibihan et al. [16] initiated a comprehensive review of various sensing technologies, which has since guided researchers towards increasingly specialized areas within wearable sensing. Notably, some studies have investigated function-specific sensing technologies, such as monitoring Behavioral and Physiological Responses [17]. Furthermore, research tailored to the unique needs of ASD individuals has gained traction, emphasizing Social and Sensory Challenges [18] and emotional difficulties [13]. Recent technological advancements have steered this field towards integrating sensors with classification algorithms [19] and developing applications [20]. Based on these studies, this paper centers on wearable systems in ASD interventions, discussing the tailored support these technologies offer. The integration of wearable systems in ASD care facilitates personalized interventions, enhancing social communication[16], [17], emotion regulation[23], cognitive training [24] and sensory regulation [25] within autism.

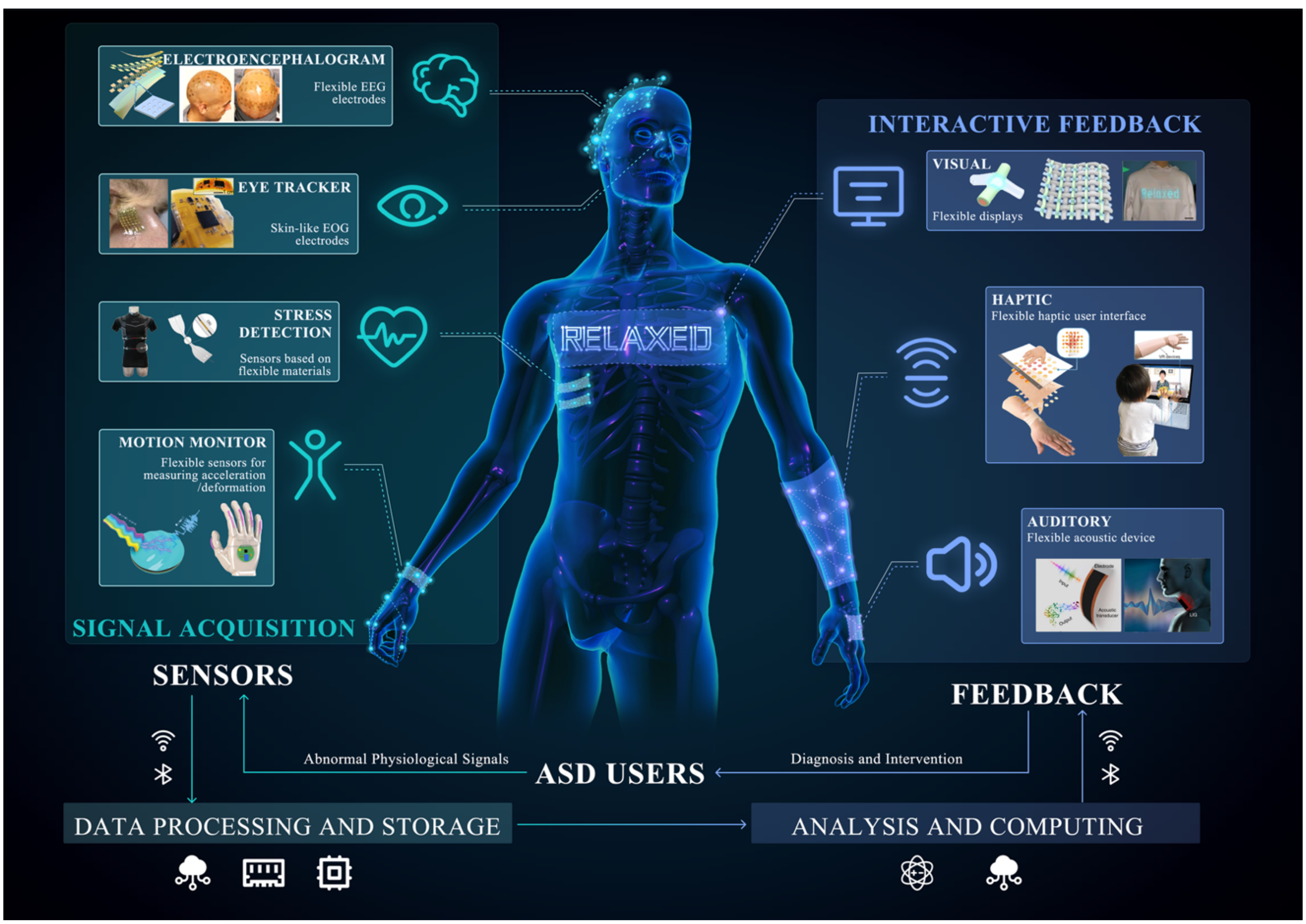

Fig. 1. Wearable systems for ASD, classification and related technologies.

Aligned with the multifaceted treatment demands of ASD, wearable systems can broadly be categorized into two types: signal acquisition and interactive feedback (see Fig. 1). The former utilizes wearable technologies such as Electroencephalogram (EEG), eye-tracking technology, emotion detectors, and motion detectors. The realization of these technologies is intrinsically associated with the development of wearable sensors. These sensors collect physiological signals such as optical, electrical and mechanical signals, which are subsequently transmuted into digital form. Through data processing and machine learning, relevant physiological information can be extracted. The latter category includes devices furnishing visual feedback via displays, auditory feedback via speakers, and haptic apparatus. In these domains, state-of-the-art research, such as wearable display textiles, ultrathin flexible loudspeakers and skin-integrated haptic interfaces have notably galvanized strides in interactive and feedback systems.

Despite the promising advancements of wearable technologies in autism intervention, several challenges endure on the application front. On the one hand, a recurrent hurdle pertains to the integration of diverse wearable products among individuals with ASD—often characterized by sensory sensitivities and hesitancy toward novel stimuli. Additionally, adapting to the personalized requirements of individuals with ASD remains a challenge [18], [26]. On the other hand, the effectiveness of products still needs to be validated due to limitations in sample size and experimental duration [27], [28], [29].

In the field of autism treatment, flexible electronics, as a leading research area in wearable technologies, present new possibilities for designing intervention systems. Wearable devices based on flexible electronics offer notable advantages in terms of comfort, flexibility, and precision [30], [31], [32], [33]. These devices have the ability to address the acceptance conundrum experienced by individuals with ASD, as they can be tailored to accommodate diverse user needs. Through integration with other electronic components, wearable flexible electronics can provide a wide range of functionalities to accommodate personalized monitoring and intervention requirements. Moreover, their affordability and high accuracy create opportunities for comprehensive effectiveness validation studies.

To assist researchers in gaining an understanding of the current research frontiers and applying these advancements to improve the quality of life of individuals with autism, this review explores the latest research findings and development directions for flexible electronics. To this end, the article commences by introducing wearable systems specifically engineered for ASD interventions. It subsequently delves into an extensive review of two pivotal pathways—signal acquisition and interactive feedback—underpinned by their therapeutic principles and approaches tailored to the ASD patients. Concluding, the paper contemplates the prospective horizons of applying wearable technologies to ASD intervention paradigms.

II. Wearable Systems for Physiological Signal Acquisition

In this section, we focus on wearable signal acquisition systems, which are further divided into EEG devices, eye tracking systems, emotion monitoring systems, and motion behavior monitoring systems. These technologies enable early diagnosis and targeted interventions, offering a comprehensive view of autism's complex manifestations, enhancing treatment and support.

A. EEG Devices: for Neurofeedback Interventions

EEG is a noninvasive tool essential for assessing the functionality and maturation of macroscopic neuronal circuits, particularly in ASD research [34]. It plays a dual role in ASD diagnosis and treatment. Firstly, EEG is used to detect ASD by identifying deviations in brain activities and circuitry. This is achieved through measuring functional connectivity — the temporal correlation between distant neurophysiological events, and spectral power analysis — which decomposes EEG signals into frequency components, providing insights into the brain's electrical activity across various frequency bands, such as alpha, beta, and gamma. These techniques are crucial for distinguishing ASD from non-ASD individuals. Secondly, Neurofeedback intervention utilizing Brain-Computer Interfaces (BCIs) stand as a safe and effective non-invasive treatment of autism. Research has shown distinct brain activity in ASDs [35], [36], [37], particularly in the dysfunctions of the mirror neuron system which affects social and cognitive functions. In contrast, BCI-based neurofeedback, aiming to normalize mirror neuron system [38], enables patients to self-regulate brain rhythms. This involves converting EEG data into digital signals processed by computers to provide feedback. This approach advances both therapeutic tools and understanding of autism's pathologies. The relationship among EEG, BCIs, and autism interventions is described in Fig. 2a.

EEG electrodes are the foundation of signal acquisition for BCI devices and can be classified as invasive or non-invasive. Invasive devices, which are implanted directly into the brain, proffer heightened accuracy and precision but entail risks such as infection or brain damage. Non-invasive wireless wearable devices [39] have found extensive utility in ASD interventions. For example, Billeci et al. [24] employed the Enobio wireless device (STARLAB, Barcelona, Spain) to reveal cognitive involvement in ASD, demonstrating the possibility of implementing individualized therapeutic programs in more naturalistic settings. Mercado et al. [40] deployed MindWave headsets to read the attention of children during a BCI video game using neurofeedback (Fig. 2b). And Amaral et al. [41] designed a P300 neural signals-based BCI virtual reality (VR) system(Fig. 2c), which used the g.Nautilus EEG system to detect attention for training social cognitive skills. These designs showed good results in training memory, attention and social skills.

However, affected by factors such as skin movement, EEG devices suffer from poor signal quality, prolonged user adaptation, and uncomfortable wearability [32]. To address these limitations, researchers are poised to flexible EEG electrodes characterized by their seamless electrode-skin interface and an unobtrusive wearing experience. The spectrum of flexible electrodes encompasses wet electrodes and dry electrodes. Hydrogels, a typical type of flexible wet electrodes, possess a Young's modulus and moisture content similar to biological tissues. This characteristic enables them to have good EEG acquisition capability similar to that of the standard wet Ag/AgCl electrodes, the gold standard for lab environments. In order to improve the motion stability of hydrogel electrodes, Han et. al. [42] integrated polydopamine nanoparticles into polyvinyl alcohol and polyvinylpyrrolidone hydrogel network (Fig. 2d). The developed electrodes were established with conformal and robust interfaces (Fig. 2e) with tissues, which had tolerance to sweat and motion. Benefiting from the development of various hydrogel networks and nanofillers, hydrogel electrodes can achieve tunable mechanical [43], [44] and conductive [45], [46] properties, showing unique advantages in high-quality EEG recordings. UV-cured electrodes have higher pattern resolution compared to hydrogels. Jiang et al. [47] introduced a second topological cross-linking network in poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), which can be cross-linked and cured under UV light irradiation by modifying the side chains of the second network. The material can be easily and greenly photopatterned using water as the developer.

Although wet electrodes offer high signal-to-noise ratio (SNR) and reliability, they face challenges in preparation time and comfort for long-term use [48], [49], [50]. Flexible dry electrodes offer promise for integration into ASD therapeutic systems as EEG device sensing modules. The key challenge of dry electrodes is the higher electrode-skin interface impedance compared to wet electrodes, which is directly affected by the contact interface. To address this, advancements in dry electrodes have incorporated various cutting-edge materials, including metals, conductive polymers, and carbons allotropes. Liquid metal/alloy, such as Ga-In [51], demonstrates excellent biocompatibility and serves as a superior alternative to traditional metal electrodes (e.g., Ag, Au). Conductive polymers, Conductive polymers are realized either with intrinsic conductive properties (e.g.

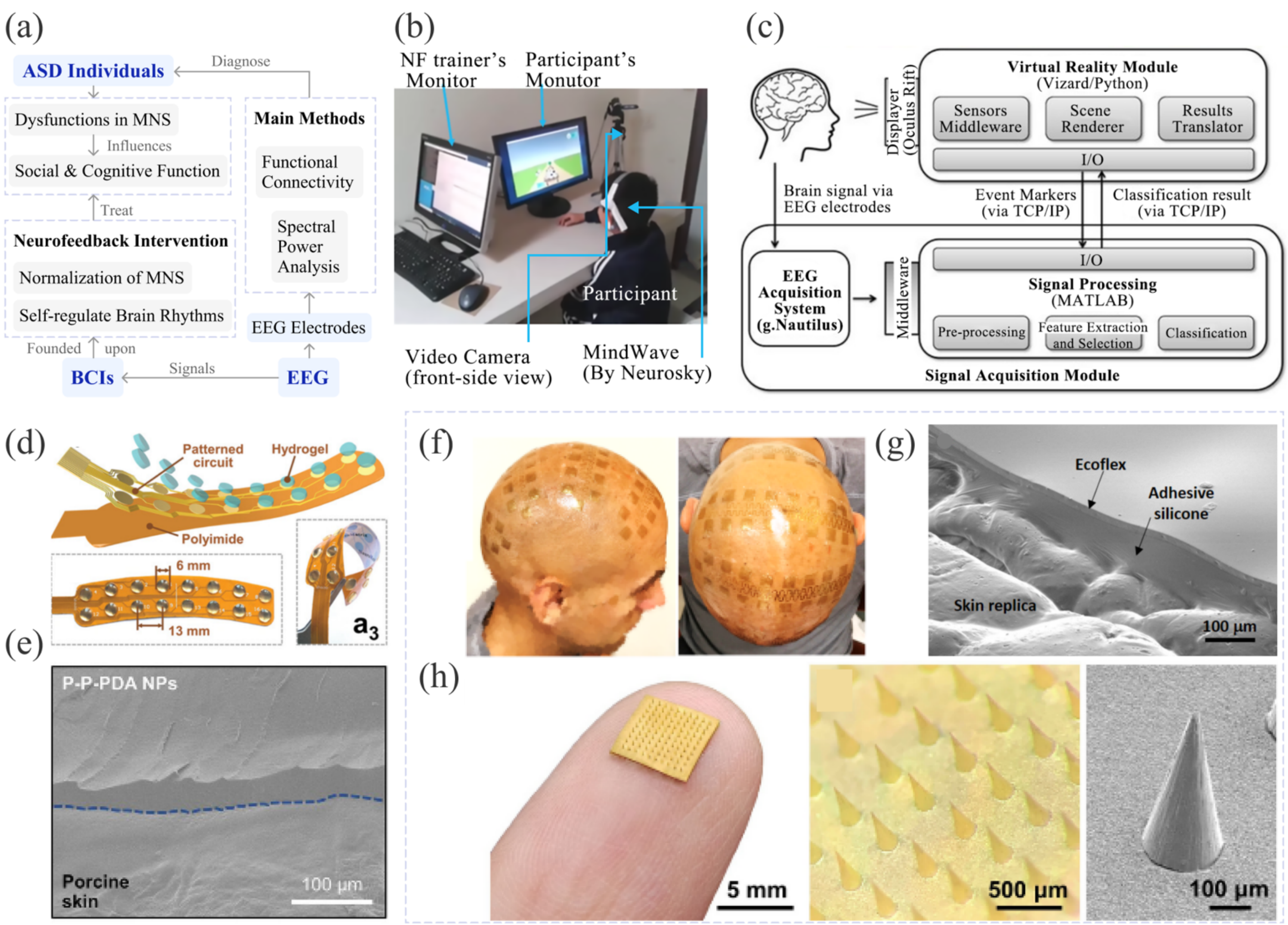

Fig. 2. EEG devices and electrodes. (a) The relationship between EEG and ASD intervention. (b) a BCI video game using neurofeedback. Reproduced from [40] with permission. (c) A BCI VR system for ASD intervention. Reproduced from [41]. CC BY 4.0 (d)(e) Multichannel hydrogel electrode [42]. (f)(g) Large-area magnetic resonance imaging compatible epidermal electronic interfaces [52]. (h) Micro-seepage electrodes with flexible and elastic tips [53].

PEDOT [54]) or by adding conductive fillers (metal/carbon-based nanomaterials) to the polymer substrate. Carbons-based materials, notably carbon nanotubes [55] and graphene oxide [56], have been proposed as alternatives to overcome obstacles such as metal corrosion, and insufficient polymer conductivity. Meanwhile, researchers have conducted numerous studies on electrodes-skin interfacial engineering. A most natural idea is to increase the contact area of the interface, which is primarily achieved by enhancing the electrodes' conformability. By optimizing the structural parameters of the stretchable serpentine mesh, a conformal contact with the skin texture can be obtained [57]. This open-mesh filamentary structure maximizes compatibility with functions such as magnetic resonance imaging (Fig. 2f), and its conformal interface (Fig. 2g) demonstrates potential in long-term EEG monitoring [52]. Another way to reduce interface impedance is microstructural design, e.g., foam[58], textile[59], micro-seepage [53], [60]. The foam and textile can make conformal contact with the irregular scalp surface, while the electrodes are extremely flexible and can adapt to the skin deformation. And micro-seepage electrodes with flexible and elastic tips can penetrate the skin stratum corneum to obtain high-fidelity EEG signals (Fig. 2h).

Flexible electrodes exhibit distinct advantages in ASD treatment, proffering heightened precision and enabling prolonged monitoring. Compared to traditional rigid electrodes, flexible variants yield more precise EEG recordings [61], elevate comfort levels, and boost participation willingness among individuals with autism. Additionally, flexible electrodes deliver superior signal quality compared to commercial products [62], increasing the accuracy of BCI systems [63] and aiding in the identification of autism brain activity patterns through intervention strategies, such as neurofeedback training. The incorporation of self-powered flexible material [64] furthers the potential for long-term monitoring, thereby facilitating efficacy validation and broader adoption.

B. Eye Tracking Systems: Capturing Gaze Data and Detecting Engagement

Eye tracking technology plays a pivotal role in the diagnosis and intervention of ASD by capitalizing on the distinctive eye movement patterns and visual attention traits of individuals with ASD (see Fig. 3a). It mainly measures fixations and saccades to provide objective data, critical for pinpointing unusual gaze patterns, such as diminished eye contact and altered focus on social stimuli [65], [66], [67]. These biomarkers are instrumental in discerning neurological differences inherent in ASD. In the realm of intervention, eye-tracking is valuable for customizing educational and therapeutic approaches. It achieves this by revealing insights into the cognitive and attentional predilections of individuals, thereby improving participation and educational outcomes [68].

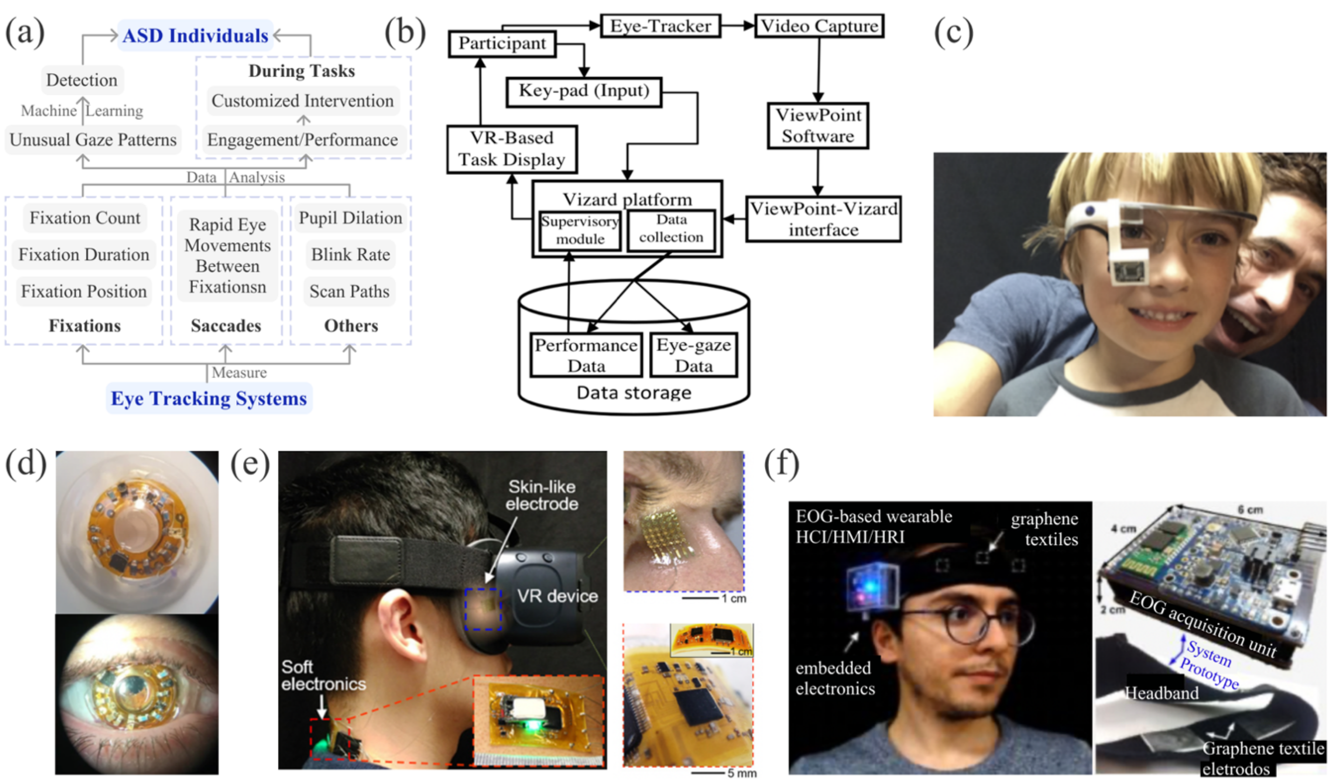

Fig. 3. Eye tracking Systems. (a) The relationship between Eye tracking and ASD intervention. (b) A VR platform uses eye-tracking to study how social distance and eye contact affect gaze physiology and task performance[21]. (c) A custom eye-tracker mounted onto Google Glass [69]. (d) Eye tracking system an infrared laser pointer embedded into a wireless smart contact lens. Reproduced from [70] with permission. (e) Soft, wireless periocular wearable electronics providing eye movement tracking through a combination of skin-conformal sensors and VR systems. Reproduced from [71] with permission. (f) Wearable eye tracking system based on graphene textiles, suitable for HMI. Reproduced from [72]. CC BY 4.0

Eye tracking technologies primarily include non-contact, invasive, and epidermal methodologies. Non-contact eye tracking devices hinge upon optics and imaging, such as desktop-mounted video oculography eye-trackers and wearable eye-trackers. While desktop-mounted video oculography devices are efficacious, their limited portability is a constraint [72]. Wearable eye trackers circumvent this limitation, yielding precise ASD biomarker measurements. Noteworthy commercial products such as those by Arrington and Tobii, have been harnessed in diverse studies. For instance, Lahiri et al. [68] captured gaze data using eye-tracker goggles in a VR system designed for communication skill training, assessing participants' task performance. Babu et al. [21], [73] developed a VR-based social communication platform (Fig. 3b), utilizing an external eye-tracker (ViewPointEyeTracker) to investigate the impact of social distance and eye contact on gaze-related physiology and participants' task performance. Nag et al. [69] mounted a custom eye-tracker onto Google Glass to measure gaze tracking and emotion recognition patterns (Fig. 3c).

Despite their convenience, these systems have notable limitations. Firstly, their accuracy can be affected by physiological variabilities [74] and image processing algorithms [75]. Secondly, the integration of eye tracking devices with VR equipment requires modification and recalibration with each movement, which increases costs and impedes technological dissemination [71].

Invasive eye tracking techniques, involving the implantation of electrodes or sensors to measure eye movements, offer heightened precision. To overcome the discomfort caused by traditional scleral search coils [76] and the inaccuracies associated with camera-based eye tracking methods, smart contact lens technology has emerged. Khaldi et al. [70] developed an eye tracking system (Fig. 3d) using an infrared laser pointer embedded into a wireless smart contact lens, providing a simpler and more compact solution to measure eye gaze. Subsequently, they encapsulated a photodetector into the scleral lens, refining gaze tracking accuracy via a camera-less paradigm [77], [78]. Recent strides manifest a multipurpose bio-monitoring integrated circuit proficient in blink detection, serving as the basis for a specific human-machine interface (HMI) [79]. However, the utilization of ocular near-infrared exposure might raise safety concerns [80]. To mitigate this, Zhao et al. [81] introduced a soft, stretchable, and flexible liquid metal material for eye movement detection. They developed an electronic device based on a Ga-In alloy and an induction coil to detect eye movements. Although these technologies enhance measurement accuracy and flexibility to some extent, direct eyeball contact remains a requisite, potentially imposing a sensory burden on individuals with autism.

Epidermal techniques mainly rely on electrodes attached to skin, which enable eye tracking by recording electro-oculography (EOG). EOG systems, admired for their simplicity and reliability, find applications in physiological state detection [82] and HMI [83], [84]. For example, Mishra et al. [71]utilized aerosol jet printing to fabricate highly stretchable, skin-like, biopotential electrodes (Fig. 3e), which can be integrated with a therapeutic VR environment to detect eye vergence with high sensitivity. Kim et al. [85]developed skin-attachable piezoelectric eye-movement sensors using safe and high-performance single-crystalline III-N thin films, which can detect saccades in children with autism, thus signifying disorder indicators. In the realm of HMI, Golparvar et al. [72]developed a wearable eye tracking system (Fig. 3f) based on graphene textiles, enabling remote control of objects through eye-operated mechanisms.

Flexible electronic technology opens new avenues for eye tracking research for ASD. Compared to conventional devices, flexible counterparts offer swifter calibration and heightened sensitivity to biological indicators. This technology can be seamlessly integrated into training platforms such as Responding to Joint Attention, providing novel HMI methods [72] and serving as objective criteria for assessing treatment progress. Additionally, flexible electronics can accurately measure eye movements, pupil diameter, and other signals [71], reflecting the visual patterns of individuals with autism. This provides important data for understanding the visual processing characteristics of them and developing effective intervention strategies. Furthermore, by analyzing eye tracking data in individuals with ASD, characteristic visual patterns can be identified as biological indicators [85], bolstering the precision of early ASD detection and diagnosis.

C. Emotion Monitoring Systems: Evaluation and Management

Individuals with ASD often experience significant emotional dysregulation, characterized by challenges managing and appropriately responding to emotional stimuli [86]. Such dysregulation manifests as heightened levels of stress [87] and anxiety [11], prevalent among individuals with ASD. These states can amplify emotional regulation difficulties, precipitating a reinforcing cycle that intensifies emotional challenges [88]. Heightened emotional reactivity and poor emotional control can lead to the emergence of challenging behaviors, such as aggression or self-injury [89], which are responses to the overwhelming emotional and sensory input that individuals with ASD may experience. These behaviors, often responses to overwhelming emotional and sensory input, can substantially diminish the quality of life for individuals with ASD and their families, highlighting the need for targeted interventions [90].

Wearable technology is emerging as a valuable intervention tool for identifying and managing emotional problems including stress and anxiety (see Fig. 4a). These devices monitor various physiological biomarkers—such as heart rate variability [91], respiratory sinus arrhythmia [92], and electrodermal activity [93]—which serve as indicators of physiological arousal and predictors of emotional and behavioral disruptions. The Affectiva Q-Sensor [94], [95], a device employed for monitoring stress and emotion in ASD interventions, assesses arousal levels by measuring electrodermal activity, though its emotion assessment capabilities are limited. Augmented by machine learning, multimodal sensors provide a more reliable approach for the measurement and interpretation of emotional states. For instance, Airij et al. [96] designed a real-time embedded device and determined user stress levels through a fuzzy-logic intelligent decision module, offering preemptive alerts regarding impending anxiety episodes in children with autism. Similarly, Tomczak et al. [97] developed a stress monitoring wristband (Fig. 4b) for an educational institution and generated reports to evaluate therapeutic effects. Furthermore, commercial wearable products, such as the LG Watch Urbane smartwatch [23] and Spire Stone [98], provide sensing systems and programmable development platforms, streamlining the development process for researchers.

However, extant research confronts challenges. The inaccuracy of traditional measurement methods underscores the necessity for advanced technology in personalized treatment [16]. Yet, the prohibitive cost of such cutting-edge technology poses a formidable obstacle to widespread adoption. In addition, wearable devices inadvertently stigmatize autism, impeding their acceptance and integration into daily life [99].

To address these concerns, flexible electronics offer new possibilities. Flexible materials, such as Polydimethylsiloxane (PDMS) [100] and Ecoflex [101], enable sensors to conform more closely to the texture of human skin, mitigating motion artifacts [102], thereby improving monitoring accuracy [103]. Additionally, flexible sensors can be seamlessly integrated into clothing, rendering physiological signal monitoring user-friendly and discreet. For example, the wearable smart T-shirt mentioned in Bin Heyat et al.'s research [104] for automatic real-time mental stress detection based on Electrocardiogram (ECG) used a silver-coated flexible dry electrode with screen printing technology, while Tocco et al. [105] employed a wearable device with a flexible sensor based on fiber Bragg gratings (Fig. 4c), detecting the wearer's fR in the working environment through chest wall deformation. Surface electromyography (sEMG) serves as a viable method for capturing emotional data and objectively assessing intervention therapy outcomes. Zhuang et al. [106] have further advanced this field by introducing a wearable facial expression recognition system that leverages deep-learning-assisted, soft epidermal electronics. This system adeptly addresses the constraints of conventional computer vision techniques, paving the way for innovative HMI modes.

Multimodal flexible sensing systems [107], [108], [109] have overcome the complexity of traditional monitoring devices and show promise as everyday monitoring devices for ASD intervention. Rosa et al. [110] proposed a multimodal sensing device based on Kapton flexible material, monitoring stress levels by collecting wearer's ECG, Galvanic Skin Response, temperature, and activity data; the skin device interface features textile electrodes, functioning as a chest patch. Extending this trajectory, Chen et al.'s research [111] incorporated a flexible amplifier with a commercially available flexible polyvinylidene difluoride mechanical deformation sensor and a pH chemical sensor, detecting the wearer's arterial pulse in the neck and sweat pH value (Fig. 4d), and integrating physical (piezoelectric) and chemical (pH) sensors with an organic thin film transistor circuit for stress assessment.

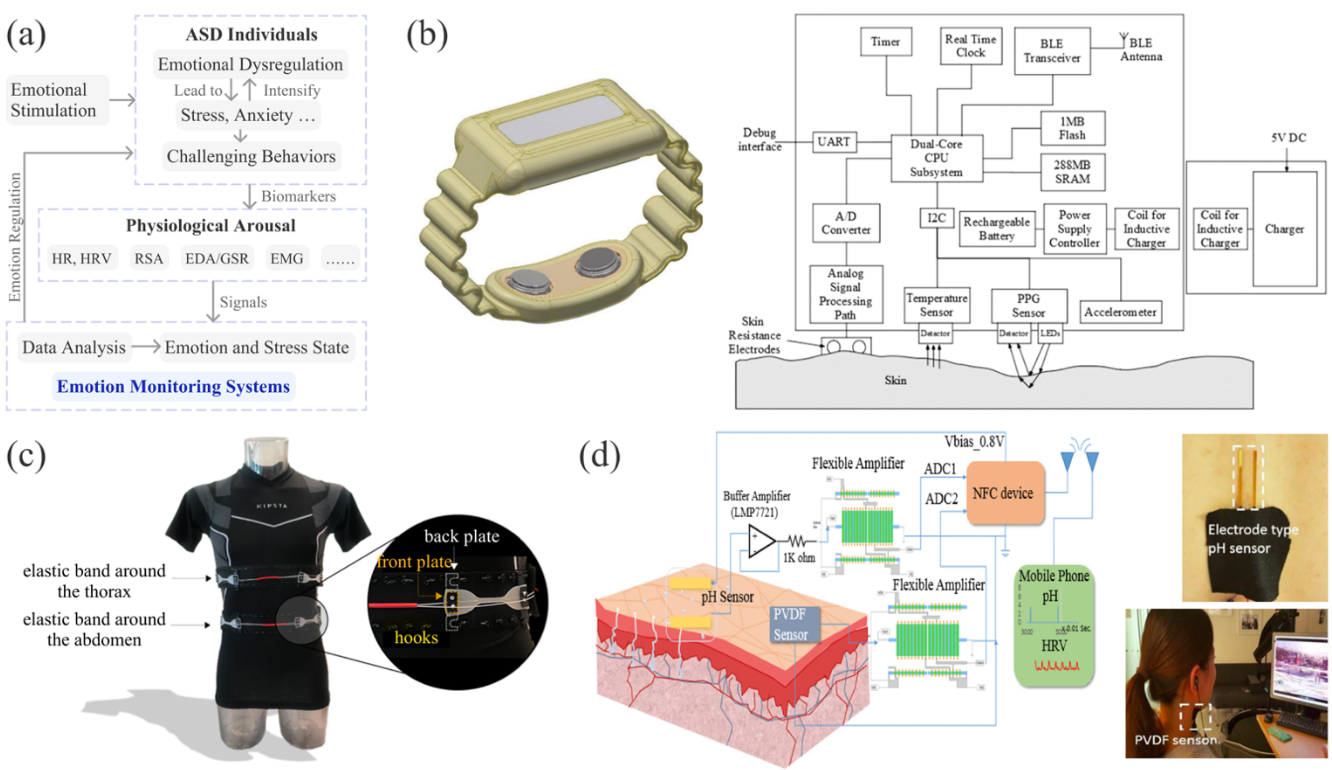

Fig. 4. Wearable system for emotion monitoring. (a) The relationship between stress monitoring and ASD intervention. (b) A stress monitoring wristband [97]. (c)Wearable device with a fiber Bragg gratings-based flexible sensor[105]. (e) A highly wearable FER system. Reproduced from [106]. CC BY 4.0 (d)Flexible wearable system with polyvinylidene difluoride sensor placed on the neck and pH sensor placed on the back [111].

In the future, the development of stress monitoring systems for individuals with ASD can take full advantage of flexible sensing electrodes, which break the form restrictions of traditional rigid sensors and allow for more natural ways of effective physiological data collection and classification recognition, such as through clothing [104] or skin patches [111]. Pioneering monitoring methodologies empower individuals with autism and their caregivers to understand patients' emotional states in real-time, enabling timely and effective stress management and further promoting the physical and mental health of them.

D. Motion Behavior Monitoring Systems: Used for Behavior Shaping, Motion Control, and Coordination

Individuals with ASD often exhibit a range of behavioral challenges, including repetitive behavior [112], aggressive behavior [113], [114], and communication difficulties [115], which significantly interfere with learning and social interactions. Traditional approaches like applied behavior analysis [116] address these issues through structured behavioral interventions. Recently, motion monitoring technology, founded on sensors and data processing algorithms, has been used to measure, identify, or predict behavioral problems. This technology not only complements traditional intervention methods, but also assists therapists in evaluating intervention effects and promotes behavioral shaping (see Fig. 5a).

Researchers have been dedicated to developing behavioral monitoring systems, seeking to bolster the potency of behavioral interventions and augment learning and social adaptation capabilities in those with ASD [117], [118]. Among these, stereotypical motor movements (SMMs), including repeated corporal rocking, mouthing, and complicated hand-and-finger gestures, are the most common behavioral characteristics of ASD. Traditional ways of measuring SMMs, such as observation and video, lack accuracy [119], timeliness, and flexibility [120] . In contrast, wearable technology proffers meticulous and time-efficient alternatives. Westeyn et al. pioneered SMM detection [121] with subsequent researchers leveraging various sensor technologies [122] and machine learning algorithms [123]. In this context, Min et al.'s research [124] tested the optimal placement of wearable accelerometers at the wrist and back. Similarly, Goodwin et al.'s research [125] used three wireless accelerometers placed on the wrist and chest, achieving an accuracy rate of about 90%（Fig. 5b）. Rad et al.'s study [126] addressed the question raised by Goodwin et al. on how to detect SMMs automatically and in real-time. The team accomplished more accurate detection through feature learning and transfer learning in convolutional neural networks.

The development of flexible motion behavior monitoring systems has enabled researchers to recognize subtle, intricate movements in individuals with ASD. For example, Amit et al. [127] designed a resistive touch-sensing glove for finger-tapping tests, which allows for the recognition of fine motor movements and can assess motion-based intervention measures (Fig. 5c). Similarly, Pezzuoli et al. [128] created a sign language translation system (Fig. 5d) called "Talking Hands" with 10 flexible sensors (Spectra Symbol), which provides assistance for non-verbal individuals or those grappling with communication difficulties.

Recent advancements in flexible sensors are poised to augment the efficacy of motion monitoring for individuals with ASD. Flexible sensors can be categorically distinguished based on their sensing principles into two types: those that assess acceleration and those that gauge deformation. Accelerometers measure acceleration along one, two, or three axes to decipher movements made by the wearer [129]. For example, Yamamoto et al. [130] proposed a multifunctional printed flexible sensor equipped with a triaxial accelerometer that can be directly attached to the skin for body motion monitoring. Subsequent endeavors affixed a triaxial accelerometer on a polyethylene terephthalate (PET) film, employing a kirigami structure to improve the comfort of wearing, though a lack of high flexibility was noted [131]. Addressing this, He et al. [132] manufactured a motion monitoring accelerometer (Fig. 5e) by combining intrinsically flexible Ecoflex, island–bridge configuration and serpentine structure connections.

Deformation measuring sensors, including pressure and strain sensors, calculate pressure or deformation by measuring resistance, piezoelectricity, capacitance, and triboelectricity during the stretching process. Researchers use various materials and structures to improve sensor performance. For instance, a strain sensor based on a 3D graphene foam and PDMS composite material exhibits high flexibility and sensitivity and has been successfully used to detect human motion, such as elbow and finger bending [133]. Beyond polymers [134], hydrogels with skin-like self-healing abilities [135], [136], and aerogels with good compliance and extensibility [137], also serve as potential substrate materials. Additionally, fabric sensors, noted for their superior breathability, skin conformity, and repeatable usability, have received attention in the wearable domain. For example, Zhou et al. [136] developed a wearable sign language translation system (Fig. 5f) based on a stretchable sensor array and wireless printed circuit board made from yarn. With the help of machine learning algorithms, the system achieved a 98.63% recognition rate for American Sign Language (ASL). Furthermore, Wang et al. has reported on tattoo-like electrodes, which hold promise for applications in ASL recognition via sEMG [138], offering assistance for communication challenges.

In terms of motion behavior monitoring, the development of flexible electronics heralds novel therapeutic prospects for ASD intervention. On the one hand, flexible sensors based on composite materials can measure and recognize subtle movements more precisely [133], pivotal for understanding and intervening in behavioral features like SMMs. On the other hand, flexible sensors extend the application range of wearable systems. With excellent biocompatibility [137], they are suitable for new scenarios such as telemedicine, sign language translation, subtle movement recognition [139] and interaction in VR [140].

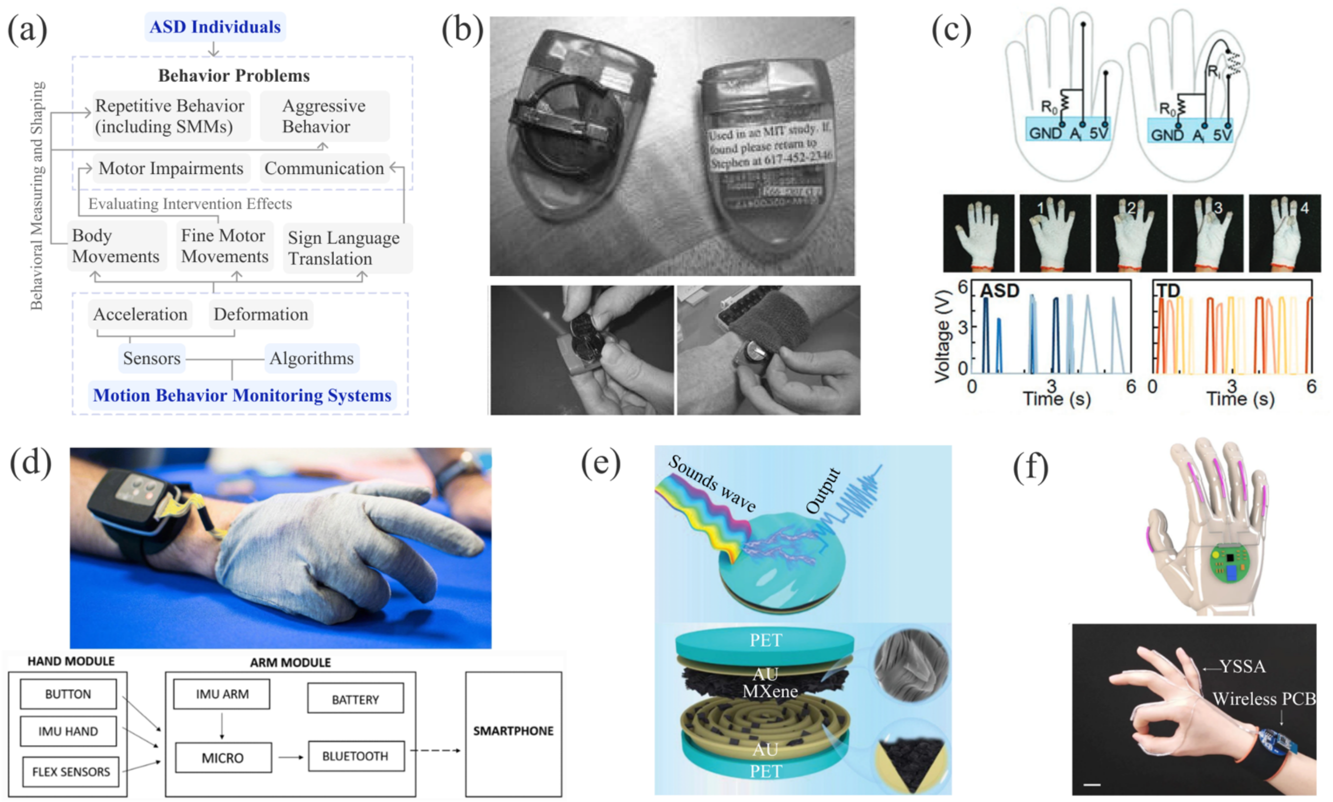

Fig. 5. Flexible Devices for Motion Monitoring. (a) The relationship between motion behavior monitoring and ASD intervention.(b)Wireless accelerometers placed on the wrist and chest to measure SMMs. [125] (c)&(d) Flexible motion monitoring systems for motion-based intervention measures and sign language translation for ASD. Reproduced from [127],[128] with permission. (e) Flexible piezoresistive multifunctional microforce sensor based on microchannel-limited MXene. Reproduced from [132] with permission. (f) Wearable sign-to-speech translation system based on yarn-based stretchable sensor arrays and wireless printed circuit boards. Reproduced from [136] with permission.

III. Wearable Systems For Interventions Through Sensory And Interactive Feedback

With the surge of technological innovation, conventional intervention approaches have been shifted towards interactive digital learning. Advanced tools such as computers, tablets, and interactive whiteboards, enhancing the learning experience beyond conventional classroom settings with educator involvement.

This section delineates the integration of visual, auditory, and tactile feedback mechanisms within wearable systems specifically designed for autism intervention. Furthermore, it elucidates state-of-the-art research in wearable electronics. These burgeoning advancements facilitate tailored sensory feedback for individuals with ASD. The developments underscore the potential for a more personalized and technologically-informed approach to ASD intervention, aligned with contemporary paradigms in both pedagogical theory and practice.

A. Wearable Displays: Visual Feedback

Individuals with ASD often exhibit visual thinking patterns and a reliance on visual environments, suggesting that visual cues can facilitate their learning and increase their engagement [141], [142]. Visual elements are widely used in traditional intervention treatments [143], including behavioral interventions [144], [145], sensory-motor support [146], and language interventions [147]. The advent of wearable displays, which provide customized, adjustable visual feedback and real-time intervention, marks a significant supplement to traditional interventions (Fig. 6a).

In response to the growing demand for personalized healthcare monitoring and more realistic wearable VR/Augmented Reality (AR) systems, there has been rapid advancements in wearable display technologies in recent years [148]. The primary devices in this domain are Head-Mounted Displays (HMDs) and smart glasses. The safety, usability, sense of presence [149], and intervention effectiveness [150] provided by HMDs have been validated, gaining positive reception among children with ASD [151]. An example is the Brain Power System (BPS), developed by the University of Cambridge based on Google Glass [152]. BPS offers targeted, personalized AR tutoring through gamified applications (Fig. 6b), encompassing emotion recognition, facial orientation gaze, eye contact and behavior self-regulation, all while facilitating directional data collection and reporting. Another notable product is the Superpower Glass (Fig. 6c), co-developed by Stanford University and Google, standing as a commercial embodiment. This product proficiently recognizes facial expressions [153] and has conducted the first randomized clinical trial demonstrating the effectiveness of wearable digital interventions in improving social behavior in children with ASD [27]. In addition, the Hand-in-Hand platform developed by Zhao and colleagues [154] offers a natural and visual approach for children with ASD to practice linguistic behavior.

At the vanguard of wearable technology lies flexible displays, poised to transform the landscape of ASD interventions with their high degree of customization and non-intrusiveness. These displays, characterized by their skin-like thinness, lightness, and functionalities [155], can be seamlessly integrated onto the skin surface, minimizing perceptual divergence from the natural state of skin. Noteworthy advancements include the use of OLEDs to fashion traditional thin-film displays [156], and the development of Polymer Light-Emitting Devices (PLEDs) [157] and highly stretchable light emitting capacitors [158] for enhanced display area and skin compatibility. Integrated into health monitoring systems as data visualization interfaces, these displays can provide real-time feedback on body data, location, motion status, emotion, and other critical information. For instance, the wearable cardiac monitor by Ja Hoon Koo et al. [159] displays real-time human ECG changes with wearable color-adjustable OLEDs integrated with carbon nanotube electronics, providing guidance for the design of wearable health indicators. Yokota et al. [160] have proposed an optoelectronic skin (Fig. 6d) by integrating green and red PLEDs with OPDs, producing a highly flexible reflective pulse oximeter (conformable three-color) capable of directly visualizing blood oxygen concentration data on the body.

Comparatively, fabric displays possess larger display areas and greater stability. These displays, composed of fibrous materials and multifunctional electronic devices, have been applied to various wearable systems [161], [162], [163]. Peng et al. [164] exhibited a wearable monochrome display textile with touch sensing and biosignal detection capabilities (Fig. 6e). It can serve as interactive clothing, health monitoring equipment for real-time brain signals and emotional state display or a language communication tool, with a keyboard and power source integrated. Similarly, Choi et al. [165] developed a smart fabric system that monitors and displays color environmental and physiological signals in real-time through temperature, biosignals, and other sensing modules.

Flexible electronic displays offer potential for enhancing ASD intervention systems. For example, within the Treatment and Education of Autistic and Related Communication Handicapped Children programs, flexible

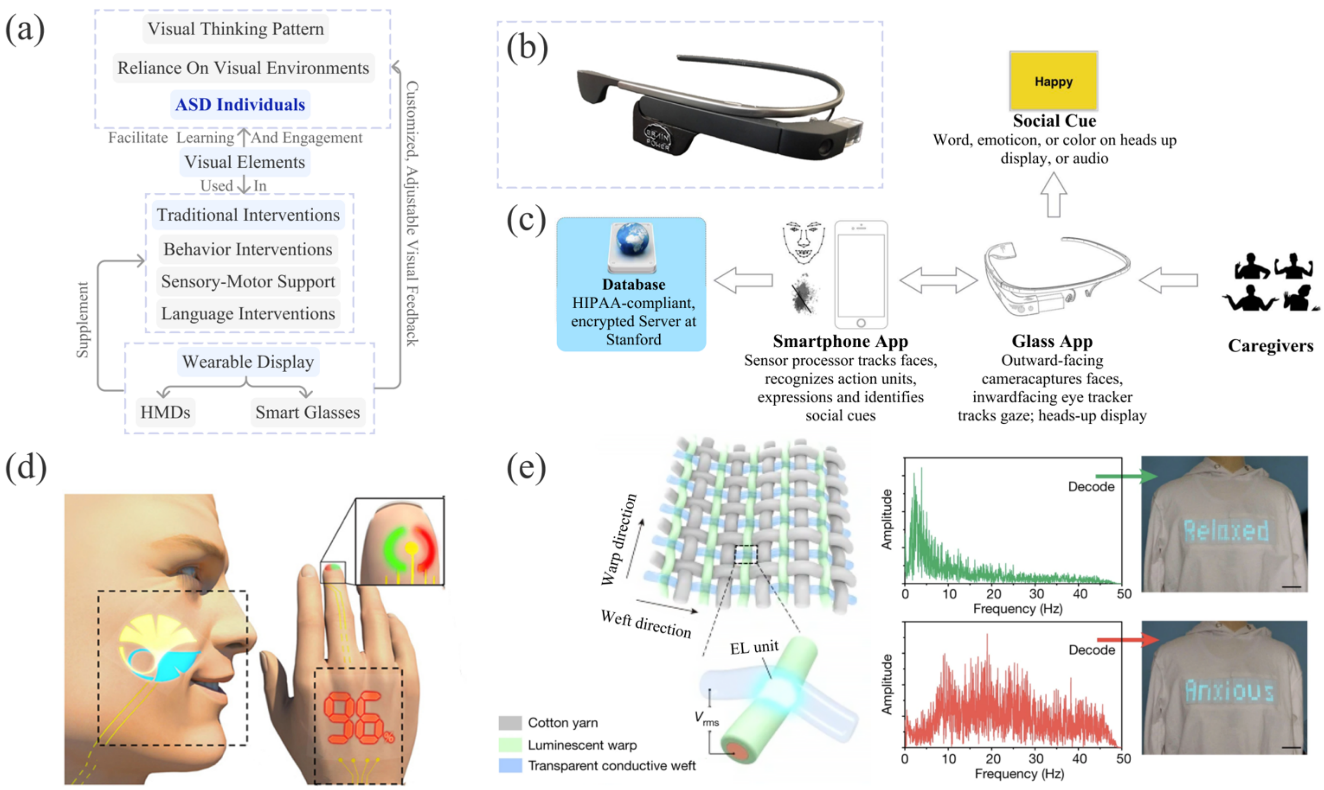

Fig. 6. Wearable visual feedback systems. (a) Visual feedback in ASD interventions. (b) BPS based on Google Glass. Reproduced from [152]. CC BY 4.0 (c) The Superpower Glass [153]. (d) Smart e-skin system comprising health-monitoring sensors, displays, and ultraflexible PLEDs. Reproduced from [160] with permission. (e) Wearable display textile, can be used as an interactive device or medical monitoring system. Reproduced from [164] with permission.

wearable wristbands can provide personalized visual prompts, aiding ASD individuals in understanding and predicting daily activities [166], [167]. Moreover, when synergized with physiological signal collection devices, they can provide real-time feedback on bodily information, facilitating timely intervention. Through this technology, information can be displayed directly on skin or clothing, rendering displays remarkably adaptable. An intriguing concept envisions real-time visualization of a patient's emotional state on clothing via flexible electronic displays, fostering understanding and support from others [164]. These applications not only offer personalized visual feedback and cultivate life skills but also furnish instantaneous insights into physical and emotional states, thereby improving intervention outcomes and quality of life.

B. Acoustic Devices: Auditory Feedback

Acoustic devices are indispensable components in ASD intervention and support systems, serving diverse functions from noise reduction to auditory feedback provision. They serve to either block noise to alleviate sensory chaos caused by the environment [165], [167], or provide auditory feedback to help patients regulate their behavior and emotions [151], [154], [168] (Fig. 7a).

Two significant applications of acoustic devices are for treating hyperacusis and music therapy. Hyperacusis, one of the major sensory difficulties faced by individuals with ASD [169]. Is commonly addressed through Habituation Training, Cognitive Behavioral Therapy and Auditory Integration Training. Wearable devices, especially noise-canceling headphones, play a role in controlling hyper-reactivity to auditory stimuli [170]. In the innovative Listening Project Protocol (LPP), computer-modified music (filtered music) that enhances the features of human prosody is provided through headphones (Fig. 7b), theoretically training the neuroregulatory function of the middle ear muscles [171]. In addition, Music therapy, another realm, is interwoven into a spectrum of wearable interactive systems [172], [173], [174], [175], [176]. This therapy takes advantage of the response patterns of individuals with ASD to music, improving their physiological responses and behavioral disorders, and establishing new adaptive responses [177].

Despite their benefits, acoustic devices can sometimes cause additional tactile stimulation, leading to overreact or drop out midway in ASD individuals. Flexible electronics technology offers a possible solution, particularly beneficial for those with sensory overload issues. Flexible audio circuits can be integrated into intricate systems and customized to meet specific intervention treatment needs. For example, a graphene-based artificial throat by Tao et al. [178] functions as both a speaker and a microphone, recognizing the unintelligible sounds emitted by people with speech impediments and transforming them into controlled and precise language expressions (Fig. 7c). Further, Han et al. [179] introduced an ultrathin flexible loudspeaker based on a piezoelectric microdome array, capable of turning surfaces into low-power, high-quality audio sources, potentially fostering low-noise comfortable environments for individuals with ASD.

However, most of the reported flexible acoustic devices exhibit inferior performance, mainly due to their inherent flexibility. Addressing these challenges is crucial, as seen in the work of Kang et al. [180], who developed transparent, volume-adjustable speakers and microphones based on hybrid nanomembranes. Their excellent thermoacoustic performance and low heat loss are particularly suitable for applications in wearable medical systems. Xiang et.al. [181] designed a rod-based, flexible piezoelectric sensor to improve the sensitivity performance (Fig. 7d). These development hold promise for wearable acoustic interactions [182], [183].

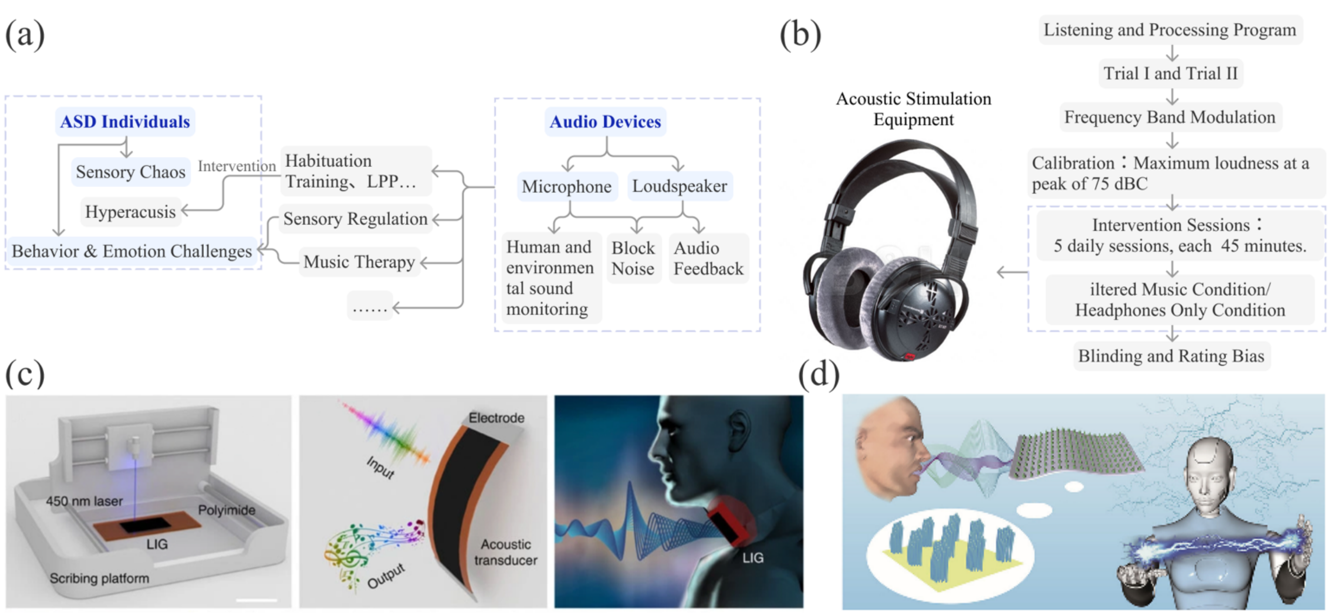

Fig. 7. Wearable audio devices. (a) Audio Feedback in Autism Intervention. (b) The Procedure of LPP and acoustic stimulation equipment (Beyerdynamic DT831) used in LPP. (c) Graphene-based artificial throat. Reproduced from [178] with permission. (d) A rod-based, flexible piezoelectric sensor [181] .

Flexible electronic acoustic devices are expected to open new avenues in ASD research and therapy. For example, flexible speakers integrated into medical systems such as motion monitoring [184], can assist ASD patients in managing their atypical behaviors more effectively through auditory feedback mechanisms. Moreover, these devices can recognize and transform ambiguous sounds [178], providing an effective communication tool for non-verbal ASD patients.

The portability and versatility of these audio devices, offering auditory cues, noise control, and Augmentative and Alternative Communication [185], surpass traditional speakers and headphones, heralding a new era in personalized and effective ASD intervention strategies. Ongoing research in this field is likely to expand these capabilities, further integrating these technologies into everyday interventions for individuals with ASD.

C. Wearable HMIs Providing Haptic Feedback

Recent advancements in wearable haptic feedback devices have been proven to help improve functional living among individuals with ASD. Their role lies in managing sensory-perceptual anomalies and supplementing visual and auditory cues. These devices enhance adaptability or the learning of new skills by simulating haptic sensations in social or learning scenarios. Haptic feedback is used in interventions such as sensory integration therapy, fine motor training, and other VR-based interventions (Fig. 8a).

Tactile sensitivity and motor anomalies in individuals with ASD may be associated with emotional factors [186]. Touch therapy, as part of sensory integration training, is beneficial for the psychological health and treatment of ASD [187]. Relevant applications include a vibrotactile gamepad developed by Changeon et al. [188] (Fig. 8b) and a vibratory haptic interface proposed by Mustafa et al. [189]. Additionally, a tactile sleeve designed by Tang et al. [25] and a wearable haptic device by Beaudoin et al. [190] use tactile stimulation to help individuals with ASD deal with the intense emotional responses caused by social activities or environmental changes.

To evaluate and improve the fine motor skills of children with ASD [154], [155], tailored wearable systems have been designed. For instance, the touch-sensing glove by Amit et al. [127], and the Haptic-Gripper virtual reality system proposed by Zhao et al. [191], [192] detect the user's grip strength and hand position, providing tactile feedback to guide hand movement and grip control (Fig. 8c).

The pursuit of heightened realism in VR environments for ASD interventions has propelled the integration of haptic interfaces [193]. To achieve this goal, Meindl et al. [194] simulated the feeling of a needle insertion using an Apple Pencil, while Simões et al. [150] created a VR environment that is completely identical to the real environment by providing identical visual and haptic inputs. Currently, the introduction of haptic interfaces is a focus of research to further enhance the realism of VR environments [168], [191], [193].

Flexible haptic interfaces, overcoming the limitations of traditional rigid component tactile devices, enable diverse sensory experiences such as temperature perception and large-area simulations, crucial for realistic VR interventions [195], [196]. Thermal tactile devices epitomize this concept, where the heat perceived by the skin can provide rich physical information about the environment and objects, such as the wearable VR skin thermal tactile device developed by Lee et al. [197] based on a feedback control algorithm. Other applications include haptic feedback through vibration or force patterns. Kahye Song et al.'s VR glove [198] uses a soft pneumatic actuator and a flexible piezoelectric sensor to cater to direct touch and virtual object interaction, which can meet the user's need for direct touch and experience of virtual objects. In addition to providing force-heat multi-touch simulations, flexible electronics have unparalleled advantages in large-area, spatio-temporally programmable simulations. For example, Yu et al. [199] demonstrated skin-integrated wireless haptic VR interfaces that convey sensory information through spatio-temporally programmable patterns of localized mechanical vibrations (Fig. 8d). This device has multiple application scenarios, with the figure showing its simulation of the sense of touch in virtual social scenarios. A study by Jung et al. [200] demonstrated a flexible device performing programmable touch patterns on a large area of skin (Fig. 8e), and this wireless haptic interface could be used as a wearable product in rehabilitation. In contrast to thermal and mechanical simulators, electrotactile feedback systems, exemplified by the innovative work of Kuanming Yao et al. [201], enrich the realm of immersive virtual reality encounters by enabling tactile stimulation and assessing users' sensation thresholds. Building on previous research, Sun et al. developed a wearable ring (Fig. 8f) with integrated triboelectric and pyroelectric sensors for tactile and temperature perception, along with vibrators and heaters for haptic feedback, enabling enhanced virtual interactions and immersive experiences in the metaverse [194].

In the forthcoming landscape, customized and large-area haptic feedback interfaces promise to revolutionize ASD intervention therapies, particularly by enhancing adaptation to environmental changes and the realism of VR systems. For example, flexible haptic interfaces can simulate haptic stimuli [192] to help individuals with ASD adapt to environmental changes and social interactions. Additionally, integrating haptic interfaces into VR systems will further enhance the realism of virtual environments, thereby promoting the effectiveness of interventions [200].

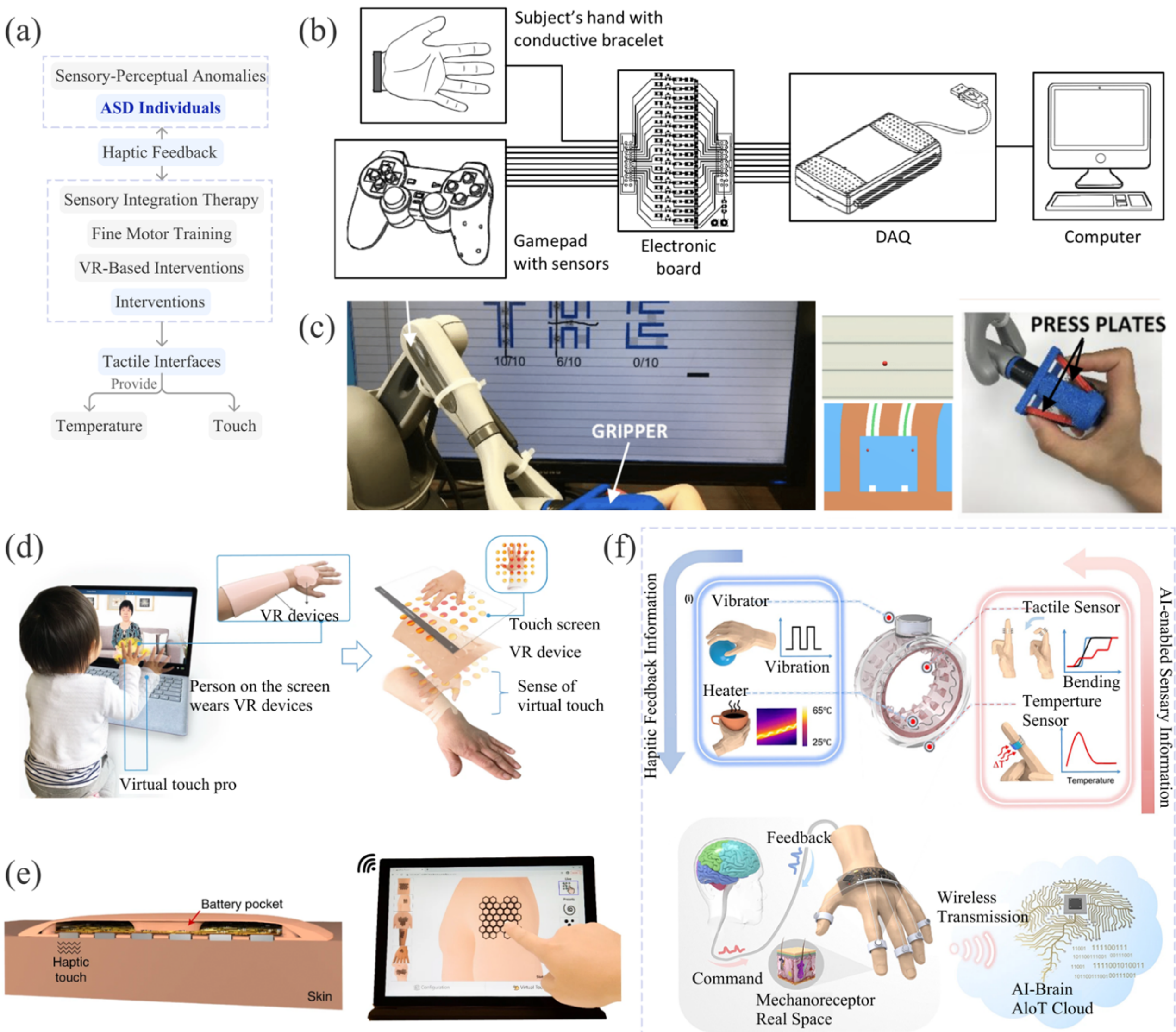

Fig. 8. Wearable tactile devices. (a) Haptic feedback in ASD interventions. (b)A vibrotactile tactile gamepad for transmitting emotional messages [188]. (c) The Haptic-Gripper virtual reality system[191]. (d) Skin-integrated wireless haptic VR interfaces. Reproduced from [199] with permission. (e) Wireless haptic interface for programmable patterns of touch across large areas of the skin[200]. (f) Augmented tactile-perception and haptic-feedback rings with multimodal sensing and feedback capabilities. Reproduced from [202] with permission.

IV. Conclusion and Outlook

We have explored a burgeoning research area that integrates wearable technology into ASD intervention systems. The objective has been to uncover novel prospects that wearable technology can introduce to daily support and intervention for individuals with ASD. Categorically, we divide wearable technology for ASD into systems of signal acquisition and interactive feedback. The former hinges on wearable sensors to gather physiological data from individuals with ASD, offering real-time monitoring of their neural activities, attention states, and stress states. This is beneficial for the implementation of targeted personalized intervention therapies and for assisting them in better participating in social life. The latter, meanwhile, provides more engaging, natural, and effective intervention strategies through sensory stimulation and feedback such as visuals, acoustics, and haptics. We have detailed the principles and specific applications of wearable technology in treatment, while also spotlighting promising flexible electronic technologies with application potential. Table 1 provides the details.

TABLE I
The Wearable Technologies for ASD

Classification	Technology Items	Measured Quantity	Purpose	Form	Applications in ASD	Limitation	Potential Novel Technologies	
							Type	Ref
Signal acquisition	EEG	Brainwaves (Delta	(1) Detection of Abnormal Brain	EEG caps /headsets	[24], [40], [41]	Poor signal quality,	Wet electrodes	[42], [43], [44], [45],

		, Theta, Alpha, Beta, and Gamma waves)	Activities; (2) Neurofeedback intervention.	/headbands …		prolonged user adaptation, uncomfort		[46]
							Dry electrodes	[52], [57], [53], [58], [59], [60].
	Eye Tracking	Fixations, Saccades, pupil diameter, blink frequency…	(1) Diagnostic identification through unique visual patterns; (2) Customizing intervention based on individual attention.	Glasses /contact lens …	[21], [68], [69], [73]	Variable accuracy, integration challenges	Invasive	[70], [77], [78], [81]
							Epidermal	[71], [72], [82], [83], [84], [85]
	Emotion	HR, HRV, RSA, fR, EDA/GSR,EMG…	(3) Predicting Emotional Problems; (4) Assisting in Emotion Regulation.	Watch/ wristband/ chest patch…	[23], [94], [95], [96], [97], [98]	Measurement inaccuracy, high costs, stigmatization concerns	Specific physiological indicators	[104], [105] [106]
							Multimodal Sensors	[107], [108], [109], [110], [111]
	Motion Behavior	Acceleration/ Gyroscope data, deformation (pressure and strain)	(1) Behavior challenge measurement; (2) Intervention evaluation and enhancement.	Wristband/ gloves…	[121], [122], [113], [124], [125], [126] [127], [128]	Restricted range of motion, insensitivity to fine movements	Acceleration	[130], [131], [132]
							Deformation	[136], [137], [138]
Interactive feedback	Displays	\	(1) Improving engagement; (2) Aiding in behavioral interventions, support sensory-motor and language development.	HMDs/ smart glasses/ clothes…	[152], [153], [154]	Intrusiveness, Integration challenges, user-unfriendliness	skin-like	[156], [157], [158], [159], [160]
							Fabric	[161], [162], [163], [164], [165]
	Acoustic Devices	\	(1) Blocking noise; (2) Behavior and emotion regulation.	Earphones …	[170], [171], [172], [173], [174], [175], [176]	Tactile stimulation	Noise-Reducing	[179]
							Auditory feedback/ communication	[178], [180], [181]
	HMIs For haptic feedback	\	(1) Sensory integration therapy; (2) Fine motor training.	Gripper/ gloves/ sleeves/ rings…	[25], [127], [190], [191], [192]	Unreality in virtual environment	Single-modal (thermal/ mechanical/ electro)	[197], [198], [199], [200], [201]
							Multi-modal	[202]

As an interdisciplinary field, wearable technology for ASD poses challenges to researchers who must grapple with understanding both the needs of individuals with autism and the potential of wearable technology. However, the two disciplines exhibit different tendencies: ASD research tends to explore the mechanisms and clinical effects of various interventions, while wearable technology focuses more on device manufacturing, performance, usability, and user experience. For the development of related products, such as BCI devices for neurofeedback interventions, technological feasibility exists, but their effectiveness in ASD intervention still needs clinical validation and support from neuroscience and rehabilitation professionals. The reported ASD wearable technology is only an initial stride, and the objectives for future work will be interdisciplinary collaboration, the introduction of more advanced technologies, improved user experience, and more reliable intervention effects.

Research in this field remains at a nascent stage, primarily encompassing conceptual design and prototype development, lacking extensive user testing and mature commercial products. Envisioning the horizon of future ASD wearable systems, several challenges beckon attention. Firstly, the technology within ASD products trails the evolution of wearable technology, implying that cutting-edge technology is yet to be fully harnessed by users. In the wearable systems discussed above, many devices employ early, immature technology, leaving ample room for improvement in terms of weight, measurement accuracy, and wearing comfort. Hence, it is imperative to integrate flexible electronic technology, which can guide subsequent developers in opting for more comfortable, durable, adaptable, and biocompatible technology. Secondly, the effectiveness of wearable technology in naturalistic settings needs verification. Many studies lack rigorous scientific validation methods, sufficient sample sizes, and long-term follow-up observations, raising doubts about their actual assistive or therapeutic effects on the autistic. Expanding sample sizes and obtaining clinical evidence can prove effective strategies in this regard. Lastly, user trust and technical applicability also require attention. Children with autism may have hypersensitive reactions to external stimuli and objects, potentially impeding their understanding or acceptance of such technologies. Therefore, wearable technology needs to provide a more comfortable user experience and easier-to-accept forms (such as cartoon characters, games, etc.). Flexible electronics have already charted a reliable direction for solving these problems.

In the future, collaborative interdisciplinary efforts will shape the trajectory of ASD wearable systems. As researchers converge insights from ASD studies and wearable technology advancements, the stage is set for innovations that elevate user experience and clinical effectiveness. By embracing flexible electronic technologies, we anticipate the refinement of existing interventions and the emergence of novel approaches that promise a more personalized, humane, and efficient direction for ASD intervention therapy. This dynamic synergy will pave the way for wearable technology to make an indelible mark on improving the lives of individuals with ASD.

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