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Braille glove design toward interdisciplinary approach for visually impaired people: developing independent sensing design with MXene and embroidery

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Abstract
This study developed a wearable device designed to aid visually impaired people (VIP) who are unfamiliar with Braille and/or struggle to learn and use Braille employing the design thinking process. VIP often face challenges in learning and using Braille, and even with existing equipment, including smart technologies, they frequently experience aesthetic and emotional discomfort beyond usability and accessibility. The interdisciplinary research team conducted mixed-method research following the double diamond module of the design thinking process. Initially, qualitative interviews to analyze VIP's Braille utilization were conducted to derive design factors. Subsequently, identified design factors were applied to conduct experiments with appropriate embroidery methods and connection structures using MXene-coated yarn. The strategies effectively enhanced pressure sensing performance by two times and realized highly localized and independent sensing to enable Braille recognition. Finally, a specific design for the wearable Braille recognition glove was proposed that incorporated these findings. The proposed wearable glove, equipped with a high-performance Braille recognition sensor, is designed to enhance the psychological and aesthetic satisfaction of VIP. The glove's universal design and accompanying technical support allow VIP to maintain their existing Braille reading methods while enjoying enhanced performance and avoiding social stigmas.

Keywords: Braille, Design thinking, Interdisciplinary research, MXene, Sensing, Visually impaired

Introduction
The life quality of visually impaired people (VIP) has emerged as a significant concern for those seeking to foster inclusive societies. Visual Impairment (VI) encompasses a broad spectrum ranging from mild vision loss to complete blindness. The etiology, classification, and severity of the impairment vary significantly based on geography, socioeconomic status, and the individual's life stage (Aghazadeh et al., 2021; World Health Organization, 2023). Approximately 2.2 billion people are visually impaired globally, and the population is growing worldwide; Moreover, half of these individuals have developed

visual impairments during their lives (Islam et al., 2020; World Health Organization, 2023). Therefore, anyone can face the widespread social issue of visually impaired in contemporary society (Bourne et al., 2021; Brunes et al., 2019; Varma et al., 2016). Loss of vision impedes VIP's efforts to carry out daily activities (Binns et al., 2012). Braille provides VIP a means of accessing important daily information, enabling them to engage in personal communication, reading, and professional correspondence (Martiniello et al., 2022). Previous studies regarding assistive devices for VIP's Braille usage have generally assumed that the users could comfortably read Braille. These studies examined swift and convenient Braille input (Yong, 2013), Braille recognition (Al-Qudah et al., 2014; Nicolau et al., 2013), and the conversion of digital information into Braille (Echenique et al., 2010; Harish, 2020). In addition, many studies aiming to develop VIP assistive technologies have focused on the production of technology-based tools rather than designs that address the actual needs and problems users experience in their daily lives (Hu et al., 2019; Khan & Khusro, 2021; Oliveira et al., 2011). However, given that VIP often face challenges in learning and using Braille, these solutions might not be effective for them in daily life. Although people with disabilities are becoming more prevalent in social and professional life, research regarding fashion item-related motivations and demands of consumers with disabilities remains limited (Chang et al., 2013).Therefore, this study aimed to develop a wearable device designed to aid VIP who are not familiar with Braille or who find it challenging, thereby making their daily Braille-reading experiences convenient and emotionally and aesthetically satisfying. Our interdisciplinary research team conducted a mixed-methods study—comprising qualitative research and experiments—following the Design Thinking Process (DTP) to understand the practical Braille usage needs of VIP and to design viable solutions that can assist them. The research questions for this study were as follows: 1) What are the challenges VIP face when acquiring Braille information, and what are the design needs for users to develop assistive devices? 2) What is the design factor-based total solution of design from formation to sensing effect concerning users' emotional and aesthetic comfort?

Literature Review

Braille system for visually impaired

VIP follow a distinct reading and writing system. Invented by Louis Braille, the "Braille System" serves as the predominant tactile language for VIP (Jiménez et al., 2009). Braille comprises coded characters arranged in a consistent configuration of six raised dots within a cell-based spatial unit. This character system is widely employed by VIP, because it facilitates the storage and transmission of information through tactile perception rather than visual cues (Saikot & Sanim, 2022). In general, Braille usage is recognized as having a positive impact on the learning and daily lives of VIP. VIP who are proficient Braille readers demonstrate higher education levels, employment rates, and financial well-being than those who have learned to read using print media (Ryles, 1996). Additionally, they dedicate significant time to reading books (Ryles, 1996). Therefore, Braille literacy influences VIP's educational attainment, academic achievements, employment prospects, and income (Bell, 2010; Martiniello & Wittich, 2019; Rosenblum & Herzberg, 2015). By enabling VIP to read, write, acquire knowledge, and access information, Braille empowers them to become independent members of society.

Challenges in using braille system

VIP typically learn Braille through a lengthy and challenging process of memorizing the dot patterns for each letter of the alphabet (Jekal et al., 2024; Saikot & Sanim, 2022). They encounter numerous difficulties during this learning journey. Despite recognizing the importance of Braille for academic pursuits, job performance, accessing information, and restoring self-esteem, the complexity of learning Braille often creates educational obstacles and exacerbates difficulties in finding suitable educational institutions. Consequently, some individuals give up on learning Braille altogether (Ardiansah & Okazaki, 2020; Martiniello et al., 2022). Moreover, only a small fraction of individuals with acquired visual impairment who are more accustomed to the visual system or experience reduced tactile sensitivity due to comorbidities can effectively utilize Braille (Röder et al., 2004; Saikot & Sanim, 2022). Furthermore, the availability of Braille education services and aids for adults or the elderly who have lost vision later in life is severely limited (Martiniello et al., 2018).

As a result, various researchers are examining ways to support the learning and practical applications of Braille by VIP in their daily lives (Al-Qudah et al., 2014; Harish, 2020; Nicolau et al., 2013; Yong, 2013). However, the situation of the majority of VIP who cannot read Braille is often insufficiently addressed. In some cases, devices specifically designed for VIP may even result in decreased satisfaction because of technology-based design issues (Shinohara & Wobbrock, 2011). Beyond usability problems, VIP tend to prefer devices with a neutral appearance to avoid social stigmas (Dos Santos et al., 2022). Instead of utilizing Braille or assistive technologies that recognize Braille, VIP often rely on systems that directly convert text into speech, leading to psychological and physical detachment from Braille as a medium (Jekal et al., 2024; D'Andrea, 2012; Martiniello et al., 2018). This highlights the need for user-centered assistive devices that facilitate comfortable and independent Braille reading for VIP.

Methods

This research framework followed four stages of the applied Double Diamond model developed by the UK's Design Council (Design Council, 2005; Kochanowska, & Gagliardi, 2022), one of the Design Thinking Process (DTP) methodologies (Fig. 1). DTP involves both divergent thinking, which explores various solutions based on observations and empathy towards humans, and convergent thinking, which selects optimal approaches to produce innovative outcomes (Kochanowska, & Gagliardi, 2022; Lawson, 2006; Norman, 1999; Paley, 2010; Razzouk & Shute, 2012; Seidu et al., 2023). This framework is beneficial for identifying innovative solutions, however, it has limitations as well. Butler and Roberto (2018) pointed out DTP is overly process-centric, contending that it becomes over-processed by focusing more on the process itself rather than genuine problem resolution. Moreover, this approach also risks neglecting multifaceted issues that reside in diverse contexts (Johansson-Sköldberg et al., 2013). Consequently, this study integrated research methodologies from other disciplines (Liedtka, 2015), adjusted the defined problems to align with specific cultural and contextual requirements (Razzouk & Shute, 2012), and employed not a linear but a flexible approach in this research (Bennett, 2010). Since many products and systems are designed without sufficiently

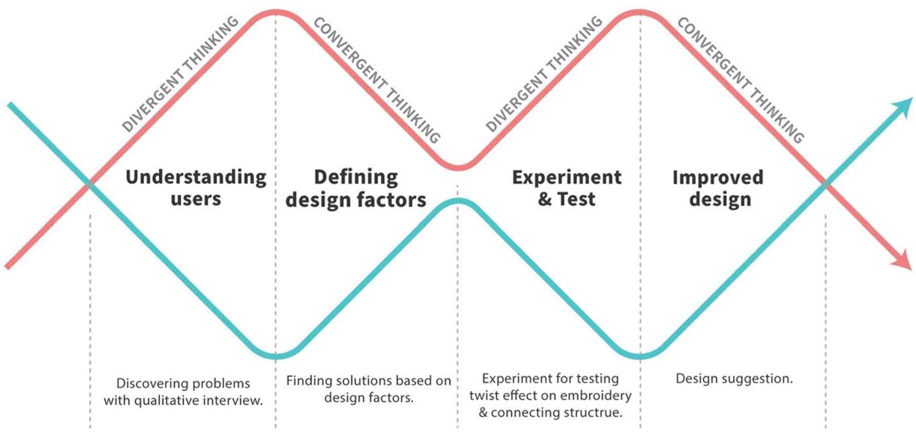

Fig. 1 Diagram of research method and process based on the double diamond model (Design Council, 2005)

considering human factors, such as safety, performance, emotional and aesthetic satisfaction during development, this research focused on addressing fundamental problems experienced by VIP. In particular, VIP show a high interest in visual appearance, regardless of the extent of their sight-related disabilities, and make efforts to find products that suit their preferences beyond technology-based usability (Liu et al., 2019; Wickens et al., 2018). First, to analyze the Braille-utilization needs of VIP, we conducted qualitative interviews with VIP participants who actively engage in social activities and show a relatively high interest in appearance and fashion items in South Korea. Second, we derived design factors using qualitative data analysis. Subsequently, we conducted experiments with appropriate embroidery methods and connection structures using MXene-coated yarn to enable Braille recognition sensibility. Finally, we incorporated these findings into a proposed design for a wearable Braille recognition smart glove.

Qualitative interview

The one-on-one interviews using a qualitative research methodology were conducted to analyze participants' desired design factors (Creswell, & Poth, 2016; Strauss & Corbin, 1990) as the primary approach. After obtaining approval (IRB Approval No: HYUIRB-202207-013) from a university Institutional Review Board (IRB), researchers recruited participants for the study through a public online community dedicated to VIP. The recruitment criteria specified individuals with visual impairment in their 20 s to 30 s who exhibited a strong interest in their appearance, actively participated in social activities, and engaged in economic activities. It was recognized that even among individuals legally classified as visually impaired, there are significant variations in degrees of visual impairment and extent of visual perceptions. Therefore, seven Korean male and female participants were recruited who fell into the severe degree of visual impairment classification in the Korean disability classification standards, excluding those who were completely blind (Table 1).

To gain insights into the current state of Braille information utilization by VIP and understand their practical needs, a semi-structured questionnaire was developed that divided into four sections: participants' lifestyle habits, methods of collecting textual

Table 1 Demographic information of participants (N = 7)

No	Gender	Age	Residence	Career	Convenience sampling	Notes
Participant 1	F	25	Seoul	Office work	Severe disability level (Formerly Grade 1)	Visual field below 5 degrees
Participant 2	F	24	Seoul	Performing arts (music)	Severe disability level (Formerly Grade 1)	Limited light detection
Participant 3	F	27	Seoul	Office work	Severe disability level (Formerly Grade 1)	Able to distinguish colors
Participant 4	M	29	Seoul	Office work	Severe disability level (Formerly Grade 1)	Impaired complexity perception
Participant 5	M	34	Gyeonggi	Service	Severe disability level (Formerly Grade 1)	Deficiency in visual stimuli
Participant 6	M	38	Changwon	Performing arts (music)	Severe disability level (Formerly Grade 1)	Limited light detection
Participant 7	M	36	Gyeonggi	Education	Severe disability level (Formerly Grade 1)	Tunnel vision, astigmatism

information, criteria and values in selecting fashion items, and technical understanding and preferences related to digital wearables. Then, interviews using this questionnaire were conducted. Our use of a triangulation approach in which we cross-verified interview data, field notes, and on-site observations enhance the validity of our research. The data obtained from the interview sessions were transcribed, and a three-step coding process (Strauss & Corbin, 1990) were used to analyze the data in accordance with qualitative research methodology.

Experiment

Using design factors identified through qualitative research interviews with VIP, this study proposes a glove-shaped wearable device for Braille recognition. Two experiments were conducted to develop a precise pressure sensor capable of recognizing Braille composed of six small, raised dots. First, conductive fibers by coating mercerized cotton fibers with MXene were created. Second, prototypes using a simple cross-stitch method and a modified French knot method were produced to explore embroidery techniques that yield high recognition rates for the pressure sensor. In the second experiment, two prototypes were developed: one with connected sensors and the other with independent sensors (Connected vs. Independent Sensing) to derive patterns suitable for high-performance, precise wearable pressure sensors.

Materials

Hydrochloric acid (HCl, 35%), and lithium fluoride (LiF, 99.995%) were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). Poly(dimethylsiloxane) (PDMS; Sylgard 184) was purchased from Dow Corning. Ethyl alcohol (99.5%), and acetic acid (99.5%) was purchased from Samchun Chemicals Co. (Seoul, Korea). Natrium hydroxide (NaOH, 97.0%) was purchased from Daejung chemicals and materials Co. (Siheung, Korea). Layered ternary carbide (Ti_3AlC_2) MAX-phase powders (particle size < 200 μm) were obtained from Carbon-Ukraine Ltd., Ukraine. Deionized water (DIW) was produced using a water purification system (Direct Q3) purchased from Millipore (Bedford, MA, USA). Unbleached 100% cotton thread (60 s/3) was purchased by Dongbang Textile Co. (Cheonan, South Korea) for cotton fibers (CFs).

Synthesis of Ti3C2Tx MXene nanosheets

$Ti_3C_2T_x$ MXene was obtained by selectively etching Al layer in the Ti_3AlC_2 MAX phase through the modified mild method (Eom et al., 2020). Briefly, LiF was dissolved in 9 M HCl at 35 °C. The solution was mixed for one day after the addition of Ti_3AlC_2 powder. After Al etching process, the excess acid was removed by centrifugation until pH ~ 6. The obtained sediment was re-dispersed in DIW and bath sonicated for 1 h. to collect delaminated $Ti_3C_2T_x$ MXene nanosheets, the supernatant was centrifugated and collected.

Mercerization of the CFs

To enhance interaction between CFs, used as the substrate and $Ti_3C_2T_x$ MXene nanosheets, the CFs were mercerized by socking those in 5, and 20wt.% NaOH aqueous solution. The mercerized CFs (MCFs) were washed using acetic acid and DIW and dried in room temperature.

Preparation of PDMS/MX/MCFs

The PDMS/MX/MCFs were fabricated by two steps: (i) MXene coating on the surface of MCFs, (MX/MCFs) (ii) PDMS coating and curing on the surface of MX/MCFs. 5 mg/mL MXene dispersion was prepared in a plastic petri dish. The MCFs was dipped in the MXene dispersion for 5 min and dried in room temperature. For confirming the mercerization effect, MX/CFs were prepared in the same way. For preparing a PDMS solution, Sylgard 184 and curing agent was mixed in a 10:1 weight ratio. MX/MCFs were dip-coated by PDMS, and then thermally treated in an oven at 80 °C for PDMS curing.

Characterization

The dimensions of the MXene sheets were characterized using a scanning electron microscope (SEM, S4800, Hitachi, Japan) at 15 kV and 10 μA, without Pt sputtering. X-ray Diffraction (XRD, mini Flex 600, Rigaku) was conducted using Cu Kα radiation (λ = 1.5418 Å). The functionalities and chemical state of MXene were characterized by X-ray photoelectron spectroscopy (XPS, Theta probe, Thermo Scientific, UK) with monochromatic Al Kα radiation. The XPS spectra were processed using XPSPEAK41 software. The resistance and capacitance were measured using a multimeter (DMM 7510 1/2, Keithley Instruments, USA). The conductivity ($\sigma = 1/\rho$) of a single fiber was calculated using Eq. (1):

$$\sigma = \frac{1}{\rho} = \frac{4L}{\pi d^2 R} \tag{1}$$

where d, R, and L represented the diameter, electrical resistance obtained via the two-point probe method, length of the fiber, respectively. The diameter of the fiber was estimated by SEM images using ImageJ.

Results

The participants' statements highlighted several problems. The VIP participants reported that they primarily rely on the text scanning function of smartphone cameras to read text; however, they pointed out that this approach has limitations related to recognition accuracy and the challenge of precisely aiming the camera at the text. Consequently, participants acknowledged the need for Braille-based information acquisition but pointed out the significant time and effort required to learn Braille. While optical character readers proved useful for VIP with residual vision, they were cumbersome to carry and limited to specific environments with consistent lighting and angles. Furthermore, participants expressed dissatisfaction with the assistive devices currently on the market, noting their generally rough design and lack of a smooth finish, resulting in a diminished overall aesthetic quality. They also highlighted the inconvenience of carrying and using such devices. Participants demonstrated sensitivity to the materials and finishing of items as they rely heavily on tactile sensations to obtain information in their daily lives. Lastly, they mentioned encountering difficulties in assessing the extent of item contamination and managing item maintenance.

Defining design factors and solutions

Design factors

Based on interview data, the design factors required for developing a wearable Braille recognition device that addresses the challenges faced by individuals with visual impairments can be summarized as follows (Fig. 2).

Portability Participants predominantly rely on smartphone applications that recognize text images and convert them into audio output. However, participants reported challenges focusing the camera to capture usable images. In addition, assistive devices for VIP are usually heavy and make reading difficult in outside environments.

> *"I have to look closely when using assistive devices. The desk also needs to be at the right height. So, if it's not a familiar space for me, it can be difficult to see." (Partici-*

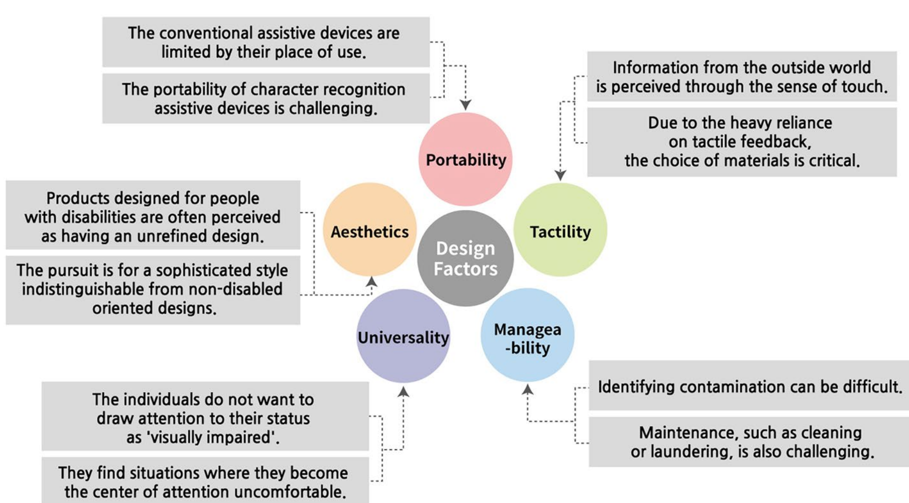

Fig. 2 Design factors based on qualitive research

> *pant 4)*
>
> *"First, I have to find where the text is located. Then I have to focus the camera on it and take a picture, and then I have to zoom in to see it. If the focus is off, I have to take the picture again, and the text might not be in a font that's easy to read. Sometimes, if there's not enough contrast between the background and the text, it's hard to see as well." (Participant 5)*

These issues highlight the importance of designing a device that preserves the usability of Braille, allowing for immediate character recognition using fingertips, while also enabling users to read with ease and speed. They also indicate that the device should be designed as a portable and versatile fashion item that can be used anytime and anywhere.

Aesthetics Designs for VIP often prioritize non-visual elements such as tactile and olfactory sensations or adopt functional-oriented approaches. However, participants expressed dissatisfaction with purely functional products designed for people with disabilities, noting that they often appear relatively unrefined. They reported that they assess the aesthetic quality of products' finish and forms through tactile sensations and often perceive them as inferior to other products.

> *"Most products designed for people with disabilities seem a bit rough. Things like Braille watches or smart glasses felt too focused on functionality. It's obvious that they are glasses for people with disabilities, right? Even with watches, it felt like they just attached electronic cells to cheap, low-cost watches."(Participant 4)*

As individual with disabilities engage in more and more social interactions, designers of VIP products should move beyond a singular focus on functional elements and consider their autonomy, independence, and personal aesthetics from a social standpoint (Chang et al., 2013; Kaiser et al., 1985). Participants frequently rejected devices that solely emphasized assistance due to their crude and uncomfortable appearance and a desire to avoid the social stigmas associated with having a disability. Therefore, designs targeting VIP should account for social factors, consumer emotions, attitudes, and behaviors, considering their impact when making decisions regarding form, materials, details, and other design factors.

Universality All participants selected "plain outfit" when asked about their preferred styles. Consistent with previous studies emphasizing a preference for neutral appearances (Dos Santos et al., 2022; Shinohara & Wobbrock, 2011), this "plain outfit" preference signals a desire to avoid attracting unnecessary attention from others. Participants indicated that excessive attention, patronizing treatment, and disrespectful generalizations from others can create psychological pressure (Participants 1, 3, 7). Despite being employed, actively participating in social activities, and managing daily life without significant difficulties, participants encountered non-disabled people in Korean society who frequently offered unnecessary assistance or exhibited pity. Participants reported feeling uneasy when others focus excessively on them.

> *"The most prominent assistive devices that VIP use outside is the white cane, which stands out to others. However, there are many individuals who hesi-*

tate to use it even when it is necessary. I cannot ignore the prejudice against VIP."(Participant 3)

"When attending gatherings with a majority of non-disabled individuals or crowded places, I pay more careful attention to my appearance." (Participant 7)

Their sensitivity to "external appearance as perceived by others" in the context of societal biases manifested as a desire to appear "normal" in Korean society. Therefore, designs for VIP should prioritize simplicity over uniqueness. Given that aesthetics for VIP involve a complex interplay between information obtained through vision and touch, as well as the evaluations of others, designs for VIP should reflect their desire not to be treated as distinct entities within our society.

Tactility Tactile perception is an important means by which VIP obtain information (Withagen et al., 2010). Even individuals with residual vision tend to rely more on texture and material cues than visual stimuli. When it comes to clothing selection, all participants reported a preference for softer materials and a tendency to utilize tactile perceptions to gather information about the items.

"I used to do a lot of online shopping, but I had many failures. So, I try to do offline shopping more often. I go and personally touch the products. I found that the actual texture is often different from what is described online."(Participant 3)

"While I do consider color and design, I tend to prioritize the tactile sensation more."(Participant 5)

In designing products for VIP, prioritizing materials that offer stability and comfort is essential. Sharp or rough textures can trigger discomfort. Even if a design concept appears visually rough, the tactile sensation or wearing experience should be crafted to be soft and stable.

Manageability Garment management encompasses both sustainability and aesthetic considerations. The difficulties VIP experience in perceiving the degree and location of contamination makes clothing maintenance a challenge that goes beyond mere inconvenience.

"In reality, it's quite difficult to be meticulous in terms of maintenance. Firstly, I don't know exactly where the stains are. Also, there are many cases where I don't know if the contamination has been cleaned or not."(Participant 2)

To avoid social stigmas associated with visual impairment and dispel the assumption that VIP neglect clothing maintenance, participants reported that they tend to purchase garments in dark colors. Therefore, implementing maintenance methods that expand the range of product options for VIP would diversify the aesthetic experiences available to them. The design factors for developing a wearable Braille device for VIP have been identified as Portability, Aesthetics, Universality, Tactility, and Manageability. Based on these five design factors for the Braille glove for VIP, the proposed solutions are as follows.

Design solutions

Wearable technology VIP want assistive devices that draw less attention from others and that they can use seamlessly in daily life. Consequently, creating an item they can "Wear" as if it were part of the body rather than a distinct "Device" could alleviate their concerns. Fashion items for VIP should be designed to facilitate easy accessibility and minimize the attention drawn to their disability (Santos et al., 2022). Considering the psychological tendency among VIP to avoid items that reveal their disability due to potential societal biases (Chang et al., 2013; Freeman et al., 1985), designing fashion items with effective wearable technology seems appropriate.

MXene It is crucial to use conductive, fabric-compatible materials for the construction of wearable gadgets. The construction of such wearable products inherently requires the generation of conductive fibers. The materials often used for their conductive properties in wearable products include conductive polymers, graphene, carbon nanotubes (CNTs), metals, and MXenes. However, conductive polymers were excluded from the material categorization due to their typically low conductivity, generally less than 1,000 S/cm. After comparing these four conductive materials (CNTs, graphene, MXenes, and metals) using a 5-point Likert scale across four criteria, we deemed MXene the most suitable material (Table 2).

In particular, given MXene's sensitivity to pressure, sensors developed using this material can technically assist in the accurate recognition and interpretation of Braille, which is constituted of raised dots in localized areas.

Gloves A glove-shaped wearable device would maintain the traditional Braille reading method without hindering the activities of VIP who rely on their hands. Additionally, it would offer convenience in portability and serve as a seasonal fashion item. Importantly, it should be a universal item that does not stand out as "special device" for VIP and can be universally utilized by both disabled and non-disabled people. In sum, a glove-shaped wearable device would effectively achieve the design elements of portability and universality for VIP. Taking into account the tactile sensation experienced by VIP, the gloves should also be made of thin, compact, and breathable materials to ensure a soft touch.

Simplification The prior studies (Hsu et al., 2016; Kim & Oh, 2017; Lee & Lee, 2019) and qualitative interviews made it clear that managing and dealing with contamination

Table 2 Decision making for suitability of new materials

	Conductivity	Durability	Surface charge density	Density	Average score
Graphene	5	5	1	4	3.75
CNT	5	4	1	4	3.5
Metal	5	4	2	2	3.25
MXene	5	4	4	3	4

[Conductivity (S/cm)] 5: Greater than 10,000 / 4: 7000–10,000 / 3: 4000–7000/2: 1000–4000/1: Less than or equal to 1000

[Durability (Young's modulus, TPa)] 5: Greater than 1/4: 0.1–1/3: 0.01–0.1/2: 0.001–0.01/1: 0.0001–0.001

[Surface charge density (Zeta-Potential, mV)] 5: 46–60/4: 31–45/3: 16–30/2: 1–15/1: 0

[Density(g/cm3)] 5: Less than 1/4: 1–3/3: 4–6/2: 7–9/1: 10–12 in fashion items pose the greatest challenges for VIP. Given the preference for universal fashion items that do not attract unnecessary attention and can be easily used at any time, using low-intensity, neutral colors were regarded as an effective means of minimizing the visibility of stains or conductive thread stitches. Additionally, a simple design should be adopted to facilitate ease of maintenance.

Prototyping and testing

Using design factors identified through qualitative research interviews with VIP, this study proposes a glove-shaped wearable device for Braille recognition. Two experiments were conducted to develop a precise pressure sensor capable of recognizing Braille composed of six small, raised dots. First, conductive fibers by coating mercerized cotton fibers with MXene were created. Second, prototypes using a simple cross-stitch method and a modified French knot method were produced to explore embroidery techniques that yield high recognition rates for the pressure sensor. Embroidery stands as one of the technologies most often used for smart textiles(Kim et al., 2023). In the second experiment, two prototypes were developed: one with connected sensors and the other with independent sensors (Connected vs. Independent Sensing) to derive patterns suitable for high-performance, precise wearable pressure sensors.

Materials selection

MXene, the one of the newly developed two-dimensional (2D) nanomaterials, demonstrated outstanding performance in various fields, such as energy storge, sensors, catalyst, flexible and transparent electrodes, etc. due to remarkable performance (Lee et al., 2020; Ma et al., 2021; Morales-Garcia et al., 2020; Shin et al., 2021). The general formula of MXene was $M_{n+1}\ X_nT_x$ (n = 1–4), where M, X, and T represented early transition metal, carbon or nitrogen, and functionalities (-O, -OH, -F, etc.), respectively (Alhabeb et al., 2017). The surface functionalities induced hydrophilic surface of MXene, inducing stable colloidal dispersion of MXene in water or polar solvents (Zhang et al., 2020).

Cotton fibers (CFs) had been extensively used natural materials in the world due to flexibility, lightweight, biocompatibility, and highly breathability. The surface of CFs was functionalized by hydroxyl groups, indicating good interaction with hydrophilic nanomaterials (Qiu et al., 2020). Besides, this surface of CFs could be easily modified with various functionalities by chemical treatments (Musino et al., 2021; Patel et al., 2019). In particular, mercerization of cotton increased hydroxyl groups to improve the hydrophilicity of surface (Karmakar, 1999). Furthermore, MXene coated on yarn exhibited stable conductivity during water-based washing process (Uzun et al., 2019). Thus, CFs was highly suitable as substrates using MXene for functional textile.

Obtained MXene dispersion showed clear Tyndall effect, representing well dispersed phase (Fig. 3a). A SEM image in an inset image of Fig. 3a showed the fully delaminated MXene nanosheets with several micrometers in size. XRD spectra (Fig. 3b) designated distinct (002), (004), and (008) peaks of MXene at 6.62°, 13.40°, and 19.46°, respectively (Shao et al., 2020). Furthermore, deconvoluted

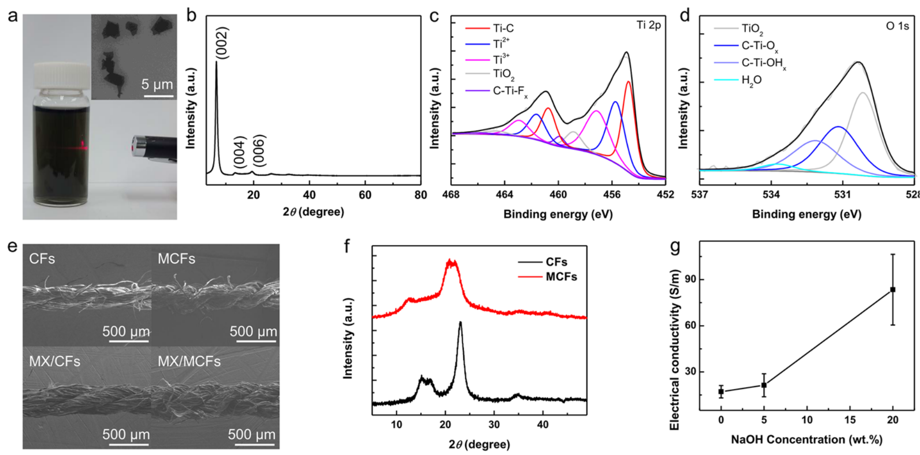

Fig. 3 **a** Optical image of MXene aqueous dispersion and tyndall effect (inset image: SEM image of MXene nanosheets). **b** XRD analysis and XPS high resolution spectra of **c** Ti 2p, and **d** O 1 s of MXene. **e** SEM images of a CFs, MCFs, MX/CFs and MX/MCFs. **f** XRD analysis of CFs and MCFs. **g** comparison of electrical conductivity for MX/CFs and MX/MCFs treated by 5 and 20wt.% NaOH solution

high-resolution XPS spectra in the Ti 2p (Fig. 3c) and O 1 s (Fig. 3d) regions certainly demonstrated Ti-C bonds (454.8 eV), C-Ti–O (531.2 eV), and C-Ti-OH_x (532.2 eV) (Natu et al., 2021). Therefore, MXene nanosheets with hydrophilic surface was well synthesized without any impurities.

Mercerization effect

A SEM images in Fig. 3e showed the morphological change of CF by mercerization with 20wt.% NaOH solution. The CFs (diameter: ~ 330 μm) exhibited dense microstructure in which twisted microfibers closely packed. On the other hands, MCFs formed slightly expanded microstructure with circularly shaped microfibers, as well as increase a diameter of ~ 370 μm. Namely, the mercerization process destroyed strong hydrogen bonds in CF, introducing swelled microstructure with more hydroxyl groups. The MX/CFs and MX/MCFs exhibited similar morphological change. Contrary to anomalously bright area in SEM images of CF and MCF due to electron charging effect, the SEM images of MX/MCFs and MX/MCF without any locally bright area indicated that the MXene was well coated on overall surface of CFs and MCFs.

The crystalline structure of CFs and MCFs was analyzed by XRD spectra (Fig. 3f) (French, 2014). CFs represented distinct diffraction peaks of ($1\bar{1}0$), (110), and (200) of cellulose I nanocrystals at 15.08°, 16.86°, and 23.16°. MCFs exhibited new peaks at 12.52°, 20.54°, and 21.94° corresponding to ($1\bar{1}0$), (110), and (020) planes of cellulose II nanocrystals, respectively, confirming that CFs were successfully mercerized. Furthermore, Fig. 3g demonstrated that increasing the concentration of NaOH solution, the electrical conductivity of MXene coated fiber was dramatically increased to ~ 83.47 S/m, implying that concentration of NaOH was critical factor to mercerize the CFs (Jin et al., 2016). Eventually, MX/MCFs showed 5 times higher electrical conductivity than MX/CFs, representing that mercerization enhanced the interaction between CFs and MXene.

Fabrication of wearable pressure sensors depending on twisting area

The MX/MCFs were applied as electrodes for wearable capacitive pressure sensors. It was fabricated by coating PDMS as dielectric and barrier layer on the surface of MX/MCFs, denoting PMDS/MX/MCFs (Mannsfeld et al., 2010; Teisala et al., 2020). Structural deformation by external pressure developed the change of capacitance in dielectric layer (such as, PDMS) of capacitive pressure sensors (Lee et al., 2015). Typically, wearable pressure sensitive textiles had been fabricated in the design of a simply continuous crossover and sensed the change of pressure occurred at each intersection. However, applying to Braille recognition that required accurate measurement of narrow areas, it was essential to develop the noble and optimal design for improving the sensing performance and blocking the signal interference between adjacent sensing points.

The prepared French knot embroidery (EMB) (sample B) and compared cross stitch EMB (sample A) with sample B. Figure 4a and b was optical images of sample A and B, and showed the relative capacitance changes ($\Delta C/C_0$) of each sample under a load of 1 N. The $\Delta C/C_0$ of sample B (~4%) exhibited twice as high sensing value than that of sample A (~2%). Besides, sample B showed higher sensitivity than sample A under a load of 0.1 and 0.5 N, as well as 1 N (Fig. 4d). Thus, French knot EMB had more substantial contact region of PDMS (dielectric layer) than cross stitch embroidery type in restricted area due to twisted structure, inducing improved sensitivity under loads.

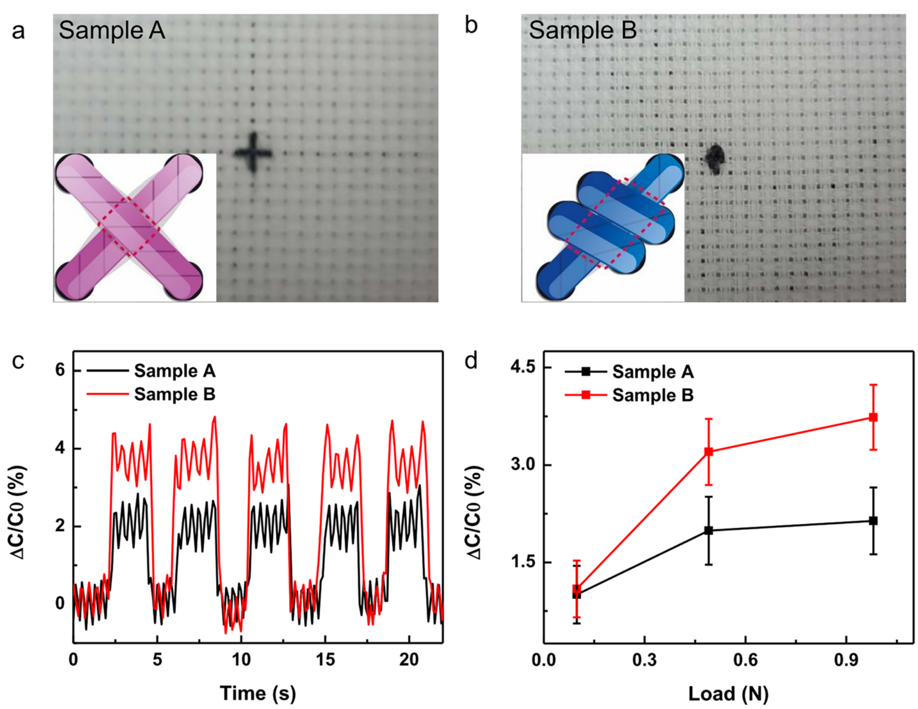

Fig. 4 **a** and **b** Optical images and **c** pressure sensing performance of sample A (cross stitch EMB) and B (French knot EMB). Schematical demonstrations of sample A and B are shown in inset). **d** comparison of sample A and B for different pressure

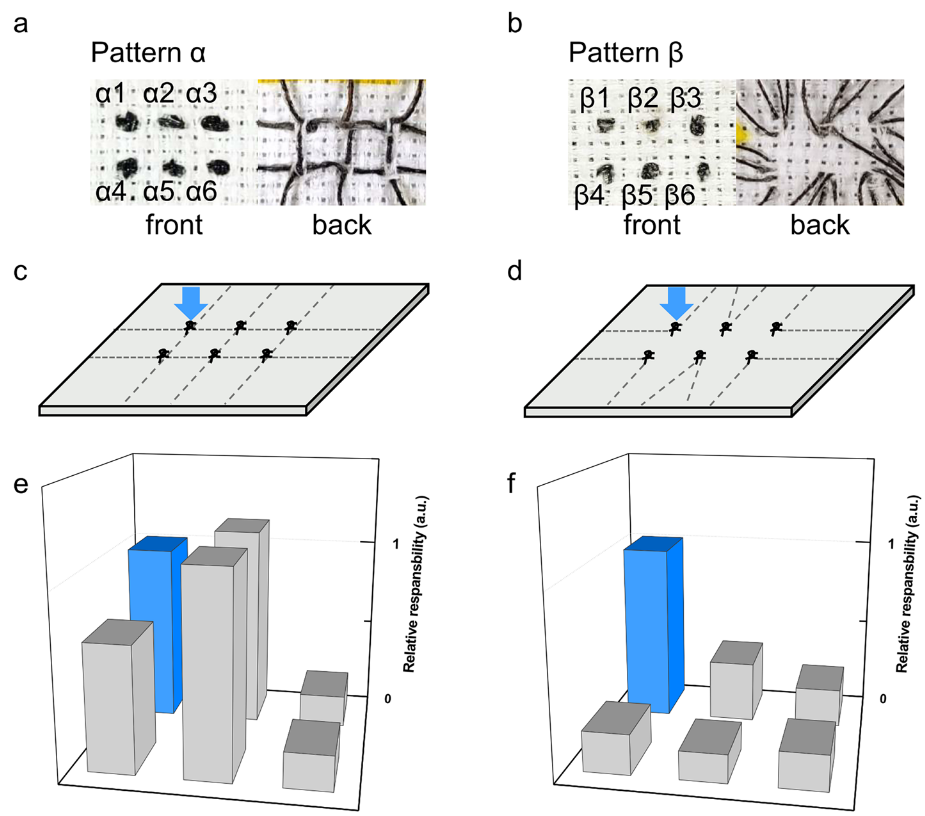

Fig. 5 **a** and **b** Optical images of front and back of pattern α and β. **c** and **d** Schematic demonstrations of pattern α and β. **e** and **f** Comparison of signal interference behavior of pattern α and β

Independently complex embroidery structure for blocking signal interference

Braile was recognized by combination of six adjacent points. Accordingly, the signal interference of adjacent points was an enormous challenge. When a signal of target point occurred and the signals of adjacent points were also generated, desired signal was disturbed, and the effectiveness of Braille recognition significantly reduced. To resolve this challenge, designed independently complex embroidery structure (pattern α and β) and compared them. Figure 5a and b represented front and back images of pattern α and β. Pattern α was fabricated with six knots (French knot EMB) interconnected with five threads (stripes) on simple structure. On the contrary, pattern β was designed with each six knots created independently with total twelve threads (stripes). It was clearly observed through back images of pattern α and β.

To confirm signal interference behavior, signals of all points were measured when a load was applied on each target point (α1 and β1) and compared the degree of response by setting the reospone of each target point as 1 (Fig. 5c and d). As shown in Fig. 5e, pattern α exhibited not only a target signal at α1, but also strong signals at points adjacent to α1 (α2, α4, and α5). This signal interference behavior was attributed to transferring of stimuli in interconnected structure (Fig. 5e). This result verified that the pattern α was unsuitable and inefficient design to applied to braille recognition. However, the responsibility values of all points other than β1 were ~ 0.34 or less due to independent French knot EMB per Braille points (without crossing over). As a results, researchers

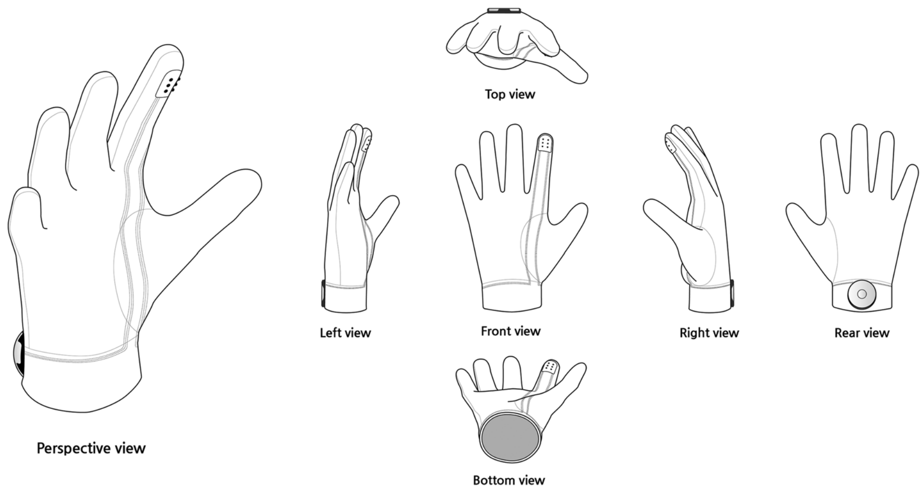

Fig. 6 Braille glove design suggestion for visual impairments

developed independently complex embroidery structure with enhanced sensing performance for wearable capacitive pressure sensor through design enginnering. Our strategy gave insights to fields that required highly localized and independent sensing, such as Braille recognition.

Improved design

The braille glove with the mechanism depicted in Fig. 6 was designed. First, researchers implemented wearable technology to facilitate convenient carrying and usage of the glove VIP in their daily lives. While ensuring the fundamental readability of braille using the index finger, we selected the glove structure to enhance the device's portability. Subsequently, precise pressure sensors capable of recognizing Braille were affixed to the index finger section.

The preference of hand reading Braille (left or/and right) depends on VIP individuals, the glove is designed as a single pair. The suggested design of Brille glove shows the possibility of smart assisted device as fashion item with high sensibility. As the device is not intended for continuous wearing as warmer gloves, a medium-thick cotton materials has been applied for combining MXene coated yarn stitches. Through two experiments, appropriate embroidery techniques and connection structures were validated for fabricating wearable pressure sensors using MXene material and subsequently integrated them into the glove. The thread coated with MXene, utilized in the pressure sensors, exhibits conductivity and is linked to a virtual computer responsible for processing Braille information. To minimize the visibility of the dark thread stitches, they were concluded with stitches that traverse the palm and encircle the wrist. Additionally, using an achromatic hue for the glove was suggested.

Discussion

In this study, qualitative research interviews were conducted with VIP to identify Braille reading challenges and extract vital design factors. To develop a wearable device prototype, researchers then fabricated conductive fibers using MXene, an optimal conductive material, introducing a dielectric layer on the surface to construct a capacitive pressure sensor. Textile-based capacitive pressure sensors generally employ a cross-stitch method to link each sensing point in the fabric. However, among various possible embroidery methods, this technique leads to a narrow fiber contact area, resulting in low efficiency and constant signal generation in adjacent areas under pressure. This condition is unsuitable for the precise sensing in localized regions for Braille recognition and often generates signal interference. To address these issues and improve pressure sensing performance, two strategies were implemented: i) the modified French knot technique and ii) independently complex embroidery structure, enhancing the sensing performance by approximately two-fold and ensuring the reactions of neighboring points were 0.34 or lower compared with that of the target. Essentially, the French knot, with unique patterns of MXene-based conductive fibers, is highly suitable for Braille sensing. Consequently, researchers proposed a smart glove design based on these findings.

While researchers have extensively examined assistive devices for VIP using Braille (Al-Qudah et al., 2014; Harish, 2020; Yong, 2013), these studies often assume that VIP users can comfortably read Braille, and few studies have focused on the majority of VIP who cannot use Braille. Through interviews with VIP, researchers learned that technologies like smart cameras pose considerable user-adoption challenges. Our proposed wearable glove, equipped with a high-performance Braille recognition sensor, is designed to enhance VIP's psychological and aesthetic satisfaction. The glove's universal design and accompanying technical support allow users to maintain their existing Braille reading methods while avoiding social stigmas. This could give them easier access to Braille and help them more accurately learn and decipher it. This study's objective was to develop a wearable device for Braille reading, emphasizing aesthetics, performance enhancement, and signal interference reduction in the design of the prototype.

Conclusions

This study was conducted as an interdisciplinary approach, rooted in the DTP. The significance of interdisciplinary research that pivots on the design thinking process thus stems from its amalgamation of diverse viewpoints, cultivation of creativity, and provision of comprehensive solutions while factoring in broader implications, including sustainability, social ethics, and equity. Over the course of our study, designers and engineers participated in the entire process of the research to develop a Braille glove design focusing on independent sensing. This tool is expected to help VIP who may not be well-acquainted with Braille read more conveniently. Utilizing qualitative research interviews to acquire a more nuanced understanding of target users, researchers discovered that VIP often encounter challenges in discerning textual information and that the effectiveness of assistive devices. In response to these findings, we designed a wearable Braille recognition glove with usability akin to conventional Braille reading and featuring the advantage of easy portability. While researching with interdisciplinary approach, several challenges, such as the differences in terminologies, approaches to problems, and ways of thinking, were faced in facilitating to achieve goals. In addition, for a very clear goal of a wearable pressure sensor development for Braille recognition, interdisciplinary team should consider specific factors in detail, and apply them to the direction of experiments, such as extremely small sensing device design considering portability, aesthetics, and tactility based on users' perspectives. Interference from nearby stimuli was essentially minimized by independent sensing structure to distinguish approach Braille dots. During the process, design and engineering researchers had time for brainstorming to take a broad understanding and divergent solutions. Furthermore, this process reduces trial and error; material compatibility for design purpose, assembled pressure sensors' incompatibility, and lack of understanding of end-users' needs for developing highly efficient Braille recognition wearable device as fashion item.

Despite this limitation by the smaller sample size for qualitative data analysis, we confirmed the value of one-on-one qualitative interviews focused on VIP's perceptions of and emotional perspectives regarding the use of assistive equipment. The qualitative data allowed us to identify new materials and a connecting method to improve sensing effectiveness. Furthermore, we did not conduct a post-survey regarding users' satisfaction with the improved design. Instead, researchers focused on a design process that began with understanding users through qualitative interviews and sought to develop an improved sensing method with a glove design based on the DTP with an interdisciplinary research team. Significantly, this study provides a useful basis for future collaborative research with software capable of converting Braille's surface information into computer data and that integrates user-satisfaction surveys and usability tests.

Abbreviations

CF Cotton fibers
DTP Design thinking process
EMB Embroidery
VIP Visually impaired people

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Author contributions

MK and MJ contributed to the research design. MK was responsible for collecting qualitative data and analyzing it with writing the first draft of the manuscript. HS conducted prototype experiments, data analysis and discussion writing and provided feedback to the manuscript draft. MJ supervised the overall research process, and participated in the experiments and qualitative data analysis, and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This research was conducted under the approval and supervision of Hanyang University Institutional Review Board (IRB Approval No: HYUIRB-202207-013) regarding ethical issues including consent to participate.

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

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