Vibrotac-Glove: Designing a Novel Haptic Glove as an Assistive Device

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***Abstract*—This paper introduces the design, development, and evaluation of a haptic electronic glove as an assistive device for people with deaf-blindness. The glove incorporates haptic electronic yarns into knitted textile channels, offering enhanced durability and functionality while enabling vibrotactile communication on the dorsal side of the fingers' proximal phalanges. A control system provides diverse feedback patterns, and wireless smartphone integration supports real-time interaction.**

Experimental trials with ten participants demonstrated the glove's ability to convey haptic cues effectively, achieving recognition rates of up to 80% by optimizing time intervals (125– 2000 ms) and pulse widths (10– 60 ms). The index and ring fingers showed superior accuracy in distinguishing haptic pulses.

A sustainability analysis evaluated the glove's environmental impact, suggesting improvements to increase durability and reduce waste. Overall, the study validates the glove's feasibility as a daily assistive tool, enhancing communication and quality of life for people with sensory impairments.

***Index Terms*—haptic, E-yarn, deaf-blindness, electronic glove, sustainability**

I. Introduction

Recent advancements in electronic textiles (e-textiles) and wearable technology have led to the development of health and well-being solutions [1]- [8]. The evolution of haptic technology within wearable devices have significantly expanded the scope and depth of the user experiences of these devices across diverse applications, including immersive and interactive platforms [9], [11]. These haptic wearables enable users

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Fig. 1. Prototype of a daily-wear haptic electronic glove featuring wireless smartphone connectivity for generating precise and varied haptic feedback cues on the hand.

to interact with digital information through tactile sensations, enhancing realism and engagement in virtual environments, improving learning outcomes in education [9]- [11], providing new tools for medical and therapeutic applications [12], [13], and communication [14]- [19]. Electronic yarn (E-yarn) technology enables electronic functionalities to be embedded within textile fibers. The core E-yarn technology is covered by a portfolio of patents (EP 1882059 B1 [25], US 10301751 B2 [26], US 10458048 B2 [27]). The technology has made it possible to design wearable devices that are more durable, flexible, and washable for daily use as textiles [22], [24]. Unlike many conventional systems, which often attach external components to the surface of fabrics, E-yarns can be integrated within knitted channels in the textile structure to ensure the stability, durability and sustainability of the e-textiles [3], [6], [29]. This study presents the development of a haptic glove utilizing an already designed haptic electronic yarn, building on the foundational knowledge of haptic embedded E-yarns established in previous research [28] (comprehensive details on the design and validation of these E-yarns will be published in an upcoming article). By embedding haptic devices directly into the textile structure, this approach aims to provide a distinct, reliable, and consistent tactile experience, introducing a novel interaction method through haptic feedback for wearable technology.

To evaluate the effectiveness of the prototype haptic electronic glove, a trail was conducted with ten healthy participants, focusing on key parameters for haptic signal differentiation, including the time gaps and pulse width of the haptic feedback stimuli. This study indicated the potential for developing a haptic signal language capable of conveying information through tactile sensations on the skin, ultimately enabling users to interpret real-time environmental cues and conversations through touch. Sufficient allowances for individuals with deaf-blindness are not commonly made, leading to challenges in terms of communication, navigation, and general interaction with their surroundings [30], [31]. For people with sensory impairments, haptic wearables hold particular promise in addressing critical needs by translating auditory and visual information into tactile feedback [34], [35]. This study, therefore, advances research toward developing an assistive device potentially capable of providing a haptic-based communication method, aiming in future to enhance the quality of life for people with sensory impairments. This work is significant because, to the authors' knowledge, no current research evaluates vibration on the proximal phalanges of the fingers, a potentially valuable area for enhancing human-computer interaction.

Sustainability and reusability are essential considerations for wearable devices, particularly for those intended for regular use [29], [32], [33]. A method for employing a combination of an interaction matrix and Kuusk's sustainability framework [32] has previously been employed to evaluate E-textile sustainability [29] and has been used in this work to analysis the glove's environmental impact, focusing on materials, energy consumption, and end-of-life recyclability. These results are intended to guide the design of an improved version of the glove, leveraging insights from user trials to enhance durability, sustainability, and overall suitability for daily use.

In summary, this paper presents a comprehensive study on the feasibility of a haptic electronic glove that can deliver distinguishable haptic cues, contributing to the design of a potentially effective assistive device.

II. Materials and Methods

A. Design and Integration

In designing a wearable device, a range of human, technological, functional, and aesthetic factors need to be considered. This study presents a design approach focused on fulfilling the functional requirements of a haptic glove aiming to assist people with deaf blindness, emphasizing comprehensive consideration of both human and technological factors. The physical glove used for the testing presented in this work is described below.

The proposed glove design incorporated haptic electronic yarns (E-yarns) previously developed in our research (full details will be available in a forthcoming article). These haptic E-yarns embed a miniature eccentric rotating mass (ERM) motor (Model No. NFP-3C-03208B, NFP Motors™, Hong Kong, China). The ERM motor was selected as the vibrotactile actuator based on critical design requirements for haptic wearable devices, including a compact form factor (ϕ = 3.4mm, length = 12.7mm, weight = 1.0±0.2g), low power consumption (2.5–3.6 V DC, 90 mA), effective vibration amplitude suited to the most sensitive range of human tactile perception (266±8 Hz, $0.028 \pm 0.11G$) and low mechanical noise (max 30 dB) [1]. Two Litz wires (Type 1 Litz, Osco Limited, Milton Keynes, Buckinghamshire, United Kingdom) were attached to the terminals of the ERM motor using soldering. The vibrotactile motor was subsequently encapsulated within a 3D-printed casing and further secured using UV-curable resin (9001-E-V3.5; Dymax Corporation, Torrington, CT, USA) providing effective isolation of the electronics from water and chemical exposure. To enhance mechanical strength, two high-tensile-strength fibers, specifically fine Vectran™ (HT110T20; Vectran™, Kuraray, Tokyo, Japan, HT110T20), were integrated alongside the E-yarn. In the final fabrication stage, the E-yarn was enclosed within a braided sheath, incorporating the Vectran™ fibers and Litz wires to securely encase the internal components. The braiding material was selected to optimize the textile's final performance characteristics; in this study, double-covered Lycra® (1x20/204 Stretchline Lycra, Long Eaton, Nottingham) was employed, and braiding was achieved using a round braiding machine (Herzog RU 1/24-80; Oldenburg, Germany). This braiding process could result in a robust haptic E-yarn with enhanced mechanical durability and a textile feel.

Given the high sensitivity of the human hand as a primary haptic sensory organ, a glove designed with tactile feedback offered an effective medium for delivering haptic stimuli. Specifically, the glove was designed with open fingers to

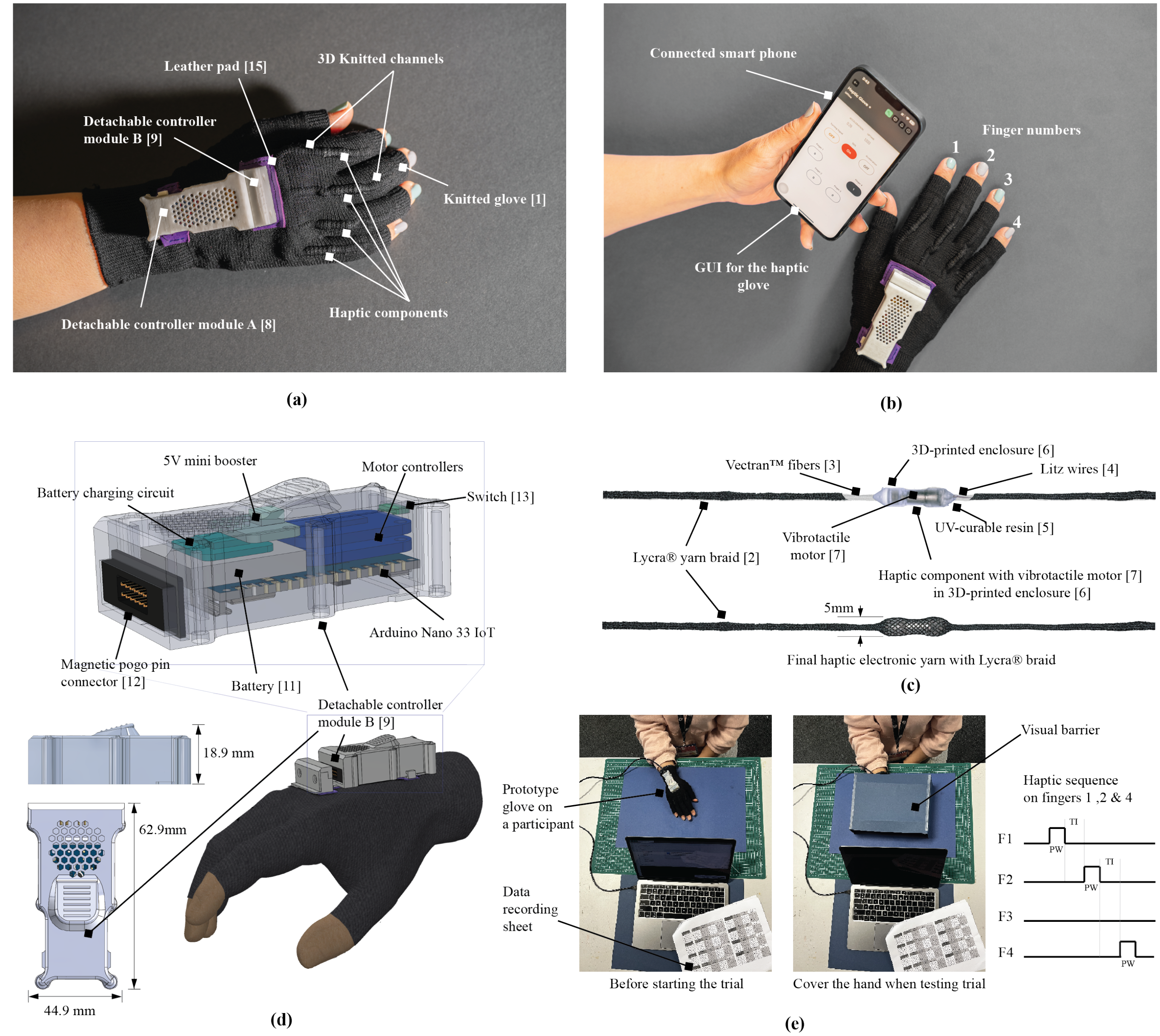

Fig. 2. Designed and developed prototype haptic electronic glove with vibrotactile haptic feedback: a) Main components of the glove worn on a human hand. b) The developed wearable glove interacts in real-time with a smartphone through an IoT platform. c) Final haptic electronic yarn showing the internal components. d) CAD model of the designed glove and the electronic controller module. e) Experimental setup for user trials of the wearable glove.

preserve full dexterity for daily tasks. The developed haptic E-yarns were integrated into the glove by inserting them through 3D-knitted channels as the final integration stage. The glove was knitted using Lycra® (1x20/204 Stretchline Lycra, Long Eaton, Nottingham) and Nylon (2/68/70, unknown company) on a 3D Seamless Flat Knitting machine (Stoll ADF32W, 7.2 gauge; Karl Mayer Stoll GmbH, Obertshausen, Germany) incorporating four channels on the dorsal side leading to the dorsal proximal phalanx (Fig. 2, a). The haptic E-yarn components were specifically positioned on the dorsal side of the proximal phalanges of each finger (excluding the thumb) to minimize interference with daily activities. This location required adequate stretchability to accommodate the flexion and extension of the metacarpophalangeal joint. Key variables included braiding parameters such as laylength, the number of carrier yarns, and the composition of the core materials (Litz wires and Vectran™ fibers). The core materials were configured in a spiral-shaped structure to further enhance stretchability. A lay length, the distance along a strand travels to make a full turn around it, of 4 mm was applied to the component region, while a lay length of 8 mm was used for the remainder of the yarn to achieve an optimal balance between braid coverage and yarn stretchability. The glove was previously showcased in a laboratory demonstration and presented at CHI 2024 in Honolulu, Hawaii [23].

TABLE I

FINGER STIMULATION SEQUENCES IN THE USER TRIAL EXPERIMENTS

Zero TI				
	i=1			
	TI=0, PW=10			
j=1	1	2		
j=2	2	3		
j=3	1	3	4	
j=4	2	4		
j=5	1	2	3	4

Variable TI																
	i=1				i=2				i=3				i=4			
	TI=125, PW=10				TI=250, PW=10				TI=500, PW=10				TI=2000, PW=10			
j=1	1	2			3	2			2	4			1	2		
j=2	3	4			1	2	3	4	1	3			2	3		
j=3	1	2	3	4	1	3			1	2	4		1	3	4	
j=4	2	4			3	4			2	4	3	1	2	4		
j=5	1	2	4		1	3	4		3	4			1	2	3	4

Variable PW																
	i=1				i=2				i=3				i=4			
	T=125, PW=10				T=125, PW=20				T=125, PW=40				T=125, PW=60			
j=1	1	2			3	2			2	4			1	2		
j=2	3	4			1	2	3	4	1	3			2	3		
j=3	1	2	3	4	1	3			1	2	4		1	3	4	
j=4	2	4			3	4			2	4	3	1	2	4		
j=5	1	2	4		1	3	4		3	4			1	2	3	4

B. Prototype Glove Control System

The control system was designed to deliver individualized vibrotactile stimuli to each finger, enable wireless communication, minimize weight, and support the washability of the glove. To achieve these objectives while reducing device bulk, a smartphone was proposed as an interface with the haptic glove, allowing for the utilization of advanced technologies and features while minimizing the wearable device's electronic load. This approach enhances wireless communication, reduces the need for extensive onboard electronics (e.g., sensors and power modules), and promotes a more compact design. The Arduino Nano 33 IoT (Arduino Nano 33 IoT, Arm® Cortex®-M0 32-bit SAMD21 processor, IMU (LSM6DS3), u-blox NINA-W102 Wi-Fi module; Ardunio©, Monza, Italy) was selected as the glove's primary controller. This device integrates an onboard inertial measurement unit (IMU) with the compact Arduino Nano platform, enabling basic Internet of Things (IoT) and pico-network applications. The smartphone further enhances the system by transforming the glove's open-loop functionality into a closed-loop control system with advanced sensing feedback, thereby allowing real-time responsiveness. In this work an iPhone 13 (iOS Version 18.0, Apple iPhone 13, Apple Inc., Cupertino, California, USA) was utilized.

The microcontroller and motors were powered by a Li-Polymer battery (3.7 V, 190 mAh, MIKROE- 2759, MikroElektronika d.o.o., Belgrade, Serbia) integrated with a power management board (MiniBoost 5 V @ 1 A, Lipoly/ LiIon battery charger; Adafruit, NY, USA) which also facilitated the charging of the battery. Additionally, two DC motor drivers (DRV8833; Adafruit, NY, USA) were employed to enable individual control of the four motors. All electronic components were designed, assembled, and compacted into a detachable 3D printed enclosure that magnetically attaches to the glove via pogo pin connectors, allowing for easy removal and reattachment.

A low-power cellular IoT platform (version 3.8.2, Blynk, © 2024 Blynk Technologies Inc., NY, USA) was used to develop a graphical user interface (GUI) application, providing users with remote control capabilities in an accessible and user-friendly environment. This configuration was designed to eventually support people with deaf-blindness by converting real-time vocal phonemes into haptic signals, facilitating communication and aiding navigation through advanced smartphone technologies, including LiDAR functionality. At present however, the system is limited to controlling the glove and providing different haptic patterns wirelessly. An image of the interface is shown in Fig. 2b.

C. Human Trials

The dorsal side of the hand contains hairy skin, in contrast to the glabrous skin on the palmar side, resulting in differences in tactile sensitivity [36], [37]. The density of Pacinian corpuscles, which are essential for perceiving high-frequency vibrations, is lower on the dorsal side [38]. Additionally, vibration propagation through both the skin and the textile structure may impact the user's vibrotactile perception. To evaluate the vibrotactile perception capabilities specific to the dorsal proximal phalanx of the fingers (top of the finger just above the knuckle), a series of experiments were conducted.

We recruited ten healthy female participants *(n=10)*, all of whom were right-hand dominant and reported no neurophysiological disorders or dermatological conditions. The human trial in this study was conducted in accordance with the approval of the Nottingham Trent University Schools of Art and Design, Arts and Humanities and Architecture, Design and the Built Environment Research Ethics Committee (Application ID 1621411, date of approval 07/10/2024). Informed consent was obtained from all participants involved in the human trial of this study. Participants wore the developed haptic glove on their right hand, ensuring correct placement of the haptic component on the dorsal proximal phalanx region. Initially participants were introduced to the finger numbering system

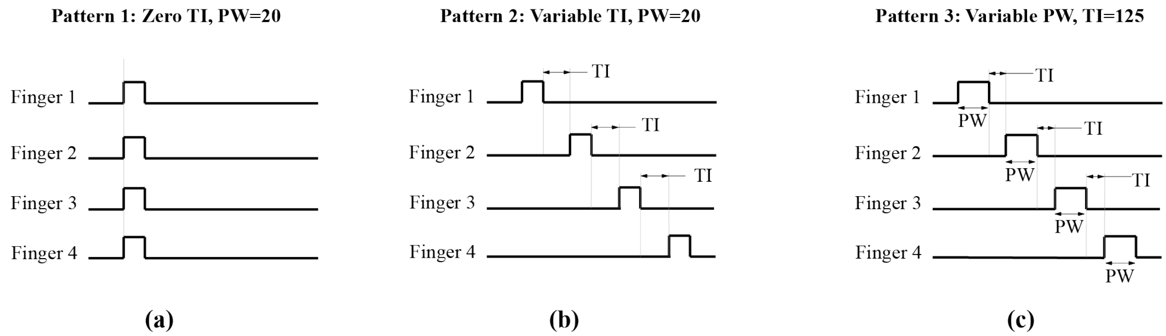

Fig. 3. Experimental patterns for the human trials: a) Pattern 1 with fixed pulse width *(PW=20ms)* and zero time interval *(TI=0ms)*. b) Pattern 2 with fixed pulse width *(PW=20ms)* and variable times interval *(TI_i [ms] = 125, 250, 500, 2000)*. c) Pattern 3 with fixed time interval *(TI=125ms)* and variable pulse width (*PW_i [ms] = 10, 20, 40, 60)*.

(as shown in Fig. 2,b) and familiarized with a sample point stimulus on each finger with a 2000 ms rest interval. For the experiment, their gloved hand was positioned under a visual barrier to prevent visual cues (Fig. 2,d).

The experimental design involved three primary patterns, n={1, 2, 3}, manipulating two variables of haptic feedback: time interval between pulses (TI) and pulse width (PW) (see Figure 3). The patterns were as follows:

1) Pattern 1: Zero TI [ms] *TI* = 0, PW= 10
2) Pattern 2: Variable TI [ms] TI_i = {125, 250, 500, 2000}, PW= 10
3) Pattern 3: Variable PW [ms] PW_i = {10, 20, 40, 60}, TI= 125

Each pattern included four sub-patterns (*i*={*1, 2, 3, 4*}), except for Pattern 1, which had a single sub-pattern due to the constant TI. Within each sub-pattern of Pattern 2, five distinct haptic sequences (*j*={*1, 2, 3, 4, 5*}) were tested to assess the response to variable TI with consistent PW. For example, the five haptic sequences in the first sub-pattern of Pattern 2 were:

- $H_{1,1}(2)$: finger 1, finger 2
- $H_{1,2}(2)$: finger 3, finger 4
- $H_{1,3}(2)$: finger 1, finger 2, finger 3, finger 4
- $H_{1,4}(2)$: finger 2, finger 4
- $H_{1,5}(2)$: finger 1, finger 2, finger 4

Full details are included in the data archive associated with this article. Each sequence in the above patterns included a 2000 ms rest interval between stimuli, with an additional 30-second rest after each sub-pattern to prevent sensory adaptation. Pattern 3 ({$H_{i,j}(3)$= Variable PW) assessed the effect of pulse intensity on perception, using a constant TI (125 ms) and varying PW to control stimulus intensity. Participants identified and named the stimulated fingers, and all responses were manually recorded and subsequently digitized.

D. Evaluation of Sustainability

As researchers, it is our responsibility to consider the environmental impact of our innovations. Therefore, this study emphasizes design and development strategies to ensure the reusability and sustainability of the glove at its end of life. This evaluation applies the methodology developed by Perera et al. for evaluating E-textile sustainability [29] and includes an interaction matrix looking at the incorporated components, and use of Kuusk's sustainability framework [32]. The interaction matrix assesses component interactions within the product and their environmental implications.

Components of the prototype glove were categorized into four primary groups: fabrics, electronics, 3D-printed components, and fixtures. The fabric materials include the 3D-knitted glove, braided yarns, Vectran™ fibers, leather pads, and stitching. Electronics consisted of the control units, motor drivers, motors, and batteries. The 3D-printed components included the housings for both electronic control elements and vibrotactile motors. Fixtures comprise pogo pin connectors, magnets, UV-curable resins, and screws. Each component and its interactions were evaluated to establish a sustainable design approach. Table II details the interaction matrix of the prototype glove, documenting the environmental impact and interaction relationships among components at the product's end of life.

III. Results and Discussion

A. Vibrotactile perception

The experimental setup for the first pattern ({$H_{i,j}(1)$}= Zero TI) assessed participants' ability to perceive haptic pulses on each finger without time intervals between stimuli on different fingers. In cases where simultaneous pulses were delivered to finger pairs or groups—finger 1 & 2, finger 2 & 3, finger 2 & 4, finger 1 & 3 & 4, and finger 1 & 2 & 3 & 4—the rates of successful identification and differentiation were 60 %, 60 %, 20 %, 0 %, 40 %, respectively (see Fig. 4a). No participants were able to fully distinguish the pulses when fingers 1, 3, and 4 were stimulated simultaneously (see Fig. 4a). Additionally, 20 % and 10 % of participants reported confusion when distinguishing between pulses on finger pairs 2 & 4 and 1 & 2 & 3 (see Fig. 4a). These results suggest that simultaneous stimulation of multiple fingers (without any time interval) reduces accuracy in finger identification. It is possible that this is due to the current positioning of the haptic motors within the glove (which are essentially next to one another).

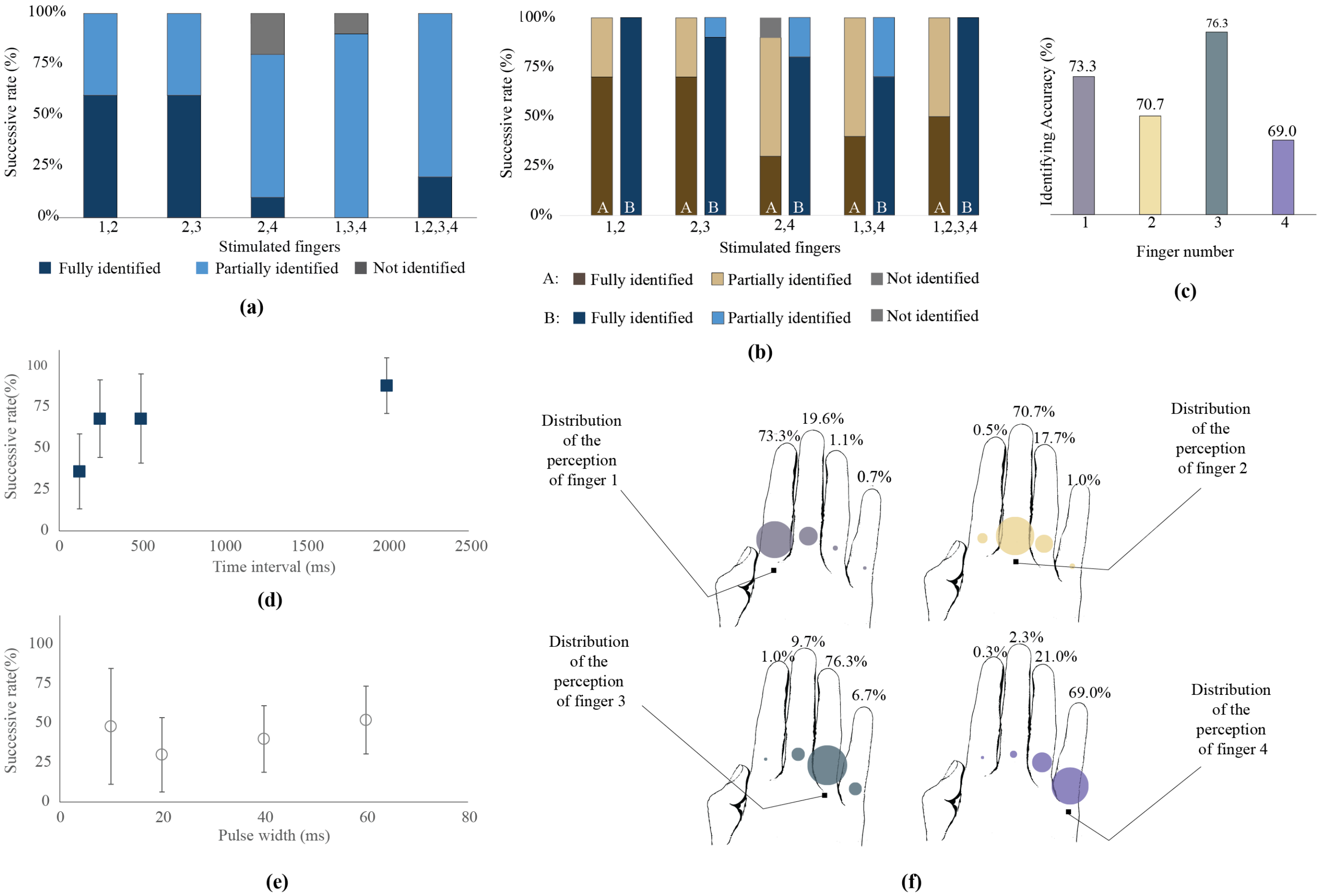

Fig. 4. Experimental results of human trials for the haptic electronic glove prototype: a) Results of identifying and distinguishing fingers with simultaneous haptic pulses (Zero TI). b) Results of identifying and distinguishing fingers with haptic pulses at a time interval TI = 125ms, B. time interval TI = 2000ms. c) Probability of accurately identifying a specific finger with haptic pulses. d) Results of identifying and distinguishing fingers with haptic pulses at varying time intervals (Variable TI). e) Results of identifying and distinguishing fingers with varying pulse widths (Variable PW). f) Distribution of identifying a specific finger to a haptic pulse.

When the time interval (TI) between stimuli was increased to $125\,\mathrm{ms}$ from zero TI, participants' ability to accurately identify and distinguish pulses improved by 10 %, 10 %, 20 %, 40 %, and 30 % for the above-stated finger sequences (see Fig. 4b). Further extending the TI to 2000 ms significantly enhanced distinguishing accuracy, with improvements of 40 %, 30 %, 70 %, 70 %, 80 %, respectively (see Fig. 4b). This trend, illustrated in Fig. 4d, indicated progressive improvement in identification accuracy as TI increases, suggesting that an adequate time interval between haptic pulses on the proximal phalanges is critical for reliable differentiation of stimuli with the current glove design.

Results from the third experimental pattern, $\{H_{i,j}(3)\}$= Variable PW, revealed a non-linear relationship between pulse width (PW) and identification accuracy. Initial increases in PW led to decreased accuracy of identification, followed by an improvement with further PW increases, as represented by the sagging curve in Fig. 4e. This curve suggested that the intensity of the haptic pulse, as controlled by PW, impacts stimulus perception accuracy. It should however be noted that this behaviour is not statistically significant, and further trails will be necessary to categorically prove if pulse width has an influence on detection accuracy.

The combined findings from experimental patterns $\{H_{i,j}(1)$ and $H_{i,j}(2)$, $H_{i,j}(3)\}$ indicated that both PW and TI may play a role in the precise localization of haptic stimuli on the fingers, potentially due to the sensory resolution of human skin and vibration propagation within the skin and textile material, which may activate surrounding sensory receptors.

Overall, aggregated experimental data (Fig. 4c) indicated an average identification accuracy of 73.3 % for finger 1 (index finger), 70.7 % for finger 2 (middle finger), 76.3 % for finger 3 (ring finger), and 69.0 % for finger 4 (little finger). Additionally, Fig. 4f highlights the rate at which each fingers are incorrectly identified as another specific finger, showing that participants often confused each finger with its neighbouring fingers. Hence, it is believed that further staggering the haptic motors in the glove (so they are not next to one another), may lead to an improvement in user's being able to identify patterns. These findings also suggest that

TABLE II
INTERACTION MATRIX FOR THE PROTOTYPE HAPTIC ELECTRONIC GLOVE

Components of the Product	**Environment**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Knitted glove (Lycra and Nylon)	Can be recycled if the elastomeric compound can be separated		T	-	-	-	-	-	-	-	-	-	-	-	C	C
2. Lycra braid	Can be recycled if the elastomeric compound can be separated	T		T	T	T	T	-	-	-	-	-	-	-	T	-
3. Vectran fibers	Less-biodegradable	-	T		T	C	C	-	-	-	-	-	-	-	-	-
4. Litz wires	Can be reused/recycled	-	T	T		C	C	C	-	-	C	C	C	C	-	-
5. UV-curable resin	Less-biodegradable	-	T	C	C		C	C	-	-	-	-	-	-	-	-
6. 3D printed motor housing (Acrylic)	Less-biodegradable	-	T	C	C	C		C	-	-	-	-	-	-	-	-
7. Vibrotactile motor	Can be reused, recycled separately as electronics waste	-	-	-	C	C	C		-	-	-	-	-	-	-	-
8. 3D printed Controller module A (Acrylic)	Less-biodegradable	-	-	-	-	-	-	-		T	H	H	H	C	T	-
9. 3D printed Controller module B (Acrylic)	Less-biodegradable	-	-	-	-	-	-	-	T		-	-	H	-	C	C
10. Electronics	Can be reused, recycled separately as electronics waste	-	-	-	C	-	-	-	H	-		C	C	C	-	-
11. Battery	Can be reused, recycled separately as electronics waste	-	-	-	C	-	-	-	H	-	C		C	C	-	-
12. Pogo pin connector	Can be reused, recycled separately as electronics waste	-	-	-	C	-	-	-	H	H	C	C		-	-	-
13. Switch	Can be reused, recycled separately as electronics waste	-	-	-	C	-	-	-	C	-	C	C	-		-	-
14. Threads/ Stitches	Can be reused/recycled	C	T	-	-	-	-	-	T	C	-	-	-	-		C
15. Leather pad	Can be reused/recycled	C	-	-	-	-	-	-	-	C	-	-	-	-	C	

(black)	N/A
H	Housing
T	Touching
C	In contact
-	No interaction

an improved glove design should prioritize haptic feedback on finger 1 (index finger) and finger 3 (ring finger), while minimizing or excluding feedback on finger 2 (middle finger) and finger 4 (little finger), to enhance the ease of distinguishing haptic pulses. These conclusions will guide the next iteration of glove development.

B. Product Sustainability

The interaction map presented in Table II categorizes interactions (e.g., in contact, touch, housing) between each component of the prototype glove. Touch refers to interactions involving relative movements between surfaces, while in contact describes fixed interactions such as stitching, gluing, or soldering. This classification aids in optimizing the design's sustainability by simplifying the approach to analyze and enhance component interactions for environmental efficiency.

The interaction matrix in Table II identifies primary limitations within the sustainable design, such as the inclusion of less-biodegradable components and the electronic waste generated due to insufficient disposal information. Notably, components 8 and 9, which consist of acrylic 3D-printed housings for electronics, show minimal critical interactions with other parts, suggesting they could be replaced with more biodegradable materials or modified in design. Conversely, components such as 5 and 6 demonstrate higher functional dependencies, making redesign or replacement challenging. To enhance sustainability, these acrylic-based components could be transitioned to biocompatible, reusable silicone-based materials. Additionally, electronic components primarily interacting with other electronics could be further compacted into a dedicated, customized configuration, ultimately reducing the total number of electronic parts and thereby minimizing electronic waste.

Following the initial analysis, Kuusk's sustainability framework [32] was applied to refine the prototype's design along eight specific sustainability qualities (SQ):

- SQ1 Minimizing Consumption

Streamline electronics by developing a dedicated circuit board that integrates functions like motor drivers, battery charging, and voltage boosters to avoid redundant electronic modules.

- SQ2 Controlling Energy and Chemical Use

Transition from acrylic-based 3D-printed components to more biodegradable, reusable, and environmentally friendly materials.

- SQ3 Developing Constantly

Integrate advanced technologies and materials into the current design and miniaturize components wherever possible.

- SQ4 Caring for Longevity

Recognize that 3D-printed electronic enclosures may degrade under repetitive stretching and compression during use; improve the attachment and durability of these housings.

- SQ5 Supporting Meaning Creation

Prioritize consumer needs by consulting people with deaf-blindness, caregivers, and relevant professionals to ensure the design aligns with user requirements.

- SQ6 Updating the Product

Enable design updates that incorporate new features with minimal material replacement to support evolving functionality.

- SQ7 Empowering Positive Emotions

Address the emotional support provided by the product, fostering a strong connection between the user and the device. This may also include improving the design of the glove.

- SQ8 Building Relationships

Promote user environments that support interactions beyond immediate surroundings, encouraging users to build wider connections over time.

The analysis based on Kuusk's framework underscores the potential for greater reusability and sustainability in the existing design. Key recommendations include replacing the 3D-printed enclosures with more durable, eco-friendly materials and adopting a customized circuit board to consolidate electronics, thereby reducing both material consumption and electronic waste. Additionally, reimagining the electronics module as a detachable wristband could eliminate the need for acrylic components and enhance the glove's washability, extending the usability and environmental friendliness of the knitted prototype design. User-friendly, design-oriented strategies should be integrated to enhance the versatility of the design.

C. Revised Glove Design

A revised glove design was developed based on feedback from human trails, understanding sustainability considerations of the existing prototype, and due to aesthetic concerns. Participant feedback was collected on both comfort and haptic perception (see Fig. 5). The glove's fit across varying hand sizes was noted to influence the accuracy of haptic feedback. Consequently, the knitted structure was selected over woven alternatives, as its stretchable nature allows for a closer and more adaptive fit to the skin. This custom-fit approach was incorporated into the revised design by introducing a ribbed structure to enhance fit, improve wearer comfort, and provide aesthetic appeal. Other key factors will include a revised supporting electronics module design (based on the analysis of the sustainability of the previous glove) and changing the positioning of the haptic actuators (based on the human trails).

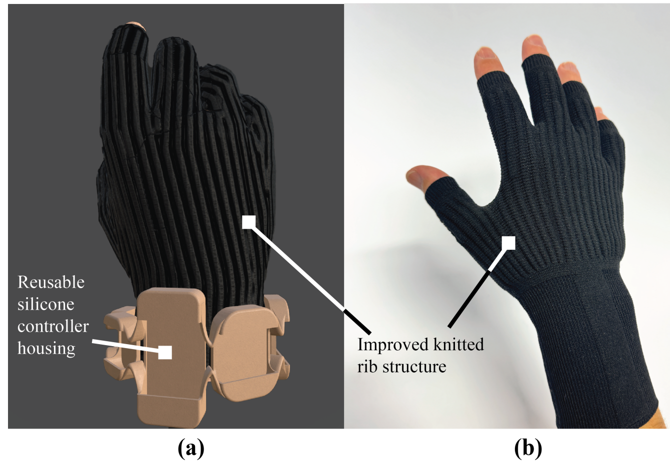

Fig. 5. Proposed new version of the improved haptic glove based on user trial results and sustainability evaluations. a) 3D model of the redesigned haptic glove featuring a detachable controller module that can be worn as a wristband. b) Actual photo of updated knitted rib design for a more adaptive and fit, and provide aesthetic appeal hiding the haptic components.

IV. Conclusion

This work presents the design and development of a haptic glove intended to assist people with deaf-blindness, which is hope will eventually address key challenges they face in communication and navigation. As an initial approach to fulfilling their needs, a wearable haptic glove has been engineered that integrates electronic haptic feedback directly within the textile using E-yarn technology. This integration secures haptic feedback mechanisms within knitted channels of the textile, offering a more durable, functional, and manufacturable design.

A control system was developed to deliver variable haptic feedback and facilitate seamless interaction with smartphones, leveraging their advanced sensing and processing capabilities. This configuration also enhances the glove's functionality by creating a closed-loop feedback system.

Experimental evaluations conducted with ten healthy participants assessed the glove's performance in perceiving haptic stimuli across different temporal and spatial resolutions. Findings highlight areas for refinement to achieve more distinct and effective haptic signals, ultimately enabling the conversion of digital signals into unique haptic cues that could facilitate real-time communication and data interpretation via tactile feedback on the skin.

A sustainability assessment was also undertaken, employing an interaction matrix and Kuusk's sustainability framework to analyze the product's environmental impact. This evaluation highlighted the need for improvements in reusability, durability, and material efficiency. Finally, the results of the study will be used to understand the drawbacks of the current design.

This work is significant as it explores an under-researched area—vibration on the proximal phalanges of the fingers—which, to the authors' knowledge, has not been previously evaluated and holds promise for advancing human-computer interaction. In conclusion, this study demonstrates the development and evaluation of a haptic electronic glove to improve as a wearable assistive device for people with dual sensory impairments, laying a foundation for future advancements in daily-use electronic textile devices aimed at enhancing quality of life for people with deaf-blindness.

V. Data Availability Statement

The human trial in this study was conducted in accordance with the approval of the Nottingham Trent University Schools of Art and Design, Arts and Humanities and Architecture, Design and the Built Environment Research Ethics Committee (Application ID 1621411, date of approval 07/10/2024). Informed consent was obtained from all participants involved in the human trial of this study. Data are contained within the article. The raw datasets collected for the analysis of this study and the anonymised data recorded form the human trials can be found on figshare at 10.6084/m9.figshare.27382146.

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