A Protactile-Inspired Wearable Haptic Device For Capturing the Core Functions of Communication*

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***Abstract*— In this paper, a novel wearable haptic device, to be worn on the hand and forearm, is introduced. Using the modalities of vibration, pressure, and heat application, the device attempts to replicate four core components of communication. The four components – co-presence, phatic communication, back-channeling, and direction giving – are simulated through haptic profiles individually unique to a section or combined as an encompassing system of the device. This paper evaluates the performance of the device through three testing phases with sighted-hearing and DeafBlind individuals. Results indicate that a strong majority of the tested haptic profiles show statistical significance in replication between individuals. This work is unique in its collaboration with the protactile DeafBlind community, individuals who communicate solely through touch, by furthering understanding on how to generate intuitive tactile profiles in wearable haptic devices.**

***Index Terms*— wearable haptics, cutaneous haptic feedback, vibrotactile stimuli, protactile, deafblind**

I. Introduction

New grammatical systems have been emerging in a group of DeafBlind (DB) signers in the United States [12] [6], who communicate via reciprocal, tactile channels; a practice DB leaders call “Protactile” [5] [17].These grammatical patterns mark a sharp separation from American Sign Language (ASL), the visual language on which the protactile (PT) language was originally built, and have emerged alongside divergent practices for interaction and communication [11]. The most consequential difference between ASL and PT language is the shift from “air space” to “contact space” [17] [6]. ASL signs and signals produced in air space do not make contact with the body of the listener, as opposed to PT signs produced on and with parts of the body. This change was part of a socio-political movement known as the “protactile movement,” which encompassed not only language and communication, but also human-environment relations, broadly construed. The movement proceeds on the assumption that all human engagement with the world can unfold entirely within tactile channels, and has pushed the bounds of tactile communication far beyond its current limits.

In the design of haptic technologies, the primary advantage of working from a PT model is that these practices are built on human-tactile intuition, using haptic and proprioceptive interactions between individuals in physical contact with one another. Fig. 1 provides a demonstration of how conversation takes place between PT communicators through direct contact. However, current tools and infrastructure do not facilitate the remote transfer of tactile cues, causing a barrier for communication without in-person touch. While there are many ways for DB people to produce and send messages, the technologies currently available provide no real-time feedback.

Fig. 1. A three-way conversation between practitioners of the PT language.

In this paper, we learn from and collaborate with PT DB leaders to understand how touch can be used to illustrate core functions of intersubjective communication, including co-presence, phatic communication, back-channeling, and direction-giving. We then present a wearable haptic sleeve that explores the types of profiles and modalities most appropriate for simulating these core functions of communication through haptic feedback. The findings are separated into two parts: a quantitative user study with sighted-hearing individuals and a qualitative case study with PT DB individuals.

Our design builds off prior successes in wearable haptics, extending this research with a specific goal of rendering intuitive, haptic profiles that facilitate conversation. As opposed to focusing on the mapping of signs and symbols to specific cues, our aim is to generate profiles that are rooted in and support human tactile capacities, specifically as it relates to core functions of communication. This investigation lays the foundation toward understanding if wearable haptic devices could support remote PT communication, and if PT cues could have intuitive meaning to sighted-hearing individuals.

1.1 Core Functions of Communication

This work focuses on rendering four core functions of communication haptically: co-presence, back-channeling, phatic communication, and direction-giving. These core functions are critical for any conversation to occur, and are often the cues missing in remote audio/video communication.

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Co-presence (CP): the simultaneous presence of individuals in the same location, creating the possibility of ”mutual monitoring” [14]. With sighted individuals, CP involves being in someone’s visual field, whereas PT individuals achieve CP through contact. For example, two PT communicators standing together might be touching at the shoulder, and two sitting together might be oriented so their legs are in contact. Sustained contact of this kind generates a stable sense that “we are here,” and is a prerequisite to a channel being established for the transmission of signs. In Fig. 1, CP occurs by touching legs. For remote settings, it is functionally equivalent to the “green dot” observed in online communication tools suggesting an individual is available.

Phatic Communication (PC): the initializing, maintaining, and ending of a communication channel [25]. In Fig. 1, the individual facing the camera, and the individual to the left are resting their hands on the bottom-right individual’s knee, thereby signalling ongoing attention and available channels. For sighted communicators, eye contact would serve a similar function. In order to open a channel, attention-getting signals are required. PT communicators do this in a variety of ways, such as tracing the back of the hand up the listener’s forearm to the listener’s hand, which is used to receive information. Channel-checking can also be done in different ways. While sighted people may wave or ask, ”Can you hear me?”, PT communicators might tap on the listener’s leg or hand, to ask them if they felt what was communicated. Finally, while sighted people close channels by walking away, or hanging up, PT communicators close channels by breaking contact.

Back-channeling (BC): the signals provided to a speaker indicating listener engagement [9]. For hearing and sighted individuals, this is commonly referred to as active listening, where nodding or verbal gestures of agreement (“mhm” or “yeah”) relay understanding. PT individuals achieve BC through cues such as a series of taps on the other person’s leg while sitting together for agreement or continued attention [23], and rubbing across the leg to indicate disagreement. Hand positioning on the bottom-right individual’s knee in Fig. 1 allows for quick BC to occur.

Direction-giving (DG): refers to (a) referents in the environment, or (b) a zero-point from which reference can be calculated, and some pathways from “here” to “there” that “we” can access [2] [18]. Applying tactile intuitions to the layout of the environment and to their linguistic system for prompting attention within that environment, PT communicators have created a new kind of DG system, which can be transmitted, received, and used without visual or auditory channels [17]. The linguistic signals themselves, or “deictics” involve tracing, pressing, tapping, and other conventionalized combinations of movements and contact on the body of the listener, as constrained by PT grammar [13].

1.2 Related Works

Recent advances in wearable technologies have demonstrated the potential of haptics to communicate incredible amounts of information. Social communication touch technology can be broken down into discriminative or affective devices. Discriminative devices focus on the subject’s sense and localization of touch, while affective devices create tactile processing with a pleasant or emotional component [22]. We briefly overview examples and findings of prior haptic devices using various types of haptic feedback in wearable systems, which were drawn on as inspiration.

Feedback through skin pressure and skin stretch is important in conveying points of interest (by moving the skin in a specific direction) and intensity (through the amount of pressure applied) [1]. Discriminative, double motor designs have been developed to apply large area pressure through straps [3], while affective designs incorporate belt torsion through a compression vest to simulate a hug around one’s chest [27]. On a smaller scale, skin stretch can be applied through rocker-like mechanisms that drag the skin in lateral or horizontal directions [7] [10]. Designs also apply localized, variable skin pressure through the use of voice coil actuators [26] [8].

Related works for wearable vibratory interfaces have shown that using different grids, spacing, or activations of vibration motors can elicit human-like touch feedback. One design was able to recreate hit, poke, press, squeeze, rub, and stroke sensations by activating sets of corresponding vibration motors [19]. Additionally, an array of vibration motors has been demonstrated to form stroking sensations along different parts of the body [20]. There have also been sets of vibration actuations that map to unique phonemes of the English language and played in certain order to form words [21]. The variety of sensations achieved through changing vibration intensity and actuation timing allow wearable devices to achieve a wide range of touch replication.

Thermal heating has also been used in prior designs to indicate CP or attention-getting schemes. Some prototypes have used applied heat through Peltier modules to simulate the warmth of a hug [15] [24]. Other designs have taken a similar idea and transformed it into linking handprints or gloves that heat up when touched by remote users [16]. Since temperature differences require more drastic changes to elicit a response and caution about direct skin contact, heat has seen limited use, but has been demonstrated to accurately depict CP or initial engagement between individuals.

Inspired by these previous advances, the design presented in this paper incorporates the use of thermal heating, coin motor vibration, and localized pressure application to capture core functions of communication through touch. Specifically, we investigate how different types of haptic feedback can be used individually and in tandem to create intuitive touch profiles for both sighted/hearing and PT DB individuals.

II. Device Description

The haptic modalities of vibration, pressure, and heat were chosen for this design, as each can be used to represent different, commonly used movement/contact types (MCs). Closely spaced vibrations have been shown to elicit tracing up-and-down the arm [4], as well as pinpointing individual spots, while pressure application covered MCs of tapping, pressing, and drumming. As a point of note, the tracing profiles were considered to be auxiliary, since it could be simulated through combinations of other MCs and is used less frequently than other MCs. Heat was included to simulate the warmth of contact between hand and arm, as well as indicating sustained presence.

To investigate haptic profiles that support these MCs, the wearable prototype design, shown in Fig. 2, consisted of two unique submodules. On the back of the hand, two grids of vibration coin motors were fixed to a modified compression glove to allow for close skin contact. The back of hand was chosen as it allows for tasks such as grabbing or holding objects without impediment, and close skin contact allows for greater user perception of the vibration motor location. Attached to the same material fabric, the forearm submodule contains a series of servo motors with replica finger tips, and a thermal patch with direct skin contact on the underside.

The device was designed to be easily attached and removed, adjustable for various arm sizes, non-restrictive for arm movement or in surroundings, and used as much skin surface as possible. To this end, a flexible high performance polyethelene arm sleeve was modified to securely hold the components and provide a snug fit without being restrictive. A low-profile design was adopted to reduce weight and increase its ease for wearing in conjunction with clothing.

2.1 Hand Submodule

The first submodule of the device was created with the intent of having tactile experiences that consist exclusively of vibration to understand the possibilities and limitations of this feedback form. The haptic profiles were created in two ways: (1) through vibration cues generated by a single coin motor buzzing in quick succession, and (2) through more complex cues such as pattern or shape tracing.

The submodule consists of 13 total 10x2 mm 5V Tatoko vibration coin motors in a 2x2 matrix within the gaps of a 3x3 matrix. The 2x2 matrix is oriented in a horizontal fashion (flat against the hand), whereas the 3x3 matrix is oriented vertically (perpendicular to the hand). By setting the motors in a perpendicular orientation, the eccentric mass within the motor produces a vibration force normal to the hand, allowing for the user to accurately pinpoint the motor location [19]. Motors in the horizontal orientation allow for the vibration forces to spread, creating a softer and less localized sensation. The spacing between the 3x3 grid motors and the 2x2 grid motors runs at 3.5 cm [1.375 in] apart, while the 2x2 grid is spaced 2.54 cm [1.0 in] apart from the 3x3 grid [19] [21]. This spacing was chosen to due to size constraints in hand sizing and prior vibrotactile localization research [4]. All motors were held by a 3D-printed PLA shell exclusive to each orientation and then stitched into the material surface to prevent shifting during vibration.

2.2 Forearm Submodule

The forearm submodule of the device was designed for pressure application and thermal heating. Similar to the vibration in the hand module, individual motor tapping cues are isolated to specific spots, while complex profiles generated by the servos could indicate tracing or could localize feedback to specific areas.

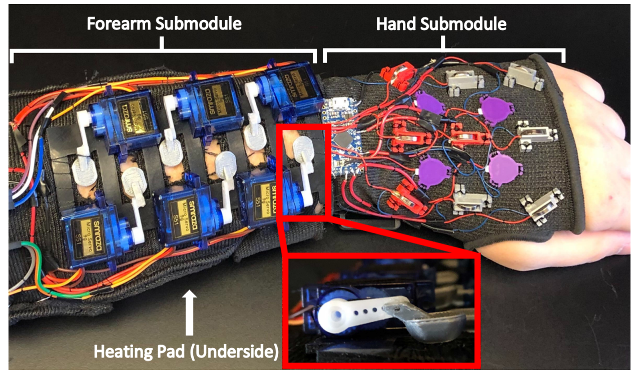

Fig. 2. Wearable haptic device with vibrotactile hand submodule (right) and servo motor and heating pad forearm submodule (left). The inset shows an enlarged view of the fingertip actuator arm.

The forearm module consists of six, SG90 9G 4.8V servo motors and a secondary heating application through a COM-11289 5x15 cm 5V flexible thermal patch on the underside of the forearm. The servo motors were staggered along the forearm and the servo arms were spaced 0.34 cm [0.875 in] apart. The spacing was set to allow for the arm to sense the individual points of pressure, but also allow for continuous tracing to exist with minimal interruption points [4]. The tips of the servo arms have a 3D-printed PLA attachment that simulates the shape of a fingertip. Fig. 2 provides a side view of the servo arm and fingertip attachment. Actuation from the servo motors cause the fingertips to apply pressure to the individual's forearm and the order of actuation creates unique patterns to represent different sensations. Different types of actuation include individual motor tapping, multi-motor tapping, long presses, and sequenced tapping. The insulated thermal patch on the forearm underside applied low-level heat to the user. The maximum temperature of the thermal patch was chosen to be 37.8°C [100°F], which is warmer than standard skin temperature of 32.8°C [91°F], but does not exceed the threshold of 45°C [113°F], after which prolonged contact can cause skin damage [28].

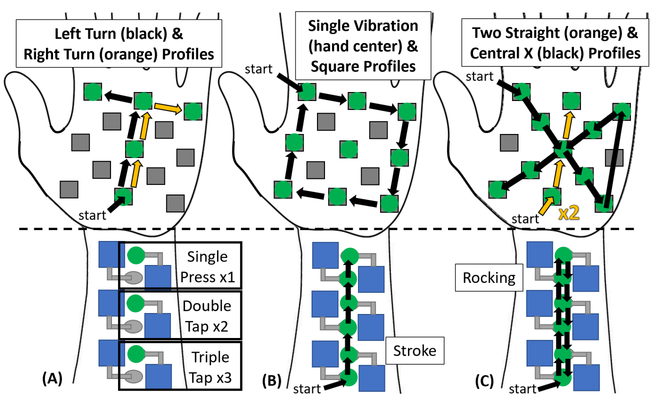

Fig. 3. Haptic profiles generated by the hand and forearm submodules. (A) Turning, sustained press, and tapping profiles. (B) Single vibration, square, and stroking profiles. (C) Two straight, central x, and rocking profiles.

2.3 Haptic Profiles

The haptic profiles of each submodule were developed based on observed patterns of taps, presses, traces, and scratches used during communication between PT users. Fig. 3 details the 12 different profiles of the submodules, with multiple profiles being shown on each arm. For the hand submodule, these included (1) a traced, L-shaped pattern to express direction to the left, (2) a mirrored L-shaped pattern to express direction to the right, (3) a single vibromotor activation in the center of the hand, (4) the traced shape of a square, (5) a repeated linear pattern to provide direction or a sense of stroking, and (6) a traced X across the center of the hand. The forearm module also had six haptic profiles developed in addition to the activation of the thermal pad. These included (1) a single press from one servo arm, (2) a rapid double tap from one servo arm, (3) a rapid triple tap from one servo arm, (4) a traced, stroking motion in sequence up the servo column, (5) a similar but slower version of the trace, and (6) a down-and-back activation of the servos akin to a rocking motion. To power and generate these profiles, the hand and forearm submodule's onboard Adafruit ItsyBitsy microcontrollers were attached to a local CPU that used serial communication to deliver the commands for actuation.

III. User Validation Studies

The objective of the user validation studies was to determine which haptic profiles and modalities were most appropriate for rendering core functions of PT communication. A two-pronged approach was used for initial validation of the sleeve: (1) a formal user study with 20 sighted-hearing participants was conducted to understand how identifiable and intuitive the profiles produced by the device were and (2) a qualitative use case trial was conducted with three DB PT individuals in order to elicit impressions of the core functions of communication rendered through the device.

3.1 Sighted-Hearing User Validation Study

The goal of this user study was to test the different tactile profiles produced from the wearable device in order to understand how they were perceived by sighted-hearing individuals. These findings will help understand how generalizeable some of the PT cues may be and to build a data set to establish themes with the PT DB feedback. We hypothesized that certain profiles in each submodule would replicate specific core functions for sighted-hearing participants. The hand submodule was hypothesized to possess intrinsic feelings of CP by a single vibration motor buzz akin to an "alert" message, BC through vibration motors turning on and off twice to simulate tapping, and DG by vibrating the motors in the linear or L-shaped profiles to indicate direction of travel. The forearm module was hypothesized to be best for CP with the heat application similar to the warmth of someone's body, PC through a "gripping" of the motors equivalent to someone grabbing an arm for attention, BC by "drumming" the motors in sequence similar to tapping, and DG through the tracing of motors in sequence.

Participant ages ranged from 20 to 62 years, with an average age of 31, and were split 10 male and 10 female. The total study time was approximately 45 minutes.

Training: Users were first instructed on how to put on the device and familiarized with the feedback modes of vibration on the hand, and motor pressure and heating on the forearm. Once comfortable with the sleeve, the user was blindfolded and asked to correctly identify the location of 10 randomized, single motor activations; five individual vibrations of the hand submodule and five individual presses of the forearm submodule. Each activation lasted one second and the user had to identify which motor had activated by pointing or tapping it after the profile was complete. If they chose incorrectly, the testing would repeat until five had been identified correctly in each submodule. This testing was done to ensure that the user was capable of feeling the feedback in multiple locations and the device was secured properly. Users were then introduced to the four core functions of communication via a reference paper which explained the four functions and gave examples that sighted-hearing individuals could relate to. For example, the reference paper associated CP with the green "active" icon found on many messaging platforms. Users could reference this sheet at any time throughout the study. Upon completion of the training, the study commenced.

Procedures: Each participant completed six, randomized profiles from the hand submodule and six, randomized profiles from the forearm submodule for a total of 12 profiles collected per user. With 20 users, this results in 240 total data points, with data collected in a number of qualitative and quantitative categories. The study was approved by the university's Institutional Review Board.

The testing was broken down into three phases: describe, categorize, and rank. In the describe phase, participants were given a profile on the corresponding submodule and asked to describe in their own words what they felt, as well as replicate the pattern with their fingers. Users were scored on their accuracy of replicating the pattern and their descriptive phrases were recorded. If users asked, profiles would be played again, but only a maximum of two times. Correctly identifying the actuation allowed the participant to continue to the next phase, while incorrectly identifying the actuation prompted the researcher to explain the pattern before continuing. The purpose of this phase was to elicit general impressions from users on what the tactile profiles might mean, as well as understand how intuitive and generalizable the profiles may be in the sighted-hearing population.

The categorize phase took the specific actuation scheme that was just displayed and had participants list which of the four core functions of communication they believe fit that cue best. Participants could choose a single function or multiple functions if they believed that actuation could represent more than one option. The purpose of this phase was to narrow the scope from general impressions to linking actuations with core functions. One limitation of the study is that users were not given the choice of "none" when associating haptic profiles with core functions, though we note that the initial describe phase of the study helped elucidate which signals tended to resonate most with users and which did not.

The rank phase was the final stage of testing. Users were asked to rank the categories they chose for the profile on a scale of 1-to-4, with #1 being the best fit and #4 being the worst fit. For example, if a participant chose PC, BC, and DG to represent a given actuation scheme, they were asked to rank those three options in order of relevance. If only one function was chosen to match a specific actuation, the ranking would default to #1.

These three phases were then repeated for all profiles. Once all profiles were tested, the thermal pad was applied to the underside of the forearm for a period of 10 minutes, after which the user was asked to describe the sensation. When the testing was complete, participants were asked a series of post-study questions to garner more feedback about the device for future iterations.

IV. Results

Through the following analyses, we were able to determine statistical significance and base-line intuitiveness for the haptic profiles generated from the wearable device.

TABLE I
DESCRIBE PHASE RESULTS

Haptic Profile	Identification Accuracy	Qualitative Themes
Single Vibration	100%	"one" "buzz"
Left Turn	65%	"direction" "left" "turn"
Right Turn	75%	"direction" "right" "turn"
Two Straight	70%	"stroke" "straight" "line"
Square	95%	"square" "perimeter" "edges"
Central X	40%	"crossing" "overlap" "across"
Single Press	100%	"one" "press-and-hold"
Double Tap	100%	"quick" "tap-tap" "two"
Triple Tap	80%	"tap-tap-tap" "angry" "three"
Fast Stroke	100%	"smooth" "all" "drumming"
Slow Stroke	100%	"slow" "sustain"
Rocking	60%	"back-and-forth" "opposite"

Table I highlights the data gathered from the describe phase of the user validation study. A one-way ANOVA test was run to determine if there was statistical significance between profiles. The data was found to have a p-value $\leq$ 0.001, so a post-hoc Tukey pairwise comparison test was performed, which found rocking and central x profiles to be statistically significant in their difference from the remaining profiles. This means that rocking and central x were not able to be reproduced in a meaningful and intuitive way. Furthermore, a list of frequently used words or phrases that correlated with the profiles was developed from the descriptions of users. It should be noted that even in cases of low identification accuracy, the qualitative themes tended to match the profiles.

Table II provides the frequency in which core functions were assigned to haptic profiles by users in the categorize phase of the user study. Data points of note include the turning profiles being heavily assigned to DG, the linear stroking and double tap being strongly linked to PC, and the linear stroking relating to BC. Another important note is that the simpler a haptic profile, the more likely a user is to relate it with the core function of CP.

Table III details the ranking system from the third phase of the user study. For brevity, we list the percentage of users who gave a haptic profile a #1 ranking, with respect to each core function. For example, 30% of participants gave a #1 ranking for single vibration to CP, whereas no user gave a #1 ranking for left turn to CP. We can observe for a single vibration, that the highest rankings were with CP and BC. Although most sections from Table II tend to line up with Table III, the fast stroke profile shows a larger spread across the core functions when ranked.

TABLE II
CATEGORIZE PHASE RESULTS, WITH % = PERCENTAGE A CORE FUNCTION WAS CHOSEN FOR EACH PROFILE

Haptic Profile	Core Functions			
	CP	***PC***	***BC***	***DG***
Single Vibration	45%	50%	60%	25%
Left Turn	5%	45%	20%	100%
Right Turn	5%	40%	25%	100%
Two Straight	10%	95%	20%	75%
Square	5%	55%	60%	50%
Central X	20%	70%	45%	40%
Single Press	50%	65%	20%	15%
Double Tap	30%	100%	30%	55%
Triple Tap	5%	30%	75%	60%
Fast Stroke	5%	30%	95%	65%
Slow Stroke	35%	25%	25%	55%
Rocking	–	65%	75%	15%

TABLE III
RANKING PHASE RESULTS, WITH % = PERCENTAGE A CORE FUNCTION RECEIVED #1 RANK FOR EACH PROFILE

Haptic Profile	Core Functions			
	CP	***PC***	***BC***	***DG***
Single Vibration	30%	25%	30%	15%
Left Turn	–	5%	5%	90%
Right Turn	–	–	5%	95%
Two Straight	–	75%	15%	10%
Square	–	25%	30%	45%
Central X	5%	45%	30%	20%
Single Press	25%	60%	10%	5%
Double Tap	15%	80%	5%	–
Triple Tap	5%	10%	40%	45%
Fast Stroke	5%	10%	50%	35%
Slow Stroke	20%	20%	20%	40%
Rocking	–	40%	55%	5%

As a final point, users paired the thermal pad exclusively with the core function of CP and were never assigned a secondary function. When asked about comfort levels, 75% found the temperature to be comfortable while applied, and 25% experienced some minor levels of discomfort. It should be noted that thermal comfort varies based on body and environmental temperature. Future work could potentially investigate if the temperature should be altered over time to accommodate such conditions. Overall, we were able to conclude that (1) only two of profiles could not be reproduced in an intuitive way, (2) certain profiles were strongly correlated with specific core functions, and (3) users chose to assign multiple core functions with those strongly correlated to one core function from the categorize phase.

4.1 ProTactile DeafBlind Use-Case

In addition to the sighted-hearing user study, the device was trialed through an open discussion session with three PT DB individuals. When presented with the wearable device, the PT DB individuals were unanimously in agreement that they preferred the forearm submodule over the hand submodule. For them, the vibrations were overpowering and did not feel as natural as the pressure application. They described vibration as being too fatiguing for continual application and numbing sensations in their hands, which is in line with vibrotactile perception theory. The forearm submodule pressure was described as the feeling of someone gripping on their arms, a frequent occurrence in PT communication. Heat application opinion was somewhat split amongst the PT DB individuals, where one was a strong proponent and the other two were neutral. The advocate expressed how the heat felt like someone was pressed against their skin, and brought more realism to the interaction. A few weeks after trialing the device, one of the PT DB individuals changed their mind on the neutral view of the heating pad. After being apart from individuals (particularly due to the pandemic), they stressed the potential value of thermal feedback as contact. Overwhelmingly, the trial session was extremely positive, with the forearm module showing promise for demonstrating CP via heat or a light press of the servos, PC and BC via single and multiple taps and gripping, and direction giving via tracing of the servos. These results overlap with the results from sighted-hearing individuals, which also categorized taps for PC and BC, and tracing profiles for DG. Taken together, these two studies illustrate the potential of PT inspired cues to provide intuitive, tactile feedback to mediate communication and validate the designed wearable sleeve in enabling these tactile capacities.

V. Conclusion

Using vibration, pressure, and heat application, the wearable device presented in this paper was able to recreate realistic tactile renderings for four core functions of communication, inspired by the PT DB community. The validation studies with both sighted-hearing individuals and DB individuals demonstrate that pressure applications, through series of taps and traces, provided the most flexibility for CP, PC, BC, and DG. Future work focuses on expanding on the design and application of this sleeve to areas including navigation, remote teaching and learning, and remote communication contexts. As researchers in haptics, we look forward to continuing to learn from the PT DB community as they push the bounds of what is possible via touch.

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