PaNDa-Glove: A Sensory Substitution Glove For Peripheral Neuropathy

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Abstract
Peripheral Neuropathy (PN) is a condition which causes diminished and potentially lost sensation in the extremities of the body, typically affecting diabetics and the elderly. We present PaNDa-Glove, an arm-mounted multi-piece device which novelly displaces tactile sensation in the fingertips, and substitutes thermosensitivity of the hand. We hypothesize PaNDa-Glove (Peripheral Neuropathy Displacement Glove) will help patients with PN better recognise the tightness of their grip, and reduce the frequency of burns to the hand. A preliminary quantitative experiment with healthy users strongly suggests, but does not conclude, that PaNDa-Glove enhances the sensitivity of grip, and an informal qualitative study suggests that the substituted feedback is clear, distinguishable and comfortable.

Author Keywords
Sensory Displacement; Sensory Substitution; Peripheral Neuropathy; Tactile Feedback; Wearable Device.

CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices; Sound-based input / output;* User studies; https://dl.acm.org/ccs/ccs_flat.cfm

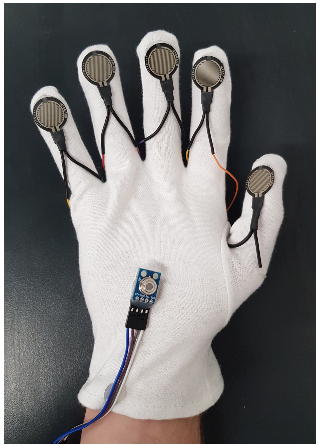

Figure 1: Receptive glove

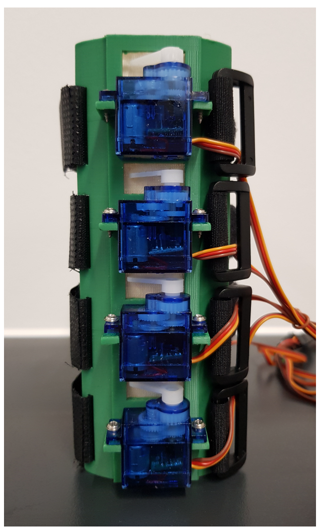

Figure 2: Tactile displacement sleeve

Introduction

Peripheral Neuropathy (PN) is a medical condition arising from nerve damage in the extremities of the body, causing a diminished sense of touch and temperature. This condition has a plethora of potential causes, including chemotherapy and HIV/AIDS, but the most common cause is diabetes [5]. People with PN tend to over-grip objects, causing unnecessary muscle strain, or under-grip objects, potentially dropping them. Such patients are also more prone to burns and cuts in affected areas, as appropriate responses are not given to dangerous temperatures and sharp objects due to lack of sensation. Further, knowledge of these injuries may not emerge until much later than they occur.

Estimates from 2015 put the worldwide prevalence of diabetes at 415 million people [10], with up to half having PN [12]. This is a significant problem, both in terms of ubiquity and impact on quality of life. With PN occurring in a primarily elderly population, solutions to problems such as this can help reduce complications and increase quality of life in a vulnerable group.

We present PaNDa-Glove, a device designed to help mitigate the loss of sensation in the hands with the use of sensory substitution and displacement. In particular, we use a novel mechanism for displacing pressure at the fingertips to the forearm, and substitute temperature sensation at the hand with vibrotactile feedback on the upper arm. Since PN can affect other extremities, PaNDa-Glove does not constitute a complete solution for every PN patient, though the methodology may be applied to other affected parts of the body, such as the feet.

Walkthrough

The wearable portion of the device consists of three components: the receptive glove (Figure 1), the pressure-displacement sleeve (Figure 2), and the temperature-substitution armband (Figure 3). Donning the device is therefore a three-step process: first, the armband should be strapped securely to the upper right arm. Subsequently, the sleeve should be securely strapped to the forearm of the right arm, with the longer plastic mount resting on the outer forearm, and the short plastic mount on the inner forearm, nearest the wrist. Finally, the glove itself can be worn.

Once in place, the functionality of the glove can be exploited. To make use of the pressure displacement capability of the glove, the user can press or grip an object with their fingertips, causing the sleeve to apply pressure to several corresponding spots along the forearm with force proportional to that sensed at each respective fingertip. When picking up objects, a user can use this feedback to gauge the amount of force they are applying to hold the object. Ideally, this intuition will develop with long-term practice.

Likewise, while wearing the glove a user can make use of the temperature substitution. When moving their palm close to an object, vibration pads on the armband will vibrate with an intensity proportional to the temperature sensed by the palm-mounted infrared thermometer. This will help a user to judge the temperature of an object before touching or gripping it. Above a 60℃ threshold, the device will continuously emit a warning beep to alert the user to the potentially harmful temperature.

Related Work

As PN affects a wide and populous demographic, research has focused on improving the quality of life of these patients through new devices.

Due to loss of sensation in the feet, PN patients are prone to blisters and ulcers as they do not feel the pressure and friction that would cause such injuries. To combat this,

Figure 3: Vibrotactile armband

Figure 4: Fingertip-mounted FSRs

Dabiri et al. propose an insole that provides feedback to the wearer when unusual pressure conditions are detected [3].

Considering the hand, an acrylic temperature sensing fingernail named ‘TeCNail’ was proposed by Vij et al. as a product concept [13]. TeCNail is aimed at PN patients, so the target audience aligns with that of PaNDa-Glove. This device alerts the wearer when their hand nears an object of unsafe temperature by providing audio feedback alongside the blinking of a LED.

Hafidh et al. present a proof-of-concept tactile substitution glove called ‘F-glove’ [6]. Much like PaNDa-Glove, F-glove features a force sensing resistor (FSR) on each fingertip, however rather than displacing the tactile sensation, F-glove instead aggregates force readings and substitutes sensation with the volume of a preselected auditory tone. Findings from their preliminary study on ten healthy subjects motivated an informal conclusion that the substitution was successful.

Nagel et al. present a somewhat different haptic feedback device: the ‘feelSpace’ belt, which uses a compass and a ring of vibration actuators to indicate the user’s orientation relative to the global north [9]. The authors conducted an interesting long-term study on the ability of users to learn a new mode of sensation with sustained practice. They found effectiveness varied significantly between participants, and present several encouraging testimonials indicating a profound change in a participant’s qualitative experience with sustained use of the device.

A study of the suitability of multi-modal force feedback was conducted by Herbst & Stark [7]. It is concluded that visual, vibro-tactile and audio feedback are all intuitively accepted as valid mediums for force feedback.

Design

As previously mentioned, our device has three main parts; a glove with attached force and temperature sensors, a pressure displacement sleeve to apply force feedback through actuation of servos (Figure 5), and an armband to provide vibrotactile feedback as temperature substitution.

We chose to displace the pressure feedback to the forearm for several reasons. Firstly, it is important to displace feedback away from the extremities, as the sensitivity of these areas are diminished by PN. The arm is chosen as the feedback site in part as it is close to the hand, therefore keeping the size of the device small and practical. Although we believe the above is sufficient to justify this choice, we also speculate that the spatial proximity and functional link of the arm and hand could potentially allow a more intuitive association between the action and the feedback. We do not test this specifically, though it would be an interesting topic for further investigation.

We chose to place the FSRs (Figure 4) on the fingertips; we reasoned that applying distinct force feedback for each fingertip is potentially intuitive due to the natural perception of digits as individual units. In testing, we assume that at least some force is applied through the fingertips to grip most items.

While the feedback mechanisms for the four fingers are located on the outer forearm, the equivalent mechanism for the thumb is instead placed on the underside. This is the result of informal testing, in which we found it was still difficult to distinguish feedback from pairs of very close motors; the solution we found was to separate out the feedback for the thumb, allowing the remaining motors to be sufficiently spaced apart. The thumb specifically was chosen for this due to its slightly distinct role in gripping objects.

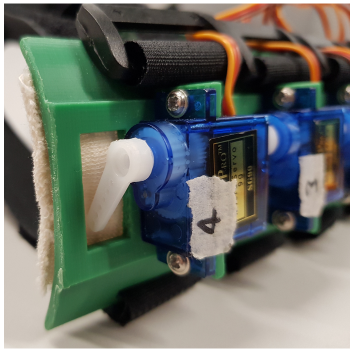

Figure 5: Feedback servo

Figure 6: Weighted flasks

We experimented with vibrotactile feedback as an alternative method of relaying pressure feedback. However, through informal testing we found that it was difficult for a user to differentiate between multiple distinct sources of vibration on the same arm, preventing the use of different levels of feedback for each fingertip.

While pressure sensitivity is displaced, temperature sensing is instead substituted with vibration feedback on the upper arm. We opted not to use displacement in this case; the heating and cooling components we were able to attain could not change temperature quickly enough for the use-case of preventing the user from burning themselves. Vibration was chosen instead as it is distinct from the existing method of pressure feedback to limit confusion, does not require active attention like a visual display would, and allows for feedback on a spectrum of values. An infrared sensor was chosen due to the quick response time compared to other components such as thermistors and thermocouples.

We augmented the temperature sensing capacity of the glove by implementing an auditory warning, to occur when extremely high temperatures are detected. This is to add a redundant layer of protection to help prevent the user from burning themselves; even if they are not yet used to the vibration feedback, or are distracted, they will still be alerted to the danger. We chose a beeping alarm tone due to the established precedent of harsh sounds conveying danger.

Evaluation

Quantitative Evaluation

To determine whether the tactile displacement component of PaNDa-Glove would be effective for PN patients, we performed a preliminary study with twelve healthy participants. If the participants performed better in the study when using PaNDa-Glove, we can extrapolate that it is likely PaNDa-Glove will assist patients with PN. Naturally, further studies would be required to confirm this.

The experiment involves a single participant at a time, and consists of a control session, in which the participant wears PaNDa-Glove with feedback disabled, and an action session, with PaNDa-Glove feedback enabled. So as to minimise the impact of learning between sessions, the participant pool was divided equally into two groups, A and B. Participants in group A started with the control session, while group B started with the action session. The gloved right arm of the participant was positioned on a flat table with fingers protruding over the edge, allowing grip isolation. Immobility of the gloved arm is paramount to this study; this best minimises the role of efference (the interpretation of internally generated motor control signals, discussed to a greater length in research by Brodie and Ross [2]) in the weight discrimination task assigned to participants in this experiment.

In each session, we presented participants with five visually identical but differently weighted opaque flasks (shown in Figure 6) in a seeded random order. The participants were subsequently passed flasks on request, and tasked with ranking the flasks from lightest to heaviest. Considering Weber's law, which states that the just-noticeable difference (JND) of a sensory stimulus is proportional to the initial stimulus magnitude [4], we can formulate for some calibration constant k a just-noticeable weight increment for a flask with weight W:

$$\Delta W = kW \tag{1}$$

Research by Pang, Tan and Durlach suggests a value of k between five and ten percent suitably expresses the JND for a pinching motion [11]. We selected a weight increment factor of $k = 10\%$ for our study, with the weight of the lightest flask equal to 200 grams.

Considering n flasks ($n = 5$ in our experiment) with true ranks given by the vector $\mathbf{y}$, our metric for the error e_x of an observed ranking vector $\mathbf{x}$ is given by the root-mean-squared deviation:

$$e_x = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \tag{2}$$

Note that we use this metric over the mean-absolute deviation to weight larger errors more significantly.

Participant		Ranking (Lowest to Highest)		Analysis
Id	Group	No Feedback	Feedback	Δe_x
1	A	$\underline{1\ 3\ 2\ 4\ 5}$	1 2 3 4 5	0.63
2	B	$\underline{1\ 2\ 3\ 5\ 4}$	1 2 3 4 5	0.63
3	A	$\underline{1\ 2\ 3\ 5\ 4}$	1 2 3 4 5	0.63
4	B	1 2 3 4 5	1 2 3 4 5	0.00
5	A	$\underline{2\ 3\ 4\ 1\ 5}$	$\underline{1\ 2\ 4\ 5\ 3}$	0.45
6	B	1 2 3 5 4	1 2 3 4 5	0.63
7	A	$\underline{1\ 2\ 4\ 3\ 5}$	$\underline{2\ 3\ 1\ 4\ 5}$	-0.46
8	B	1 2 3 4 5	1 2 3 4 5	0.00
9	A	1 2 3 4 5	1 2 3 4 5	0.00
10	B	1 2 3 4 5	1 2 3 4 5	0.00
11	A	1 2 3 4 5	$\underline{2\ 1\ 3\ 4\ 5}$	-0.63
12	B	$\underline{1\ 2\ 3\ 5\ 4}$	1 2 3 4 5	0.63

Table 1: Experiment results with incorrect rankings underlined

We hypothesize that wearing PaNDa-Glove leads to a lower average ranking error $\overline{e}_x$. A one-tailed paired t-test comparing the ranking errors of the control session with the action session gives a p-value of 0.07. Considering a significance level of $\alpha = 0.05$, the experiment does not provide sufficient evidence to accept our hypothesis. Similarly, a conclusion cannot be drawn that PaNDa-Glove changes the average ranking error $\overline{e}_x$, as a two-tailed paired t-test with the same data results in a p-value of $0.014 > \alpha$. We believe the noise in our results is due to a combination of several factors, including the infancy of our prototype. We observed that users did not strictly keep their arm in place, potentially compromising grip isolation; in future studies, a more rigorous approach to grip isolation would be required, perhaps involving a mechanical restraint. Further experiments and considerations are discussed in the Future Work section.

A complete listing of our experimental results is shown in Table 1.

Qualitative Evaluation

It is important to establish how PaNDa-Glove is perceived by participants; the device should be comfortable, practical and be considered as an enhancement. To this end, a short questionnaire was developed with Likert-type questions on a five point scale, as well as open feedback to allow participants to elaborate on their responses. In total, ten participants completed the questionnaire, with the results summarised in Table 2.

Sixty percent of participants agreed or strongly agreed that the device was comfortable, and all participants disagreed or strongly disagreed in saying the force feedback was painful, suggesting that the comfort of the device is not an issue.

Notably, sixty percent of participants agreed or strongly agreed that the feedback helped them in ranking the flasks by weight, despite no instruction being given to pay attention to the feedback. The individual who disagreed mentioned the feedback was distracting, suggesting there was an effort to focus on existing sensory feedback.

Question	Answer Frequency (%)				
	SD	D	NAND	A	SA
The servo mount was comfortable	0%	10%	30%	30%	30%
The feedback helped you in ranking the flasks by weight	0%	10%	30%	50%	10%
The force feedback was painful	70%	30%	0%	0%	0%
You were able to distinguish the feedback for each finger	0%	10%	50%	30%	10%

Table 2: Qualitative results, where SD: Strongly Disagree, D: Disagree, NAND: Neither Agree Nor Disagree, A: Agree, SA: Strongly Agree

Finally, forty percent of participants agreed or strongly agreed that they were able to distinguish the feedback for each finger. The nature of the task did not necessitate nor facilitate distinguishing fingers, so this is not necessarily indicative of the capability of the device in this respect.

Future Work

PaNDa-Glove raises a range of implementation-specific and experimental questions, each ripe for exploration. Firstly, it would be interesting to formally and directly compare feedback mediums for tactile substitution, including, but not limited to, the substituted auditory feedback presented by F-glove [6] and the displaced forearm feedback demonstrated by PaNDa-Glove. Further, a potential extension to research by Hafidh et al. could be included in this comparison: a modification of F-glove where audio pitch is varied instead of volume.

Considering the PaNDa-Glove sleeve, alternative tactile displacement locations could be investigated; the forearm may not be the most suitable place, and potential candidates including the back and the forehead have proven successful in previous studies [1, 8].

To enhance PaNDa-Glove, additional force sensors could be included on both the palm and inner lengths of the fingers, and (smaller) temperature sensors could be applied to each fingertip, similar to TeCNail [13]. Also, different output functions could be compared, including both linear and sigmoidal responses.

To confirm the effectiveness of PaNDa-Glove, and fingertip tactile displacement in general, a future formal quantitative study involving PN patients is necessary. In addition to this, a longer-term experiment with such patients similar to that carried out by Nagel et al. [9] would provide interesting insight into the impact of sustained practice on performance.

Conclusion

PaNDa-Glove is a proof-of-concept device which affords the displacement and substitution of diminishing sensation in the fingertips of patients with PN. When tested solely on healthy individuals, a preliminary study strongly suggests PaNDa-Glove improves tactile sensitivity, although there is insufficient evidence to claim this conclusively. Given the encouraging experimental results, one-to-one tactile displacement to the forearm shows strong promise as a medium for fingertip sensory substitution.

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