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 (Peripheral Neuropathy Displacement Glove), an arm-mounted device which displaces tactile sensation in the fingertips to the forearm, and substitutes thermosensitivity of the hand with vibrotactile and audio feedback. We hypothesize PaNDa-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 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** → *Haptic devices; Sound-based input / output;* •**Social and professional topics** → *People with disabilities; Seniors;* •**Applied computing** → *Consumer health;* •**General and reference** → Experimentation;

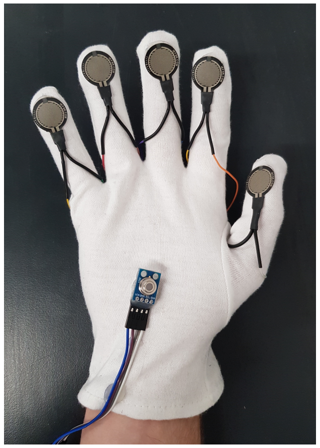

Figure 1: Receptive glove with force sensors at the fingertips and an infrared temperature sensor on the palm.

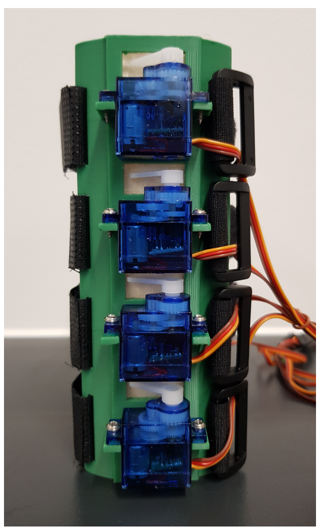

Figure 2: The forearm-mounted tactile displacement sleeve.

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 most commonly diabetes [5]. People with PN tend to over-grip objects, causing unnecessary muscle strain, or under-grip objects, potentially dropping them. They are also more prone to burns and cuts in affected areas, as appropriate responses are not given to dangerous temperatures and sharp objects.

Estimates from 2015 put the worldwide prevalence of diabetes at 415 million people [10], with up to half having PN [12]. With PN occurring in a primarily elderly population, this ubiquity highlights the importance of solutions which help reduce the impact of PN on quality of life in a particularly vulnerable demographic.

We present a Peripheral Neuropathy Displacement Glove (or 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 sensations at the fingertips with force feedback to the forearm, and substitute temperature sensation at the hand with vibrotactile feedback on the upper arm, with additional auditory warnings.

In this paper we present the design of our wearable device as well as the results of two initial user studies demonstrating the potential of our sensory substitution device. Since PN can affect other extremities we believe our work is a first step toward creating a design and research method that can be applied to other affected parts of the body, such as the feet, and thus generalize to many diverse patients affected by the loss of tactile senses.

Related Work

There has been much work around sensory substitution, with arguably the most known by Nagel et al. and their ‘feelSpace’ belt. The belt uses a compass and a ring of vibration actuators to indicate the user’s orientation relative to the global north [9]. The authors conducted a 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. To complete these findings, 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.

Sensory substitution techniques have also been looked at under the light of PN. For example, Dabiri et al. propose an insole that provides feedback to the wearer when unusual pressure conditions are detected in the feet [3]. Indeed, PN patients are prone to blisters and ulcers as they do not feel the pressure and friction that would cause such injuries. Regarding loss of sensation in the hand, an acrylic temperature sensing fingernail named ‘TeCNail’ was proposed by Vij et al. as a product concept [13]. TeCNail 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]. F-glove features a force sensing resistor (FSR) on each fingertip, however rather than displacing the tactile sensation, F-glove aggregates force readings and substitutes sensation with the volume of a pre-selected auditory tone. Findings from their preliminary study on ten healthy subjects motivated an informal conclusion that the substitution was successful.

Figure 3: Vibrotactile armband mounted on the upper arm for temperature feedback.

Figure 4: Fingertip-mounted Force Sensitive Resistors.

Device Overview

Our device consists of three components:

The receptive glove (Figure 1) is worn on the hand and serves to detect pressure applied by the fingertips on objects as well as read the temperature of objects in close proximity.

The pressure-displacement sleeve (Figure 2) comprises 5 actuators (rotating servo motors) that apply force feedback to the forearm, with each actuator corresponding to a fingertip.

The temperature-substitution armband (Figure 3) provides vibrotactile feedback in response to temperature changes around the palm.

Donning the device is therefore a three-step process: first, the armband is strapped securely to the upper arm; the sleeve is then securely strapped to the forearm of the same 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 is worn. Once in place, the functionality of the glove can be exploited: 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. A user can also make use of the temperature substitution: when moving their palm close to an object, vibration pads on the armband will activate 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.

Design

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 is 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. 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 placed the Force Sensing Resistors (FSRs) on the fingertips (Figure 4), reasoning that applying distinct force feedback for each fingertip is potentially intuitive due to the natural perception of digits as individual units. An aggregated feedback mode was also a possibility, although the loss of information with this method motivated our choice for the former. In pilot 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 (Figure 6). This is the result of pilot 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.

We experimented with vibrotactile feedback as an alternative method of relaying pressure feedback. However,

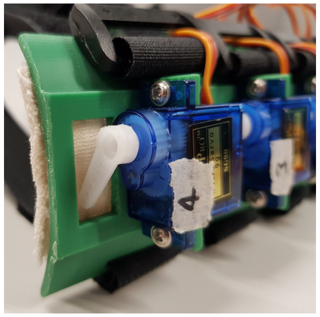

Figure 5: One of the feedback servos that applies pressure to the forearm through a padding membrane.

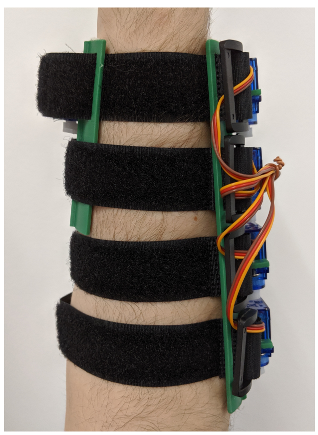

Figure 6: Side profile view of the feedback sleeve when worn, showing the separate displacement sites for the thumb and remaining fingers.

through pilot 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 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. We hypothesised that if healthy participants performed better in the study when using PaNDa-Glove, superior sensitivity is demonstrated and so it can be extrapolated that PaNDa-Glove will improve the sensing capabilities of patients with PN. Naturally, further studies with PN patients 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 by Brodie and Ross [2]) in the weight discrimination task assigned to participants.

In each session, participants were presented with five visually identical but differently weighted opaque flasks (Figure 7) in a seeded random order. The participants were subsequently passed flasks on request, and asked to rank them 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 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

Figure 7: Weighted flasks used in evaluation of the device.

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	1 3 2 4 5	1 2 3 4 5	-0.63
2	B	1 2 3 5 4	1 2 3 4 5	-0.63
3	A	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	2 3 4 1 5	1 2 4 5 3	-0.45
6	B	1 2 3 5 4	1 2 3 4 5	-0.63
7	A	1 2 4 3 5	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	2 1 3 4 5	0.63
12	B	1 2 3 5 4	1 2 3 4 5	-0.63

Table 1: Experiment results with incorrect rankings underlined.

A complete listing of our experimental results is shown in Table 1. Without feedback from PaNDa-Glove, 58% of participants incorrectly ranked the flasks. With feedback enabled, this proportion is much smaller, with only 25% of participants incorrectly ranking the flasks. Considering the ranking accuracy rather than the boolean result, we hypothesize that wearing PaNDa-Glove leads to a lower average ranking error $\overline{e}_x$. The ranking error data is not normally distributed, so a paired t-test is not appropriate. Instead, a non-parametric approach is applied; although the data size is insufficient to accurately calculate a *p*-value, a one-tailed Wilcoxon signed-rank test comparing the ranking errors results in a *W*-value of 21, just short of the critical value 26 for a significance level of 5%. Subsequently, the experiment does not provide sufficient evidence to accept our hypothesis, however we are hopeful that a different conclusion can be drawn given further samples.

Qualitative Evaluation

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.

It is important to establish how PaNDa-Glove is perceived, i.e. if the device is comfortable, practical and how it could be improved. 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. Ten participants chose to complete 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. 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]. In addition, the possibility of stronger vibrotactile feedback for high temperatures to trigger a reflexive response from the user is worth future investigation.

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. Research looking at quality of life and usability would be greatly beneficial, to see if the device assists with common household tasks.

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 suggests PaNDa-Glove improves tactile sensitivity, although further tests are needed 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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REFERENCES

[1] Paul Bach-y Rita. 1972. *Brain mechanisms in sensory substitution*. Academic Press Inc.

[2] Eric E Brodie and Helen E Ross. 1984. Sensorimotor mechanisms in weight discrimination. *Perception & Psychophysics* 36, 5 (1984), 477–481.

[3] Foad Dabiri, Alireza Vahdatpour, Hyduke Noshadi, Hagop Hagopian, and Majid Sarrafzadeh. 2008. Ubiquitous personal assistive system for neuropathy. In *Proceedings of the 2nd International Workshop on Systems and Networking Support for Health Care and Assisted Living Environments*. ACM, 17.

[4] Gustav Theodor Fechner, Davis H Howes, and Edwin Garrigues Boring. 1966. *Elements of psychophysics*. Vol. 1. Holt, Rinehart and Winston New York.

[5] The Foundation for Peripheral Neuropathy. 2019. Peripheral Neuropathy Risk Factors + Facts. `https://www.foundationforpn.org/what-is-peripheral-neuropathy/types-risk-factors/`. (2019). Accessed: 2019-12-13.

[6] Basim Hafidh, Hussein Al Osman, Majed Alowaidi, Abdulmotaleb El-Saddik, and Xiaoping P Liu. 2013. F-Glove: a glove with force-audio sensory substitution system for diabetic patients. In *2013 IEEE International Symposium on Haptic Audio Visual Environments and Games (HAVE)*. IEEE, 34–38.

[7] Iris Herbst and Jörg Stark. 2005. Comparing force magnitudes by means of vibro-tactile, auditory, and visual feedback. In *IEEE International Workshop on Haptic Audio Visual Environments and their Applications*. IEEE, 5–pp.

[8] Kurt A Kaczmarek and Paul Bach-Y-Rita. 1995. Tactile displays, Virtual environments and advanced interface design. (1995).

[9] Saskia K Nagel, Christine Carl, Tobias Kringe, Robert Märtin, and Peter König. 2005. Beyond sensory substitution—learning the sixth sense. *Journal of neural engineering* 2, 4 (2005), R13.

[10] K. Ogurtsova, J. D. da Rocha Fernandes, Y. Huang, U. Linnenkamp, L. Guariguata, N. H. Cho, D. Cavan, J. E. Shaw, and L. E. Makaroff. 2017. IDF Diabetes Atlas: Global estimates for the prevalence of diabetes for 2015 and 2040. *Diabetes Research and Clinical Practice* 128 (June 2017), 40–50. DOI: `http://dx.doi.org/10.1016/j.diabres.2017.03.024`

[11] Xiao-Dong Pang, Hong Z Tan, and Nathaniel I Durlach. 1991. Manual discrimination of force using active finger motion. *Perception & psychophysics* 49, 6 (1991), 531–540.

[12] Rodica Pop-Busui, Andrew J. M. Boulton, Eva L. Feldman, Vera Bril, Roy Freeman, Rayaz A. Malik, Jay M. Sosenko, and Dan Ziegler. 2017. Diabetic Neuropathy: A Position Statement by the American Diabetes Association. *Diabetes Care* 40, 1 (Jan. 2017), 136–154. DOI: `http://dx.doi.org/10.2337/dc16-2042`

[13] Aaraj D Vij and Vishnu R Murthy. 2017. Novel device to detect extreme temperatures and prevent injuries in patients suffering from peripheral neuropathy. In *2017 IEEE Integrated STEM Education Conference (ISEC)*. IEEE, 96–99.