Development and Validation of a Wearable Device to Provide Rich Somatosensory Feedback for Rehabilitation After Sensorimotor Impairment

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Research

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Abstract

BACKGROUND

This study describes the development and validation of a non-invasive wearable device to provide haptic feedback and train sensory discrimination. The ultimate aim of this device is to be used as part of a treatment for functional and/or pain rehabilitation due to sensorimotor impairment.

METHODS

The development was guided by a structured design control process to ensure the verifiability and validity of the design outcomes. Two sub-systems were designed to systematically provide various types of somatosensory stimulation: 1) a tactile display for touch and vibration, and 2) a set of bands for sliding, pressure, and strain sensations. The device was designed with a versatile structure that allows for its application on different body parts. We designed an interactive computer program to command the device and enable training sessions. The validation of the device was performed with 11 able-bodied individuals whose upper arm tactile sensitivity was measured over 5 training sessions conducted daily. Tactile discrimination and perception threshold were measured using the standard 2-point discrimination and Semmes-Weinstein monofilament tests, respectively.

RESULTS

The development and verification procedures ensured that the device successfully complied with the pre-established requirements, which were selected to enable the device clinical application. The results on tactile discrimination and sensitivity showed high subject-dependent variability but trended towards improvement (p=0.05). This trend was also confirmed by the scores achieved during the training sessions.

CONCLUSIONS

We introduced a wearable device to deliver somatosensory stimulation and to train sensory discrimination. The design is versatile enough to allow for its application on different body parts. The device was found robust enough for clinical application, and it showed to increase tactile sensitivity on upper arms of able-bodied individuals. Further studies will be conducted to determine if our current findings transfer to individuals with sensorimotor impairment and if this approach is suitable for functional and/or pain rehabilitation after sensorimotor impairments.

Introduction

Sensorimotor impairment is an umbrella term for diseases and injuries related to the body's function to move and/or sense. It has been hypothesized that sensory training has the potential to reduce pain due to sensorimotor impairments and potentially increase sensorimotor function [1]. This idea has been explored in the treatment of phantom limb pain and stroke rehabilitation with promising results [2]–[4]. However, sensory stimulation in previous work was delivered manually, which poses constraints on replicability of intensity, duration, and location, as well as on the possible interactions between the patient and the stimuli (i.e., interactive games). Automation of the delivery of stimuli is thus desirable to enable replicability and interaction. Furthermore, the ideal automated device would optimally stimulate all the different types of skin mechanoreceptors.

We conducted a literature review prior to this study to identify state-of-the-art actuators for somatosensations and haptic feedback technologies. The review included actuators currently on the market, as well as devices only available within research environments. We found a variety of promising mechanisms for haptic feedback, such as micro-
magnetic pin actuators, vibration actuators, wrapped bands, pneumatic systems, ultrasound, and Peltier elements. Each of these methods gives a different sensory input. Micro-sized solenoids [5], [6], or an ultrasound display [7], can be used to provide tactile feedback sensed by Merkel's disks. Vibration actuators [8], [9] can be incorporated to stimulate Meisner's and Pacinian Corpuscles. Bands or strings can be used to create sensations of stretch, stroke, or pressure [10], [11], which could also be accomplished by a pneumatic system [12]. Peltier elements can be used for temperature sensation by free nerve endings [13]. Another possibility is to provide electro tactile stimulation [14], [15], although this is often perceived as unnatural [16], and thus is perceived as less desirable. In principle, several of these methods could be combined to create one wearable haptic device, albeit the challenge seems to lay on the density of actuators one can place side-by-side to reach enough resolution to deliver rich somatosensory stimulation.

In this study we present a wearable device intended to provide various somatosensations varying from touch, vibrations, sliding, pressure, and strain. The device was designed to be easily adaptable to different users, e.g., different sizes and different residual limbs in case of amputees, as well as different stimulation setups. We verify the functionality of the device in bench tests and consequently validated it with able-bodied volunteers. Our tests showed that the device can safely provide rich somatosensations and that it can be used clinically as part of treatments for functional rehabilitation and/or alleviation of pain due to sensorimotor impairments.

**Materials And Methods**

**Design approach**

The wearable device was designed according to the waterfall-model as described in the "Design Control Guidance For Medical Device Manufacturers" document of the FDA [17], and following a similar implementation to the one included in the European Medical Device Regulation [18]. The user needs and the consequent technical requirements were set prior to the developmental process. For the sake of brevity, we report here only the main features of the functional prototype as well as its bench verification and user validation.

The intended device was designed to be able to target as many different sensory receptors as possible. Therefore, mechanisms (i.e., actuators) that could stimulate multiple sensory receptors were given priority, as well as those that can be easily adapted to different body parts. The literature study that was conducted prior to this study resulted in the actuator-receptor matrix in Table 1. It visualizes which mechanoreceptors can be activated with each actuator mechanism. Every day sensations are a combination of signals of all mechanoreceptors, but the matrix indicates which mechanoreceptor is optimized for each of the sensations.

**Table 1. Actuator-receptor matrix**
The magnetic actuators could stimulate three mechanoreceptors. The wrap band could stimulate four receptors, of which three were different from the magnetic actuators. Thus, when combining these two mechanisms, six out of seven receptors could be activated. Only free nerve ending receptors would remain inactivated responsible for sensations related to temperature and pain. However, at this stage, the activation of free nerve endings was not intended as a priority considering its increased complexity in matters of safety and subjective experience.

Following this rationale, magnetic actuators and wrap bands were deemed as the actuators to be included within the design of the intended device scope of this study. Figure 1 illustrates how the actuators are linked to each of the mechanoreceptors.

### The wearable somatosensory device

The wearable device, shown in Figure 2, included a central unit for control electronics, two tactile displays, two sliding bands, and two strain bands. The control electronics were based on an ARM Cortex-M4 microcontroller and connected via USB port to a computer while the actuators were powered via external power supply certified for medical use.

### Tactile displays

| Meissner’s corpuscle - Touch - FA-I | Pacinian corpuscle - Vibration - FA-II | Ruffini’s ending - Skin stretch - SA-II | Hair follicle plexus – Sliding and Air - IA | Merkel’s disks - Light touch and small vibration - SA-I | Free nerve endings - Temperature and pain - IA | Kinesthetics - Joint movement | # |
|-----------------------------------|---------------------------------------|----------------------------------------|------------------------------------------|------------------------------------------------|----------------------------------|-------------------------------|---|
| Ultrasound                        | Peltier elements                      | Airflow                                | Stretch pulleys                          | Wrap band                                      | Kinesthetic device               | Vibration actuators           | Magnetic actuators |
| x                                 | x                                     | x                                      | x                                        | x                                               | x                                | x                             | 3 |
| Pacinian corpuscle - Vibration - FA-II | x                                     | x                                      |                                          | x                                               | x                                |                               | 2 |
| Ruffini’s ending - Skin stretch - SA-II |                                         | x                                      |                                          | x                                               | x                                |                               | 2 |
| Hair follicle plexus – Sliding and Air - IA |                                         | x                                      |                                          | x                                               | x                                |                               | 3 |
| Merkel’s disks - Light touch and small vibration - SA-I |                                         |                                          |                                          | x                                               |                                   |                               | 1 |
| Free nerve endings - Temperature and pain - IA |                                         |                                          |                                          | x                                               | x                                |                               | 2 |
| Kinesthetics - Joint movement      | x                                     | x                                      |                                          | x                                               | x                                | x                             | 4 |
| #                                  | 2                                     | 1                                      | 2                                        | 3                                               | 4                                | 1                             | 1 |

The wearable device, shown in Figure 2, included a central unit for control electronics, two tactile displays, two sliding bands, and two strain bands. The control electronics were based on an ARM Cortex-M4 microcontroller and connected via USB port to a computer while the actuators were powered via external power supply certified for medical use.
Each tactile display was designed to provide touch and vibration sensations. The tactile display consisted of a 4x4 1-cm resolution grid of solenoid-like actuators. Each point in the grid was an assembly of an electromagnetic coil and a magnetic rod as a core (Figure 3A). By allowing electric current to flow through the coil (i.e., activating the electromagnet) a magnetic field is generated resulting in a force applied on the rod. This force pushes the magnetic rod outwards, resulting in a tactile sensation on the skin. This sensation would primarily be received by the Merkel’s Disks. Vibration could be created by activating and deactivating the electromagnetic coil at a given frequency. A stimulating frequency of about 30 to 50 Hz would be received by the Meisner’s Corpuscles. Frequencies above 60 Hz would be received by the Pacinian Corpuscles, with an optimal sensitivity at 250 Hz [19]. The tactile grid design presented here can sustain vibrations up to 250 Hz.

**Sliding and strain bands**

Two sets of moveable bands were designed to provide sliding, pressure, and strain sensations. These bands were moved by a system of servomotors whose configuration is illustrated in Figure 3C.

The first set consisted of two servomotors, each connected to one end of a rope that could be wrapped around the targeted body part. Activating the two servomotors in the same direction would create a sliding sensation mainly related to the activation of the hair follicle plexus. Activating the two servomotors in opposite directions would create a pressure sensation mainly related to the activation of the Pacinian Corpuscles [19]. This set was replicated so to achieve sliding and pressure sensations at both top and bottom sides of the device.

The second set consisted of two symmetrically placed servomotors connected to short ropes. The other side of the ropes was a fixed point to be located on the targeted body part, preferably with its direction aligned with muscle fibers. Activating the servomotors would tighten the correspondent rope, which would create a strain force on the skin mainly related to the activation of Ruffini’s Endings. It is known that skin stretch can create the illusion of proprioception (i.e., alternating joint configurations [20]), therefore this set of servomotors can be strategically located on a joint in the body so to infer changes (e.g., flexion and extension of the wrist).

**Versatile enclosure**

All feedback modalities were combined in an agile and flexible sleeve meant to be wearable. The concept sketch of this design is illustrated in Figure 3D. Each set of actuators was placed in a case with a surface of 45x45 mm. The cases were covered with a layer of tricot fabric to ensure comfort on all skin-applied parts. The sleeve consisted of a grid where the cases could be placed above and next to each other. The sleeve could be made from columns with 1, 2, or 3 rows above each other. The flexibility in the length allowed for the use of patients with different limb and/or stump sizes. Each column of the sleeve was a separate piece. Multiple columns could be connected to create a wide band. Due to the flexible material of the sleeve, the band could be wrapped around the limb. The variable number of columns allowed for different limb circumferences. The flexible spacers in between the columns of the sleeve allowed for the sleeve to wrap around the limb. Such modular system was ideal for the first prototype which was tested on different users. However, future versions could potentially be custom-designed in different sizes to allow for a more robust device.

**Validation with able-bodied volunteers**

The proposed device was validated with able-bodied individuals. Eleven able-bodied volunteers (6 male, 5 female, age 30.9±6.8) were enrolled. All participants signed informed consent prior any this study. The study was approved by the Swedish regional ethical committee in Gothenburg (Dnr:2021-03272).
Such validation meant to demonstrate the feasibility of training tactile sensitivity in non-dominant upper arms. The tactile sensitivity was measured via 1) conventional tactile assessments, and 2) scores of the sensory exercises. The assessments were taken before and after the training sessions.

A total of five sensory training sessions was performed by each participant. Before the first and after the final session the static two-point discrimination (2PD) and the Semmes-Weinstein monofilament tests (MFT) were performed to measure the influence of the sensory training on the tactile detection thresholds. The wearable training device was placed over the same patch of skin during each training session. Similarly, six related areas of the skin were selected for the tactile sensitivity assessments: four points under the tactile displays (i.e., trained skin area), and two points outside (i.e., untrained skin area or control). All points were within 1 cm from the midline of the training device. Removable skin marks and pictures were used to reposition precisely the device between sessions, as well as to perform the assessments on the same points.

**Tactile assessments**

**2-Points-Discrimination test**

The 2PD test was meant to find the minimum distance that can be perceived between two points. The test required an applied part, namely the discriminator, with two prongs distributed at predefined distances of 60, 55, 50, 45, 40, 35, 30, 25, 20, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2 mm. During the test, the discriminator was applied longitudinally and perpendicularly to the selected skin areas with one or two prongs, ten times randomly. The application was kept as uniform as possible for about 1 second, with a pressure just sufficient for skin blanching. Starting from the largest, each distance was applied 10 times in random order (one/two prongs), and 7 correct answers were needed to proceed to the next lower distance. [21]

**Monofilament test**

The MFT was meant to find the minimum force that can be perceived. The test required a set of applied parts (i.e., the monofilaments) ordered by different sizes and equivalent applied force: 0.6, 0.4, 0.16, 0.04, 0.02 g. During the test, the filaments were applied for about 2 seconds perpendicularly to the skin targeting a bend of approximately 1 cm. Starting from the smallest, each filament was applied at most 3 times randomly in each of the six selected areas. The participant was asked to report the sensation, if any, in combination with the corresponding location. One correct identification of sensation and location was enough to verify the detection threshold. Moving to the next larger force if the sensation was not correctly identified at a certain location. [22]

**Training sessions**

A training session was designed to promote the development of tactile sensory acuity by challenging the participants in sensory discrimination tasks using serious games.

Each training session lasted about 30 minutes. In each session, participants were sat in a comfortable position in front of a screen where the training tasks were running. Instructions about the tasks were shown on the screen and explained by the experimenter when needed. Result scores were automatically calculated and plotted out at the end of each task. Participants were isolated from the sound of the actuators by listening to loud-enough white noise via noise-canceling headphones. This setup is shown in Figure 4.
The training tasks comprised of recognizing and discriminating different somatosensations provided by the wearable device in combination with screen instructions. For example, executing sensory discrimination tasks like “which of the following vibrations has a higher frequency?”, or “are the bands sliding or applying pressure?”, or “in which direction are they moving?”, or “which pattern is now on the tactile display?”. These tasks were then proposed as single events iterated multiple times or as part of more complex games, like the Memory game where discrimination and recognition were tested together. Finally, these tasks were grouped and ordered by difficulty (i.e., easy, medium, and hard). The experimenter supervised all training sessions and decided which difficulty level to perform based on previous scores (i.e., at least 80% to advance to the next level), trying always to keep the participant at an adequate engagement. All training software was written in Matlab (Mathworks, USA).

**Statistical analysis**

Datasets were analyzed using built-in statistics functions of MATLAB 2018b. The one-sample Kolmogorov-Smirnov test ($p > 0.7$) was used to verify the normality of the distributions of the datasets. Since the datasets exhibited non-normal distributions, the Wilcoxon signed-rank test was used for the paired comparisons of tactile sensitivity assessments between the trained and untrained skin areas before and after the training sessions.

**Results**

**Specifications of the device**

**Tactile displays**

Each tactile unit consisted of a coil with 0.1 mm thick copper wire, with an inner diameter of 3.5 mm, an outer diameter of 5.5 mm, and a height of 9.3 mm. The coils had a total of 750 windings per piece. The magnetic rod in the center of the coil had a diameter of 3 mm and was 8 mm long. The rods had a magnetic rating of grade N42. The coils were surrounded by an aluminum case to shield the magnetic field. The tactile units were positioned in a grid of solid 3D printed plastic material. This diamagnetic material reduced the interference of the coils and magnets on each other. Moreover, the tactile units were disposed in the grid with alternated supplies polarity, so to further reduce interferences. The center distance between each of the tactile points was 11.0 mm. This distance was set below the two-point discrimination functionalities of limbs (the lowest threshold is 21.5 mm at the medial lower arm [23]). At the same time, the distance was large enough to ensure limited interference.

The electronic circuit driving each point in the grid was designed to reduce power consumption. This circuit consisted of a transistor in common emitter configuration and a large capacitor placed in series between the coil and the transistor collector. When the transistor is activated, the charge of the capacitor would allow an immediate high current (0.150 A) to flow through the coil, generating enough field to move the rod. Then, as soon as the capacitor is fully charged the current would settle on a lower steady value (0.050 A) determined by a resistor placed in parallel to the capacitor. This circuit allowed a reduction of power consumption by 67% and a maximum impact force of each tactile point of 90 mN when activated with 5 V (Figure 3B).

**Sliding and strain bands**

The slide and pressure band used continuous servomotors and two spools to allow the band to wind around them. A knot was added on the slide band so to indicate a specific location on the slider axis. The servomotors had dimensions of 50.4 x 37.2 x 20 mm and weighed 40 g. The spool had a radius of 0.6 cm. The servomotors required a current of 0.2 A at 5.0 V when operated, producing a torque of 2.0 kg/cm. Having two servos at opposite sides resulted in a maximum force of 2.4 kg. The rope applied pressure over its whole surface of roughly 6 cm$^2$ (20 cm in length and 0.3 cm in
width). The resulting maximum force was about 3.9 N/cm². This is far below the average pain pressure threshold in extremities, which varies between 100 and 200 N/cm² depending on the location [24]. This implies that in case of erroneous activation of both servos, the band could not do any harm to the user. This configuration resulted in a sliding speed between 0 and 0.05 m/s. The total length of the rope was decided as at least two times the circumference of the targeted limb to ensure that the knot could travel fully around the limb. The case around the servo and spool was designed to ensure that the rope was neatly wound on the spool without unraveling.

For the compression band, micro-sized position-controlled servomotors were used. The servomotors had dimensions of 2.5x2.5x1.5 cm and weighed less than 10 grams. The servomotors required a current of 0.35 A at 5.0 V when operated, producing a torque of 2.5 kg/cm.

**Verification of the device**

The technical requirements regarding device safety and comfort were verified by looking at the rationale of the above-described design. None of the aforementioned actuators can reach an activation force that can be considered hazardous for the user. The case was designed in such a way that the parts in contact with the skin were comfortable and not hazardous. The agile design of the case allowed for wide variability in sizes. Anyone could wear the device on an upper or lower limb. The device was within the ergonomic weight limitations of 2.2 Kg [25]. The device was found easy to wear using only one hand, as it can be worn as a sleeve.

The technical requirements regarding device functionalities were verified by bench tests meant to put the whole assembly under intense stress and unveil issues within the electronic and mechanic parts. For this, all actuators were automatically and intensively tested over multiple 2-hours sessions. Such bench tests did not result in any major issue. The calibration of the servomotors suffered minor deviations after hours of continuous activations. This indicated that a recalibration might be needed after intense use.

The delay between software commands and actuator activations was measured to be 261.6 ms on average, slightly above the commonly used threshold of 250 ms for humanly perceivable delays. A delay above 250ms might reduce the user's performance [26].

**Validation with able-bodied volunteers**

The results from 2PD and MFT are shown in Figure 4 presented as improvement between before and after the training (i.e., difference between day 1 and day 5). As expected, the training sessions had little to no effect on the tactile sensitivity of the control areas (i.e., untrained skin patches) for both 2-points and force discrimination (p=0.683 and p=0.193, respectively). Interestingly, the force discrimination slightly worsened. When it comes to the stimulated skin patches, a trend of improvement was found for both 2-point and force discriminations. However, this trend was found significant only for the force discrimination (p=0.05) and not significant for the 2-points discrimination (p=0.12). It is good to note that the improvements have high subject-dependent variability. Outliers present both below the lower inner fence and above the upper inner fence, indicating mild outliers on both sides[27].

The scores from the training tasks and games overall improved for all participants. All participants advanced to more difficult levels, and the majority settled on medium and hard levels. Usually, participants passed the easy level after one or two sessions. The medium level was used the most on average from day 2 to day 4. Seven participants reached the hard level at least twice during all sessions, and the other four at least once.

**Discussion**
In this study, we present the design, verification, and validation of a wearable device capable of applying different types of somatosensory stimulation on the skin. The bench verification proved that the device can safely and systematically generate the intended stimuli over long-term and repetitive activations. All actuators were fully functional after intense testing, and the verification process confirmed that all technical requirements were met. The chosen actuators were capable of stimulating the major mechanoreceptors of the human skin as intended.

A delay larger than 250 ms was found between the software commands and the stimuli generation on the device. This delay was slightly over the perceivable delay threshold, and therefore might result in a reduction of users’ performance. For the current version of the device, this slight deviation was deemed acceptable, but we aim to reduce it in future development iterations.

The tactile display’s resolution is still limited. Currently, the intensity of stimulation is fixed and depends on the supply voltage. The impact force produced with 5 V supply was comparable with other work in literature [28], [29] and sufficient to be perceived by all able-bodied participants. However, this might not successfully translate to compromised anatomical situations such as amputations, scar tissue, or excessive fat tissue. Lastly, the current display has 4x4 actuators, which can be easily expanded to larger matrices. Importantly, the resolution of stimulation is below the standard perception threshold for 2-points discrimination on arms and legs, thus providing enough stimulation resolution.

Despite the promising preliminary results obtained in this study, further improvements can make the device more robust to mechanical breakage, and thus more reliable over time. In addition, a second iterative design approach will try to pursue unsupervised home-use and single-handed user-friendliness.

The validation proved that this device has promising potential to be used for training tactile acuity. Trends of sensitivity improvements were found in both 2PD and MFT assessments. Limitations on statistical significance could be attributed to the limited training regime, composed of only five training days of 30 minutes each. This protocol is considerably more compact than conventional protocols for functional and pain rehabilitation [30]–[32]. We aim to conduct further studies on patients with sensorimotor impairments where changes in sensory acuity will be evaluated.

We believe the presented device is a potentially useful tool in rehabilitation and pain treatment [1]. The different actuators for somatosensory stimulation can be mapped to different serious gaming features by software. Serious gaming has been investigated for decades as a valid tool for rehabilitation as well as prosthetic use training [33]. The different types of feedback could be mapped to different in-game events or variables. The mapping can be done in numerous ways, such as sliding the bands to left and right to represent the turns of a car in a racing game or the paddle in the breakout game; activating the bands to create proprioceptive illusion to mimic particular joint motions; activating the tactile grid to represent the particular patterns like the pixels of a Tetris game; activating vibration and pressure to notify the user of sudden events like collecting an item or crashing a car. Similarly, a custom training program could be developed to train discrimination of sensations between different body parts, e.g., the affected limb vs contralateral limb. In future work, this device will be used to explore novel rehabilitation protocols for individuals with sensorimotor impairments[1].

**Conclusions**

The objective of this study was to design and test a wearable device capable of providing rich somatosensory stimulation to be ultimately used as an intervention for functional and/or pain rehabilitation. This objective was achieved by combining tactile displays of small electromagnets with sets of moving bands. The 1-cm resolution of the 4x4 tactile displays could create touch sensations on the skin as well as vibrate up to 250 Hz. The moving bands could
generate sliding, pressure, and stretching sensations. All actuators were combined in an agile, wearable, sleeve system that easily allows for sizes and configuration adjustments. The device was successfully verified proving reliability and safety suitable for clinical use. Moreover, the device showed promising potential for training tactile sensitivity. Further studies will be conducted to verify if our current results transfer to individuals with sensorimotor impairment.

**Declarations**

**Ethics approval and consent to participate**

The study was approved by the Swedish regional ethical committee in Gothenburg (Dnr: 2021-03272).

**Consent for publication**

The participants signed informed consent for this study and its publication, including publication of the media obtained in scientific venues.

**Availability of data and material**

Data and materials produced during this study can be made available upon reasonable request.

**Competing interests**

The authors have filed a patent related to the technology described in this article.

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**Authors’ contribution**

EM and MB drafted the study protocol and its ethical approval. EM and MB drafted the manuscript. EM, MB and MOC ideated the wearable device. MOC ideated the sensory training and obtained funding for the project.

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**References**

1. M. Ortiz-Catalan, “The stochastic entanglement and phantom motor execution hypotheses: A theoretical framework for the origin and treatment of Phantom limb pain,” *Front. Neurol.*, vol. 9, no. SEP, pp. 1–16, 2018, doi: 10.3389/fneur.2018.00748.

2. C. E. Seim, S. L. Wolf, and T. E. Starner, “Wearable vibrotactile stimulation for upper extremity rehabilitation in chronic stroke: clinical feasibility trial using the VTS Glove,” *J. Neuroeng. Rehabil.*, vol. 18, no. 1, pp. 1–11, 2021, doi: 10.1186/s12984-021-00813-7.

3. D. von Bornstädt, K. Gertz, N. Lagumersindez Denis, P. Seners, J. C. Baron, and M. Endres, “Sensory stimulation in acute stroke therapy,” *J. Cereb. Blood Flow Metab.*, vol. 38, no. 10, pp. 1682–1689, 2018, doi: 10.1177/0271678X18791073.
4. H. Flor, C. Denke, M. Schaefer, and S. Grüser, “Effect of sensory discrimination training on cortical reorganisation and phantom limb pain,” *Lancet*, vol. 357, pp. 1763–1764, 2001.

5. S. Gallo, C. Son, H. J. Lee, H. Bleuler, and I. J. Cho, “A flexible multimodal tactile display for delivering shape and material information,” *Sensors Actuators, A Phys.*, vol. 236, pp. 180–189, 2015, doi: 10.1016/j.sna.2015.10.048.

6. V. Vechev, J. Zarate, D. Lindlbauer, R. Hinchet, H. Shea, and O. Hilliges, “TacTiles: Dual-mode low-power electromagnetic actuators for rendering continuous contact and spatial haptic patterns in VR,” *26th IEEE Conf. Virtual Real. 3D User Interfaces, VR 2019 - Proc.*, pp. 312–320, 2019, doi: 10.1109/VR.2019.8797921.

7. T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, “UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces,” *UIST 2013 - Proc. 26th Annu. ACM Symp. User Interface Softw. Technol.*, pp. 505–514, 2013, doi: 10.1145/2501988.2502018.

8. H. A. Sonar and J. Paik, “Soft pneumatic actuator skin with piezoelectric sensors for vibrotactile feedback,” *Front. Robot. AI*, vol. 2, no. JAN, pp. 1–11, 2016, doi: 10.3389/frobt.2015.00038.

9. F. Clemente, M. D’Alonzo, M. Controzzi, B. B. Edin, and C. Cipriani, “Non-Invasive, Temporally Discrete Feedback of Object Contact and Release Improves Grasp Control of Closed-Loop Myoelectric Transradial Prostheses,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 12, pp. 1314–1322, 2016, doi: 10.1109/TNSRE.2015.2500586.

10. M. Bianchi, “A fabric-based approach for wearable haptics,” *Electron.*, vol. 5, no. 3, pp. 1–14, 2016, doi: 10.3390/electronics5030044.

11. J. L. Sullivan et al., “Multi-Sensory Stimuli Improve Distinguishability of Cutaneous Haptic Cues,” *IEEE Trans. Haptics*, vol. 13, no. 2, pp. 286–297, 2020, doi: 10.1109/TOH.2019.2922901.

12. N. Agharese et al., “HapWRAP: Soft Growing Wearable Haptic Device,” *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 5466–5472, 2018, doi: 10.1109/ICRA.2018.8460891.

13. Y. Ueda and C. Ishii, “Development of a feedback device of temperature sensation for a myoelectric prosthetic hand by using Peltier element,” *Int. Conf. Adv. Mechatron. Syst. ICAMechS*, vol. 0, pp. 488–493, 2016, doi: 10.1093/ICAMechS.2016.7813497.

14. A. Mazzoni et al., “Morphological Neural Computation Restores Discrimination of Naturalistic Textures in Transradial Amputees,” *Sci. Rep.*, vol. 10, no. 1, pp. 1–14, 2020, doi: 10.1038/s41598-020-57454-4.

15. G. K. Patel, S. Dosen, C. Castellini, and D. Farina, “Multichannel electrotactile feedback for simultaneous and proportional myoelectric control,” *J. Neural Eng.*, vol. 13, no. 5, 2016, doi: 10.1088/1741-2560/13/5/056015.

16. M. Ortiz-Catalan, J. Wessberg, E. Mastinu, A. Naber, and R. Branemark, “Patterned Stimulation of Peripheral Nerves Produces Natural Sensations with Regards to Location but Not Quality,” *IEEE Trans. Med. Robot. Bionics*, vol. 1, no. 3, pp. 199–203, 2019, doi: 10.1109/TMRB.2019.2931758.

17. Food and Drug Administration Center for Devices and Radiological Health, “Design control guidance for medical device manufacturers,” *Des. Hist. File*, p. 53, 1997.

18. “Medical Device Regulation,” *Off. J. Eur. Union*, 2017.

19. D. Purves et al., *Neuroscience*, Third. Sunderland (MA): Sinauer Associates, 2004.

20. B. B. Edin, “Strain-sensitive mechanoreceptors in the human skin provide kinaesthetic information,” in *Somesthesia and the Neurobiology of the Somatosensory Cortex*, O. Franzén, R. Johansson, and L. Terenius, Eds. Basel: Birkhäuser Basel, 1996, pp. 283–294.

21. Erik Moberg, “Two-point discrimination test. A valuable part of hand surgical rehabilitation, e.g. in tetraplegia,” *Journal of Rehabilitation Medicine*, vol. 22, no. 3. pp. 127–134, 1990.

22. S. Weinstein, “Fifty years of somatosensory research: From the Semmes-Weinstein Monofilaments to the Weinstein Enhanced Sensory Test,” *J. Hand Ther.*, vol. 6, no. 1, pp. 11–22, 1993, doi: 10.1016/S0894-1130(12)80176-1.
23. K. Shibin and A. J. Samuel, “The Discrimination of Two-point Touch Sense for the Upper Extremity in Indian Adults,” vol. 2, no. 1, 2013, [Online]. Available: http://www.scopemed.org/?mno=33496.

24. M. Melia et al., “Pressure pain thresholds: Subject factors and the meaning of peak pressures,” *Eur. J. Pain (United Kingdom)*, vol. 23, no. 1, pp. 167–182, 2019, doi: 10.1002/ejp.1298.

25. E. B. Weston, A. M. Aurand, J. S. Dufour, G. G. Knapik, and W. S. Marras, “One versus two-handed lifting and lowering: lumbar spine loads and recommended one-handed limits protecting the lower back,” *Ergonomics*, vol. 63, no. 4, pp. 505–521, 2020, doi: 10.1080/00140139.2020.1727023.

26. T. Waltemate et al., “The impact of latency on perceptual judgments and motor performance in closed-loop interaction in virtual reality,” *Proc. ACM Symp. Virtual Real. Softw. Technol. VRST*, vol. 02-04-Nove, pp. 27–35, 2016, doi: 10.1145/2993369.2993381.

27. “NIST/SEMATECH e-Handbook of Statistical Methods,”.

28. F. Pece et al., “MagTics: Flexible and Thin Form Factor Magnetic Actuators for Dynamic and Wearable Haptic Feedback,” *UIST 2017*, vol. October, pp. 143–154, 2017, doi: 10.1145/3126594.3126609.

29. X. Yu et al., “Skin-integrated wireless haptic interfaces for virtual and augmented reality,” *Nature*, vol. 575, no. 7783, pp. 473–479, 2019, doi: 10.1038/s41586-019-1687-0.

30. M. Ortiz-Catalan et al., “Phantom motor execution facilitated by machine learning and augmented reality as treatment for phantom limb pain: a single group, clinical trial in patients with chronic intractable phantom limb pain,” *Lancet*, vol. 388, no. 10062, pp. 2885–2894, 2016, doi: 10.1016/S0140-6736(16)31598-7.

31. E. Lendaro et al., “Phantom motor execution as a treatment for phantom limb pain: Protocol of an international, double-blind, randomised controlled clinical trial,” *BMJ Open*, vol. 8, no. 7, p. e021039, Jul. 2018, doi: 10.1136/bmjopen-2017-021039.

32. S. Damercheli, M. Buist, and M. Ortiz-Catalan, “Mindful SensoriMotor Therapy with Brain Modulation for the Treatment of Pain in Individuals with Disarticulation or Nerve injuries: A Single arm clinical trial,” *Under Rev.*

33. L. Sardi, A. Idri, and J. L. Fernández-Alemán, “A systematic review of gamification in e-Health,” *J. Biomed. Inform.*, vol. 71, pp. 31–48, 2017, doi: 10.1016/j.jbi.2017.05.011.

**Figures**
Figure 1

Overview of the actuators in the design and the relation with the corresponding mechanoreceptors. Merkel's Disks respond to the touch activation of the tactile grid. Meissner's Corpuscles respond to low frequency vibrations of the tactile grid. Pacinian Corpuscles respond to high frequency vibrations of the tactile grid and activation of the compression band. Hair follicle plexus respond to activation of the slide band. Ruffini’s Endings respond to activation of the strain band [19].
Figure 2

Wearable somatosensory device for training tactile sensitivity.
Figure 3

Design sub-systems. (A) Tactile unit cross section. (B) Coil force diagram. The line shows the force upon activation at $T = 0$ s and deactivation at $T = 1$ s. (C) Bands. The two servos on the top are activating the strain bands. The other servos are activating the pressure and sliding bands. (D) Modular case system concept sketch.

Figure 4

Schematic illustration of the setup used for the validation experiment. The wearable training device (A) was placed on the upper arm of the non-dominant arm of the participant. A user-interface (B) provides instructions for the training. Noise-canceling headphones (C) with a white-noise soundtrack were used to isolate the user from the sounds of the actuators.
Figure 5

Results from 2-points-discrimination, or 2PD, test (left) and monofilament, or MFT, test (right). The results are presented as improvement between before and after the training (i.e., difference between day 1 and day 5).