

Novel Wearable Device for Mindful Sensorimotor Training: Integrating Motor Decoding and Somatosensory Stimulation for Neurorehabilitation

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Abstract—Sensorimotor impairment is a prevalent condition requiring effective rehabilitation strategies. This study introduces a novel wearable device for Mindful Sensorimotor Training (MiSMT) designed for sensory and motor rehabilitation. Our MiSMT device combines motor training using myoelectric pattern recognition along sensory training using two tactile displays. This device offers a comprehensive solution, integrating electromyography and haptic feedback, lacking in existing devices. The device features eight electromyography channels, a rechargeable battery, and wireless Bluetooth or Wi-Fi connectivity for seamless communication with a computer or mobile device. Its flexible material allows for adaptability to various body parts, ensuring ease of use in diverse patients. The two tactile displays, with 16 electromagnetic

actuators each, provide touch and vibration sensations up to 250 Hz.

In this proof-of-concept study, we show improved two-point discrimination after 5 training sessions in participants with intact limbs ($p=0.047$). We also demonstrated successful acquisition, processing, and decoding of myoelectric signals in offline and online evaluations.

In conclusion, the MiSMT device presents a promising tool for sensorimotor rehabilitation by combining motor execution and sensory training benefits. Further studies are required to assess its effectiveness in individuals with sensorimotor impairments. Integrating mindful sensory and motor training with innovative technology can enhance rehabilitation outcomes and improve the quality of life for those with sensorimotor impairments.

Index Terms—Machine learning, motor learning, motor training, neurorehabilitation, plasticity-guided treatment, sensory training, serious games.

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I. INTRODUCTION

A. Motor Execution

MOTOR learning strategies, such as Motor Execution (ME) play a crucial role in rehabilitation strategies for individuals with sensorimotor impairments [1, 2, 3, 4, 5, 6]. Current rehabilitation approaches emphasize the promotion of motor recovery through task-oriented exercises and repetitive practice of functional movements. By engaging patients in purposeful activities and facilitating the activation of affected muscles and neural pathways, ME-based interventions aim to improve motor control, coordination, and functional abilities. A promising recent development is the integration of decoding motor volition using myoelectric pattern recognition (i.e., machine learning applied to electromyographic signals recorded from an affected or residual limb), with real-time feedback via virtual and augmented reality (VR-AR) [7, 8]. This approach has shown promising results in facilitating recovery in individuals with sensorimotor impairments, such as Phantom Limb Pain (PLP) [9], and stroke [10]. However, this technique has not been effective for everyone, and therefore the need for further improvement remains [9].

B. Sensory Training

Another important aspect of rehabilitation for individuals with sensorimotor impairments is sensory training (ST). ST, intended as the training of somatosensory acuity, has the potential to reduce pain due to sensorimotor impairments and increase sensorimotor function [11, 9, 12, 13]. The conventional way to provide ST is with the manual application of stimulations [14]. Recently, our research group developed a wearable system to provide ST and showed that such a device can improve sensory acuity [15]. Other studies have also reported positive outcomes related to ST interventions. For instance, Flor *et al.* [16] demonstrated improvements in two-point discrimination thresholds and reduced phantom limb pain. This study followed a ten-day ST procedure where participants had 90-minute sessions of discriminating non-painful electric stimuli. Similarly, Moseley *et al.* [17] observed similar positive results in patients with complex regional pain syndrome, when doing 2 weeks of Two-Point Discrimination training. Furthermore, Dogru Huzmeli *et al.* [18] reported improved functional outcomes in stroke patients as a result of ST using stimulation with varying objects.

C. Sensorimotor Training

In recent years, there has been a growing acknowledgment of the role sensory feedback plays in motor learning and rehabilitation outcomes. Bolognini *et al.* [19] underscored the sensory aspects of post-stroke motor rehabilitation, highlighting the significance of sensory feedback in facilitating motor learning. Moreover, Sigrist *et al.* [20] reviewed the literature and highlighted how augmented sensory feedback, including visual, auditory, and haptic modalities, can enhance motor learning outcomes. Additionally, recent systematic reviews by Serrada *et al.* [21] and Islam and Lim [22] provided valuable insights into the incorporation of sensory training in motor learning applications. Sigrist *et al.* also emphasized the potential of multimodal feedback to improve motor learning [20]. However, they noted the importance of delivering feedback effectively to maximize its impact, aiming to make it intuitive and avoid overwhelming cognitive load. While Bolognini *et al.* acknowledged that there are challenges in determining the optimal type and dose of sensory therapies, they also underscored the need to view sensory-based interventions as potential substitutions [19]. This perspective presents opportunities for refining sensory-based training strategies, aligning with our study's objective to explore the integration of somatosensory stimulation into a novel sensorimotor training paradigm. The integration of ME and ST can thus be a promising tool for sensorimotor rehabilitation [9, 23]. Emerging technologies, such as wearable tactile displays, offer new possibilities for enhancing ME-based interventions with targeted sensory stimulation. The stimulation can be used as real-time feedback, which allows for immediate self-correction, promoting active engagement and self-awareness during sensorimotor training [24]. Another strategy for incorporating sensory stimulation in ME-based interventions is using sensory stimulations as a guide on how to perform the ME exercises. These sensory cues can enhance

TABLE I
SPECIFICATIONS OF THE MICROCONTROLLER UNIT
ESP32-WROOM-32 AND ANALOG FRONT END ADS1299

ESP32-WROOM-32	
CPU	Xtensa® 32-bit LX6 (Dual Cores)
Frequency	240 MHz
FPU	Yes
RAM	520 kB
Flash	8MB or 16MB
GPIOs	34
SPI	4 (2 for external communication, frequency up to 80MHz)
I2C	2
UART	3
Wireless Module	Wi-Fi, Bluetooth, Bluetooth Low Power (BLE)
ADS1299	
Differential channels	8
Power x Channel [mW]	5
Gain[V/V]	1,2,4,8,12,24
Signal BW Range [Hz]	65 ÷ 4193
Output sampling rate [SPS]	250,500,1k,2k,4k,8k,16k
Stimulator	No
ADC resolution	24 bits
CMRR [dB] (f = 50, 60Hz)	120
Input-Referred Noise [μ V]	0.32 (SPS = 1k, Gain = 12) 2.17 (SPS = 1k, Gain = 1)

the quality and precision of motor execution, facilitating more effective motor learning [25, 26].

The development of a compact wearable system that integrates ME and ST has the potential to optimize interventions for sensorimotor impairments. This manuscript presents the development and validation of such a novel device, which addresses the challenges in sensorimotor rehabilitation, using Mindful Sensorimotor Training (MiSMT). MiSMT utilizes electromyography (EMG) technology for targeted motor control training and incorporates a tactile display for real-time feedback and ST. The integration of ME using EMG acquisition and ST using tactile displays addresses the current lack of such technologies and presents a comprehensive solution for sensorimotor rehabilitation.

II. METHODS

A. Device Development

The MiSMT device is an embedded system built around an ESP32 microcontroller [27], offering powerful computation capabilities with built-in WiFi and Bluetooth modules for flexible and convenient data transfer and interaction. The specifications of the microcontroller can be found in Table I. To capture EMG signals effectively, the device is equipped with the ADS1299 integrated Analog Front-End (AFE) (Texas Instruments, USA) [28]. This EMG acquisition module was based on the design of an open-source EMG-acquisition device hereafter referred to as the ADS-BP (ADS1299 and Booster Pack) [29]). It supports up to 8 bipolar EMG channels with a maximum sampling frequency of 2kHz. The specifications of the AFE can be found in Table I. The MiSMT device is user-friendly, featuring a single On/Off button with a Bi-Color LED (Red/Green) for clear status indication. Additionally, it offers eight connectors for easy attachment of electrode leads,

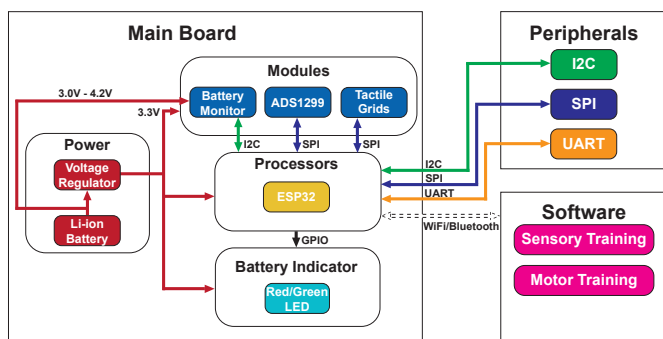


Fig. 1. Hardware Structure Diagram of the hardware architecture of the MiSMT device. The MiSMT device is built around an ESP32 microcontroller which communicates via Serial Peripheral Interface (SPI) to both actuate the tactile displays and acquire EMG data. The device can be controlled through custom software via a WiFi or Bluetooth connection.

ensuring efficient EMG signal recording using disposable skin surface electrodes. Two tactile displays, previously developed by our research group [15], are integrated with the main board through Serial Peripheral Interface (SPI) connectors. A full diagram of the hardware architecture can be seen in Figure 1. The device is encased in a protective housing with a removable lid to access the battery compartment, containing a rechargeable 3.7V battery. For added comfort during usage, the device features a flexible silicone cover which securely attaches the tactile grids to the case. An elastic strap added convenience and stability, enabling the MiSMT device to be wrapped securely around the body for optimal placement and usability. This device can accommodate body parts ranging in sizes of diameter from 20 cm up to the width allowed by the attached strap, covering the requirements of the diverse patient population. The design of the device's housing can be seen in Figure 2.

B. Software

The software presented in this article is meant for the purpose of this study only. Specific software was developed for this manuscript that aids the quantification of the desired outcome measures, for both ME and ST. The primary focus of this manuscript is to describe the development of the MiSMT device as well as the validation of the two major components for ME and ST, separately. All software presented here was developed using Matlab (Mathworks, USA) [30].

1) *Sensory Training*: The training software for the ST study comprised four sensory training modalities. These modalities included a multiple-choice question format, a vibration game, a discrimination task, and the two-alternative forced choice (2AFC) test. In the multiple-choice questions, participants were presented with various sensations and had to identify the initial given sensation from a set of multiple-choice answers. In the vibration game, participants were presented with a vibration stimulus and then provided with 4-6 alternative vibrations, each with a different frequency (number of alternatives depended on the difficulty level). The participants were tasked with matching the presented vibration to the corresponding frequency among the alternatives. The discrimination task required participants to differentiate between similar or different

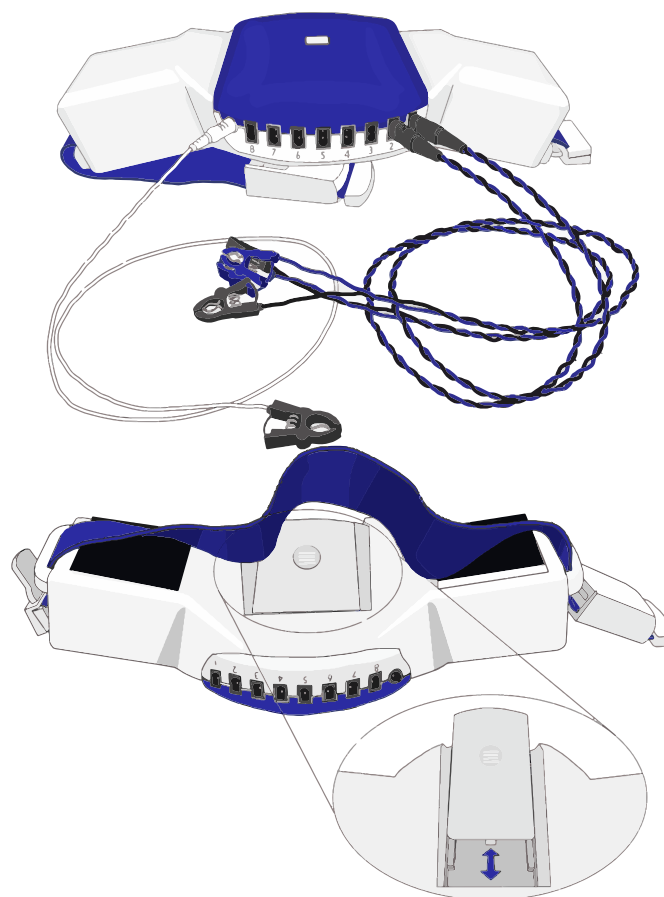


Fig. 2. Design of the MiSMT device. The 8 bipolar electrode jacks are situated on the front of the device. Two of the eight electrode leads, and the reference lead, are drawn. The tactile displays are placed on either side of the device. The battery can be accessed from the bottom.

sensations presented on the two tactile displays. The 2AFC test involved presenting participants with two alternatives and requiring them to choose between them based on specific characteristics. This test focused on the discrimination of vibrations with different frequencies. The multiple-choice and discrimination game comprised vibrations at different frequencies, movement directions, and diverse shapes or locations on the tactile grid. The other two modalities comprised only vibrations with different frequencies.

2) *Motor Execution*: The software for ME training was developed based on pattern recognition methodologies such as in the open-source platform BioPatRec [31]. This allowed for the analysis and interpretation of the EMG signals. The software incorporated pattern recognition algorithms that enabled the identification and classification of specific movement patterns within the EMG data [32]. Two main phases were required for the ME-exercise. The first phase involved the recording of movements, which was necessary for the supervised training of the pattern recognition algorithms. Here, participants performed various movements while EMG signals were recorded at 1000Hz from surface electrodes placed on their arm. The participants sat comfortably in front of a computer screen where they were prompted to perform different finger movements. The collected dataset was then

divided into windows with a time length of 200ms and a 150ms overlap. From these windows, four features (mean absolute value, zero crossing, slope sign changes, and waveform length) were extracted channel-wise, z-score normalized, and used to train a 6-layer feed-forward neural network (as described in [32]). The second phase involved human-in-the-loop real-time use. Here, the trained algorithm was used to predict and classify movements in real-time based on incoming (and unseen) EMG data. Specifically, the Motion Test [33] was used in this study to assess the real-time myoelectric pattern recognition performance. Thus, the participants were instructed to perform specific movements as guided by the software instructions, while output predictions were logged and used for final accuracy calculations.

C. Study Design for Sensory Training

1) *Study Aim*: To validate the device's capability of delivering an effective training for somatosensory perception.

2) *Participant Selection Criteria*: Participants with intact limbs were enrolled to participate in the ST intervention. Fluency in either English or Swedish was required to ensure clear communication throughout the study. Participants who had previously participated in other ST studies within the past year were excluded here to minimize potential confounding effects. Power calculations were conducted to determine the optimal sample size for achieving statistically significant results. Based on these calculations, it was determined that a minimum of 14.3 participants would be required. To maintain statistical power and ensure reliable findings, it was decided to recruit at least 15 participants. The study had ethical approval from the Swedish regional ethical committee (Dnr: 2022-00883-02), and all subjects signed an informed consent document before starting.

3) *Study Protocol*: The ST intervention consisted of a total of five training sessions for each participant. To assess the impact of the training, tests for tactile detection thresholds, static Two-Point Discrimination (TPD), and Semmes-Weinstein Monofilament Test (MFT) were performed before the first session, after the final session, and in a follow-up visit at 1 to 2 weeks after the final session. The study timeline is depicted in Figure 3. During each training session, the wearable device was placed over the same patch of skin. Six designated areas of the skin were selected for tactile sensitivity assessments: four points within the trained skin area under the tactile displays and two points outside the trained skin area serving as a control. All selected points were within 1 cm from the midline of the training device. Semi-permanent skin marks and pictures were used to ensure precise repositioning of the device between sessions and accurate assessment on the same points.

The training sessions aimed to enhance tactile sensory acuity by challenging participants with tactile sensory discrimination tasks through serious games. Each session had an approximate duration of 50 minutes, two times 20 minutes with a 10-minute break. Participants were comfortably seated in front of a screen where the training tasks were presented. The tasks described are elaborated upon in the subsection on Software, Sensory

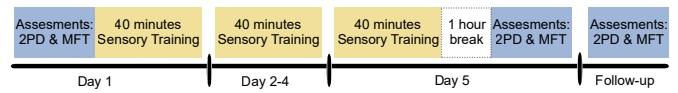


Fig. 3. Timeline for study protocol of ST. Day 1-5 consists of 40 minutes of effective training. The assessments are done before the training session of day 1, (at least) 1 hour after the session on day 5, and at a 1-2 week follow-up.



Fig. 4. Setup for the ST. The MiSMT device is worn on the upper arm of the non-dominant side, and the participant wears noise-cancelling headphones.

Training. Each of the four modalities in the ST software was executed consecutively, repeating from the first one until the 20 minutes were over. Upon completion of the fourth modality, the sequence resumed from the first, ensuring a continuous rotation through all four modalities until the allotted time expired. To minimize auditory distractions, participants wore noise-canceling headphones and listened to white noise of sufficient volume. This setup is depicted in Figure 4. On-screen instructions guided participants through the tasks, with additional explanations provided by the experimenter when necessary. Result scores were automatically calculated and displayed at the end of each task. The tasks were organized into difficulty levels (easy, medium, and hard), and participants advanced to the next level if they achieved a minimum score of 80 percent, ensuring an appropriate level of engagement [34].

4) *Assessment Methods*: Two-Point Discrimination. The TPD test was conducted to determine the minimum perceivable distance between two points. The test utilized a specialized apparatus called the discriminator, consisting of two prongs positioned at predetermined distances ranging from 60 to 15 mm, with 5mm intervals, and 15 to 2 mm, with 1mm intervals. For distances equal to or below 25 mm, the "Dellon Disk-Criminator" was employed, while a 3D printed probe resembling the "Dellon Disk-Criminator" was used for larger distances, which we designed ourselves. This design choice eliminated the need for time-consuming adjustments

of compasses or calipers for each distance, ensuring efficiency and accuracy. During the test, the discriminator was applied randomly with either one or two prongs, to selected areas of the skin. The application was performed longitudinally and perpendicularly, maintaining a uniform pressure for approximately 1 second to induce skin blanching. Each distance was applied ten times in random order (using one or two prongs). A participant needed to provide seven correct responses to proceed to the next lower distance. [35]

Monofilament test. The MFT was conducted to determine the minimum force threshold that can be perceived. The test involved using a set of monofilaments, which were ordered based on their sizes and equivalent applied force: 0.6 g, 0.4 g, 0.16 g, 0.04 g, 0.02 g, and 0.008g. During the test, the filaments were applied perpendicularly to the skin, targeting a bend of approximately 1 cm, and maintained for about 2 seconds. Starting from the smallest monofilament, each filament was randomly applied up to three times in each of the six selected areas. Participants were asked to report any sensation experienced and the corresponding location. A correct identification of the sensation and location was considered sufficient to establish the detection threshold. If the sensation was not correctly identified at a certain location, the next larger force was applied, and the process was repeated accordingly. [36]

5) Outcome Measures: Primary Outcome Measures. The primary outcome measures included the TPD test and the MFT. By comparing the pre-and postintervention measurements of these tests, we aimed to determine the immediate effects of the ST intervention on tactile discrimination abilities and tactile sensitivity.

Secondary Outcome Measures. In addition to the primary outcome measures, we incorporated secondary outcome measures to assess the long-term effects of the intervention. The secondary measures involved follow-up assessments using the TPD test and MFT conducted at a designated time after the completion of the intervention. These follow-up assessments aimed to capture any sustained improvements or changes in somatosensory function beyond the immediate post-intervention period. By including these secondary measures, we sought to evaluate the persistence and durability of the ST intervention's effects on tactile discrimination and sensitivity.

6) Data Analysis and Statistics: All data processing and statistical analyses were performed in MATLAB R2020b [30]. Statistical methods were employed to analyze the impact of the ST intervention on the TPD and MFT. To assess the normality of the data distributions, the Shapiro-Wilks test was utilized. The resulting p-values indicated that the data were not normally distributed, as they were lower than the predetermined significance level of 0.05.

For the primary outcome analysis, the Wilcoxon signed-rank test was applied to compare the pre-and postintervention measurements of the TPD and MFT. These measurements were taken at two specific time points: before the initiation of training on day 1 and approximately 1 to 2 hours after the completion of training on day 5. The Wilcoxon signed-rank test, known for its suitability with paired samples and non-parametric nature, facilitated accurate evaluation of the

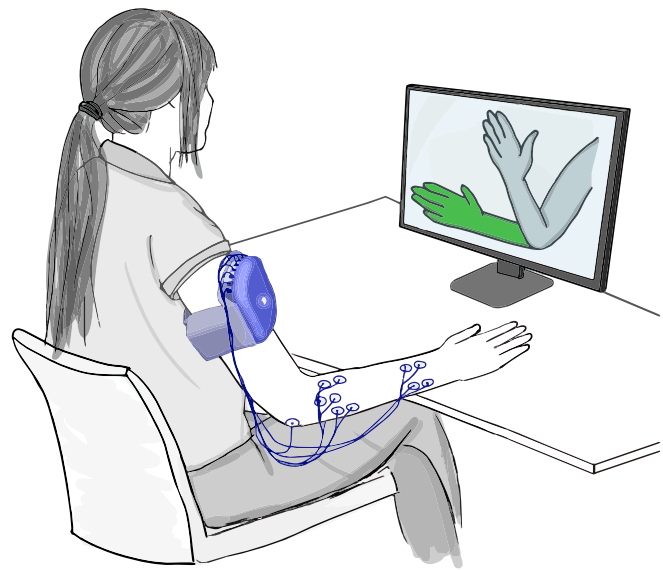


Fig. 5. Setup for the ME. The MiSMT device is worn similarly as in the ST. Disposable electrodes are attached to the skin and connected with leads to the device.

differences between these paired measurements. The significance level for this test was set at 0.05. A two-tailed test was used, to account for both positive and negative change in the tactile sensory acuity, resulting in a significance threshold of 0.025 for each tail of the test.

Regarding the secondary outcome analysis, which focused on the follow-up assessment, the Wilcoxon signed-rank test was employed to compare the pre-intervention measurements with the follow-up measurements and the post-intervention measurements with the follow-up measurements for both TPD and MFT. To address the issue of multiple comparisons and maintain an appropriate level of statistical significance, a Bonferroni correction was applied. The significance level for the secondary outcome analysis was adjusted to 0.0025 (0.05/2) to account for the two comparisons conducted. Similar to the primary outcome analysis, a two-tailed test was used, resulting in a significance threshold of 0.0125 for each tail of the test. By implementing these data processing and statistical approaches, the study aimed to provide robust and reliable insights into the effects of the ST intervention on the TPD and MFT measurements.

D. Study Design for Motor Execution

1) Study Aim: To validate the ME functionality of the MiSMT device. This was done by validating the EMG acquisition and classification accuracy. The results are put in context by comparing it to a previously developed, and extensively used, EMG acquisition system from the same research group, the ADS-BP [29].

2) Study Protocol: The study is based on previous work of Mastinu *et al.* where the ADS1299 is compared to the RHA2216 [37]. This study is a post-hoc analysis of participants who participated in two previous studies [38, 32]. Only participants who partook in both studies were included in this analysis to allow for pair-wise comparisons. In one session,

the participant used the MiSMT device, while in the other session, they used the ADS-BP.

For both sessions, eight pairs of bipolar electrodes were placed on the participant's forearm, and one reference electrode on a bony area. The setup can be seen in Figure 5. Each session consisted of a recording session and a motion test, as described in the software section above.

The participants were asked to do the following movements: thumb flex and extend, index finger flex and extend, a combined middle/ring/little finger flex and extend, thumb and index finger flex and extend, and hand open and close. For each movement, the participants were asked to do one recording of the Maximal voluntary contraction (MVC), and 5 recordings of 5 seconds with moderate intensity (around 60% MVC).

The study had ethical approval from the Swedish regional ethical committee (Dnr: 2022-06513-01), and all subjects signed an informed consent document before starting.

3) *Outcome Measures*: The outcome measures for this post-hoc study included the Signal to Noise Ratio (SNR), and Offline and Online Accuracy. SNR provided an indication of the device's ability to acquire distinguishable EMG signals from the background noise. Offline Accuracy was evaluated using the Exact Match Ratio (EMR) and F1 score, which assessed the accuracy of predicting and classifying movements during offline analysis. The online accuracy shows the performance of the classification in real-time as new EMG data is being recorded. These outcome measures collectively provided comprehensive insights into the effectiveness and reliability of the device in capturing, analyzing, and predicting user movements using EMG data.

4) *Data Analysis*: All data processing was performed in MATLAB R2020b [30].

In order to assess the SNR, a statistical ratio of signal and noise powers was computed using the recorded data from the previous sessions. For each movement, the average activity across all channels was determined. The channel with the highest activity was then compared to the average activity during rest periods. The identified segments were concatenated into two separate arrays, representing the signal and noise data, respectively. Root mean square (RMS) values were calculated and utilized in Equation (1) to obtain the SNR. This procedure was performed for each movement, considering the channel with the strongest muscle activation. The entire process was repeated for all movements and all subjects.

$$SNR_{db} = 10 \cdot \log_{10} \frac{S_{RMS}^2}{N_{RMS}^2} = 20 \cdot \log_{10} \frac{\sqrt{\frac{1}{n} \sum_1^n S_i^2}}{\sqrt{\frac{1}{n} \sum_1^n N_i^2}}. \quad (1)$$

The offline accuracy was assessed using two metrics: the EMR and F1 score. The EMR considered only predictions that exactly matched the requested movement, while the F1 score accounted for partially correct movements as well (e.g., flexing only the thumb instead of closing the whole hand). For online accuracy, the software's Motion Test results were analyzed. The key outputs from the Motion Test included

TABLE II
TACTILE ACUITY DATA FROM DAY 1, DAY 5, AND THE FOLLOW-UP ASSESSMENTS

		Mean	IQR	MDN	P-value	P-value
		compared to Day 1				
		to Day 5				
Day 1	Control	30.875	12.5	30	-	-
	Stimulated	29.065	10	25	-	-
TPD Day 5	Control	29.375	10	30	0.27	-
	Stimulated	29.562	10	25	0.047	-
Follow-Up	Control	26.500	12.5	25	0.0021	0.097
	Stimulated	25.218	10	27.5	0.0022	0.23
Day 1	Control	0.0488	0.062	0.02	-	-
	Stimulated	0.0424	0.032	0.02	-	-
MFT Day 5	Control	0.0466	0.032	0.008	0.28	-
	Stimulated	0.0725	0.062	0.02	0.044	-
Follow-Up	Control	0.0314	0.032	0.02	0.39	0.40
	Stimulated	0.0386	0.032	0.02	0.99	0.20

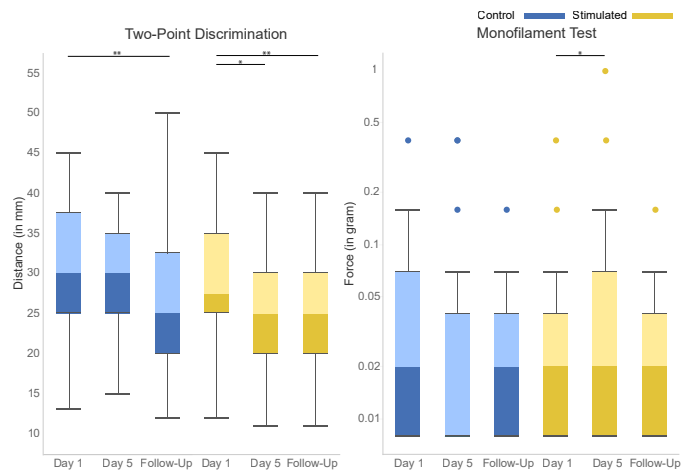


Fig. 6. Results from TPD (left) and MFT (right) on Day 1, Day 5, and Follow-Up assessments, comparing non-stimulated (control) sites to stimulated sites. * = ($p < 0.05$) ** = ($p < 0.025$)

the Completion Rate (expressed as a percentage), Completion Time (in seconds), and EMR and F1 scores. For all metrics, the average value across all movements was calculated. The results of the ADS-BP were compared with those of the MiSMT device.

III. RESULTS

A. Sensory Training

1) *Participants*: A total of 16 individuals with intact limbs were recruited for this study, consisting of five males and eleven females. The age range of the participants was between 21 and 61 years, with a mean age of 29.3 ± 11.3 years. The sample size of 16 participants was determined to be sufficient to potentially achieve significant results. Including an additional participant to account for possible drop-outs during the study, ensuring the feasibility of obtaining statistically significant findings. All 16 individuals completed the study including the follow-up visit.

2) *Data*: The results of the ST study can be found in Table II and Figure 6.

3) *Statistical Analysis*: To compare the pre- and postintervention data, an alpha level of 0.05 was applied. Consistent

with expectations, the training sessions had minimal impact on the tactile sensitivity of the control areas (i.e., untrained skin patches). Statistical analysis revealed non-significant differences between the pre- and postintervention measurements for both TPD ($p=0.26$) and MFT ($p=0.28$). These findings suggest that the training did not significantly affect the tactile sensitivity of the control areas. In contrast, a noteworthy improvement was observed in the stimulated skin patches for two-point discrimination following the intervention ($p=0.047$), indicating a significant enhancement in tactile discrimination ability. However, there was a statistically significant worsening in force discrimination between the pre- and postintervention assessments ($p=0.044$). It is interesting to note that there were several outliers in the MFT with remarkably high values in the post-intervention data.

To account for multiple comparisons, and avoid potential Type I errors, a Bonferroni correction was applied, and thus an alpha level of 0.025 was used for the comparison of pre-intervention data with the follow-up measurements. Surprisingly, during the follow-up assessment, significant improvements in two-point discrimination were not only sustained for the stimulated sites but also emerged for the control sites ($p=0.0021$ and $p=0.0022$, respectively). These results indicate that the training intervention not only led to significant improvements in tactile sensitivity in the trained areas but also resulted in a transfer or generalization of the training effects to the untrained areas. No significant differences were observed for force discrimination at either the control or stimulated sites ($p=0.38$ and $p=0.98$, respectively).

Overall, there was a notable improvement in the scores of the training tasks and games for all participants. Each participant demonstrated progress by advancing to more challenging levels, with the majority reaching medium and hard difficulty levels. Typically, participants successfully completed the easy level within one or two sessions for the two-alternative forced choice (2AFC) and Sensory Tasks, while it took approximately three or four sessions to accomplish the same for the discrimination and vibration game. By the fifth day, the majority of participants had reached the medium or hard levels for all the games. This study confirms the device's capability of delivering effective training for somatosensory perception.

B. Motor Execution

1) *Participants*: The data of 6 individuals with intact limbs were used for this analysis. The participants consisted of 4 males and 2 females. The age range of the participants was between 24 and 29 years.

2) *Data*: The ME study yielded valuable insights into the performance of the MiSMT device. The data is presented here and compared to the ADS-BP, and depicted in Figure 7. The average Signal-to-Noise Ratio (SNR) across all movements was $23.4 (\pm 6.8$ standard deviation) for the MiSMT device and $28.6 (\pm 4.8$ standard deviation) for the ADS-BP. This indicates the devices' ability to acquire and distinguish the desired EMG signals from the background noise.

In terms of offline accuracy, the MiSMT device demonstrated a high level of performance, similar to the ADS-BP. The

average Exact Match Ratio (EMR) for the MiSMT device was 0.93 ± 0.05 , indicating the proportion of correctly predicted movements that precisely matched the requested tasks. Additionally, the F1 score, which considers both exact and partially correct movements, achieved a value of 0.98 ± 0.02 . For the ADS-BP the EMR and F1 score values were 0.94 ± 0.05 and 0.98 ± 0.02 respectively.

The online accuracy results further reinforce the device's effectiveness in real-time motion prediction and classification. The Completion Rate, representing the percentage of correctly completed movements, reached an average of $89 \pm 10\%$. The Completion Time, measuring the average time taken to complete a movement, was 3.5 ± 0.4 seconds. The average EMR and F1 scores for the online accuracy of the MiSMT device during the motion test were 0.64 ± 0.09 and 0.78 ± 0.07 , respectively. For the ADS-BP these values were $74 \pm 13\%$ (Completion Rate), 3.8 ± 0.6 seconds (Completion Time), 0.50 ± 0.13 (EMR), and 0.65 ± 0.12 (F1).

Comparing the performance of the MiSMT device with the ADS-BP device, the results indicate similar outcomes. The values obtained for the average SNR, Offline Accuracy (EMR and F1), and Online Accuracy (Completion Rate, Completion Time, EMR, and F1) were comparable between the two devices. This suggests that the MiSMT device performs on par with the established ADS-BP device, validating its potential as an alternative solution for EMG acquisition and motion prediction.

Overall, the results of the EMG acquisition test demonstrate the promising performance of the MiSMT device, supporting its efficacy in acquiring accurate EMG signals and accurately predicting and classifying user movements.

IV. DISCUSSION

The objective of this manuscript was to introduce a novel device designed for sensorimotor rehabilitation, unifying Motor Execution (ME) and Sensory Training (ST) capabilities, and subsequently validate its effectiveness through studies conducted with participants with intact limbs. Our results from both ME and ST investigations confirm the MiSMT device's ability to fulfill its intended functions. The ST study revealed a notable and statistically significant enhancement in tactile sensory acuity, particularly in Two-Point Discrimination (TPD), following the intervention. Concurrently, the ME study showcased that the device's performance closely parallels that of the well-established ADS-BP, thereby affirming its potential as a reliable alternative for ME exercises.

One of the remarkable findings is that the results of the somatosensory discrimination assessments deviate from similar studies such as Buist *et al.* [15]. In the earlier study, the MFT improved significantly, while the TPD did not. A potential explanation as to why the MFT became worse after the intervention, while a similar but less rigorous intervention did show improvements, is that the participants might have felt numbness in the skin after the extensive training. In both studies, the assessment was done (at least) one hour after the intervention. In this study, the prolonged duration of the intervention with repetitive vibrational sensations may have

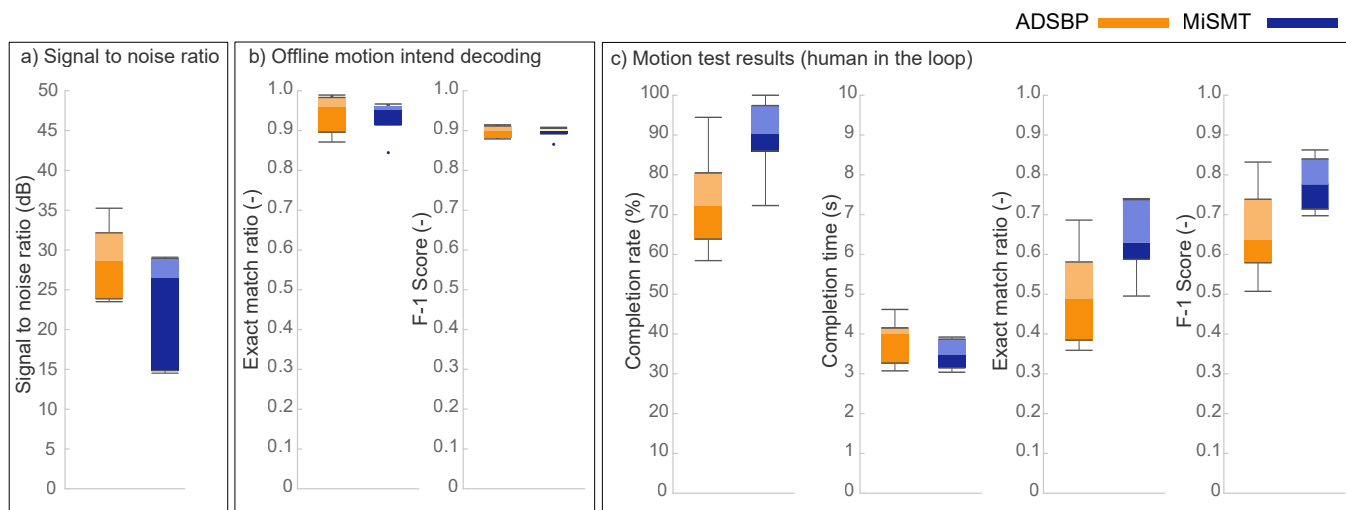


Fig. 7. Results from the ME study; comparing an open-source EMG acquisition System (ADS-BP) to the device presented in this manuscript (MiSMT), (a) SNR (in dB), (b) Offline Accuracy as EMR and F-1 scores, and (c) Online Accuracy as completion rate (in percentage), completion time (in s), EMR, and F-1 scores

temporarily increased the numbness of the skin [39]. Fatigue and a reduction in focus is another potential factor, as the MFT requires full concentration from the participant. An alternative explanation for the observed worsening in force discrimination may be related to participants' initial proficiency in this skill. Notably, the median evaluator size was positioned near the second-to-last filament, indicating that participants possessed a relatively advanced level of force discrimination ability at the beginning of the study. In this study, 64% of the baseline measurements were at 0.02 grams or below, while this was only 39% in the earlier study. This high baseline proficiency could have introduced a 'ceiling effect,' where participants had little room for further improvement and, unexpectedly, showed a decline in performance instead. However, these explanations remain speculative, and further research is needed to provide a more definitive understanding of the factors contributing to the unexpected worsening in force discrimination observed in our study.

The improvement in the TPD in the control sites during the follow-up assessment is another remarkable finding. The observed improvement in the control sites after a retention period can be attributed to the phenomenon of transfer or generalization of the training effects, which can be explained by sensory learning and neural plasticity [40]. The repeated and focused stimulation during the training sessions might have led to neural changes and strengthened somatosensory processing capabilities. This enhanced somatosensory perception and discrimination ability extended beyond the trained areas, resulting in improved performance in the control sites. While this finding surely has to be further confirmed with rigorous clinical investigations, it highlights the dynamic nature of the brain and its capacity for adaptive changes, providing preliminary evidence of the potential for targeted ST interventions to induce broad improvements in sensory abilities. The retention of improvements in the control sites could suggest that the acquired skills during training influenced the participants' overall tactile perception, demonstrating the

potential for lasting effects and generalization of training benefits to untrained areas.

The ME study has shown that the MiSMT device has comparable functionality in EMG recording as the known ADS-BP. All tested parameters, SNR, Offline Accuracy and Online Accuracy had similar performances in both devices. These outcomes show that the MiSMT device is able to do EMG acquisition and signal processing and can thus be used as an alternative for ME exercises.

Limitations of the presented study include a short duration of the follow-up for the sensory discrimination study. The study has a relatively short follow-up period, of one to two weeks, this limits the understanding of long-term effects and sustainability of the observed improvements. A longer follow-up period could provide insights into the durability of the training effects over time. Another challenge in the sensory discrimination study is the potential bias associated with the assessment methods, as these assessments are subjective and can vary between different assessors. Additionally, a smaller distance than 5 mm could have been used to enhance the resolution of our TPD findings. However, this was a practical limitation in our study, as the associated increase in testing time would have posed a non-negligible cost of time and compromised participants' attention to the task. For the ME study, a small sample size is a limitation. The results seemed comparable to the ADS-BP, however, a more extensive study with a larger sample size would be needed to do statistical analysis to confirm these findings.

The presented device has the potential to be used in clinical interventions for sensorimotor impairments. The device has the ability to train motor and sensory abilities in a structured and automated manner. Further development of the software is needed to fully explore the potential of integrating ME and ST modalities for enhanced therapeutic outcomes. Subsequently, further research is needed to demonstrate the transferability of these findings to individuals with sensorimotor impairments and to investigate the potential impact on their functional

recovery and/or pain reduction. This would involve studying the effectiveness of the MiSMT intervention in a clinical population, such as individuals with phantom limb pain or those with motor and/or sensory deficits following stroke or peripheral nerve injury. By examining the generalizability of the results in such populations, we can gain insights into the broader implications and potential therapeutic applications of this approach for improving function and overall well-being in individuals with sensorimotor impairments.

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