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# Movement-contingent electrotactile feedback improves tactile sensitivity and sensory recovery after stroke: a randomized preregistered and controlled trial

**Maria Volodina**

mariavolodina@yandex.ru

Federal State Autonomous Educational Institution of Higher Education «N.I. Pirogov Russian National Research Medical University» Ministry of Health

**Alexey Tumyalis**

Federal Center of Brain Research and Neurotechnologies of FMBA of Russia

**Ekaterina Ivanova**

Federal Center of Brain Research and Neurotechnologies of FMBA of Russia

**Timur Ivanov**

Federal Center of Brain Research and Neurotechnologies of FMBA of Russia

**Andrei Kirichenko**

Federal Center of Brain Research and Neurotechnologies of FMBA of Russia

**Galina Ivanova**

Federal Center of Brain Research and Neurotechnologies of FMBA of Russia

**Alexei Ossadtchi**

Federal Center of Brain Research and Neurotechnologies of FMBA of Russia

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# Abstract

Background

Somatosensory deficits affect most persons with stroke yet remain underdiagnosed and undertreated. Closed-loop movement-contingent sensory feedback may provide a scalable way to drive user-dependent plasticity, improving hand sensation and the quality of life after stroke.

Methods

In this pilot randomized controlled trial, 20 adults in the recovery stage after ischemic or hemorrhagic stroke (≥1 month post-onset) with impaired upper-limb somatosensation were randomly allocated to an experimental group or control group. All participants continued standard physician-prescribed rehabilitation; only the experimental group completed 10 sessions of an Active Touch Paradigm over 2 weeks (60 trials/session, 15–30 minutes). During training, participants used the affected index finger to scan pairs of invisible virtual textures on a tablet screen; each crossing of a virtual line triggered a single electrotactile pulse to the dorsum of the same finger, creating movement-contingent electrotactile feedback. The primary outcome measure was tactile detection threshold at the trained index fingertip (Semmes–Weinstein monofilaments, evaluator size). The secondary outcome measures were tactile thresholds at the thumb and middle fingers of the affected hand, thresholds in a subset of ipsilateral digits, and upper-limb motor and functional measures. The outcomes were assessed pre- and post-intervention.

Results

A significant Time × Group interaction was found for the affected index-finger threshold ($F(1,18)=6.90$, $p=0.017$, partial $\eta^2=0.28$). The experimental group improved from 5.34±1.10 to 4.79±1.30 evaluator size, whereas the control group changed from 4.82±1.16 to 4.69±1.15. No significant interactions were observed for thumb or middle-finger thresholds, although a trend emerged for the thumb. Using North Coast sensory grades, 7/10 experimental participants versus 2/10 controls improved by at least one grade at the trained digit. Both groups improved over time on Fugl-Meyer and Action Research Arm Test scores.

Conclusions

A brief, tablet-based, movement-contingent electrotactile training protocol selectively improved tactile sensitivity at a single trained digit after stroke without additional benefit on broader motor outcomes. The Active Touch Paradigm appears feasible, clinically practical, and specifically effective for post-stroke tactile rehabilitation, warranting larger mechanistic trials and integration with task-oriented upper-limb training.

Trial registration

ClinicalTrials.gov. NCT06962397 (retrospectively registered on 30 April 2025)

# Introduction

Stroke is a major global health concern and remains one of the leading causes of death and long-term disability worldwide. Recent estimates indicate that the global number of incident strokes, prevalent cases, and stroke-related disability-adjusted life years has continued to rise over the past decades, underscoring the growing burden on patients and health systems [1, 2, 3]. International guidelines now emphasize that improving outcomes requires not only timely acute care, but also effective, evidence-based rehabilitation across the entire continuum of stroke care [4].

Although post-stroke motor impairments are widely recognized and systematically targeted in rehabilitation, somatosensory deficits remain comparatively underdiagnosed, undertreated, and under-researched. Somatosensory loss — including impairments in light touch, tactile discrimination, proprioception, and stereognosis — has been reported in approximately 50–80% of persons with stroke and often persists into the chronic phase [5, 6, 7]. These deficits are not merely secondary symptoms; they have profound functional consequences. Impaired tactile and proprioceptive feedback limits the ability to plan and execute precise movements, manipulate objects, and perform activities of daily living such as grasping, dressing, and utensil use [8, 6, 7, 9]. Inadequate sensory information can promote compensatory strategies, maladaptive movement patterns, and learned non-use of the affected limb, ultimately contributing to long-term disability and reduced quality of life [5, 6, 7].

Current approaches to post-stroke tactile rehabilitation can be broadly classified into passive sensory stimulation techniques and active sensory retraining methods [10]. Passive methods, such as transcutaneous electrical nerve stimulation (TENS) [11], repetitive sensory stimulation (RSS) [12], vibration, and thermal [13] interventions, deliver externally driven afferent input to enhance cortical excitability and plasticity. Although systematic reviews indicate moderate motor recovery benefits, evidence for durable, functionally meaningful tactile improvements remains inconsistent due to heterogeneous protocols in dosage, timing, and patient selection [10].

In contrast, active sensory retraining emphasizes patient engagement through perceptual learning in tasks like texture, shape, limb-position, and object discrimination [10, 14, 15]. Pioneering work by Carey et al. demonstrated tactile and proprioceptive gains even in chronic stroke, while the SENSe randomized controlled trial showed superior outcomes over nonspecific stimulation, with effects persisting up to 6 months and generalizing to untrained stimuli [16]. Recent pilots, such as SENSUPP [15], further support integrated sensory relearning with task-specific upper limb training. Motor-intensive programs (e.g., constraint-induced movement therapy, game-based rehabilitation) can also produce improvements in tactile sensation alongside motor recovery, consistent with bidirectional sensory–motor links [17].

Despite promising results, these active protocols face scalability challenges: they require substantial therapist time, specialized materials, and customization, while monotonous tasks may reduce

adherence. These limitations drive innovation toward engaging formats like augmented reality and robotic haptics to broaden clinical access.

In recent years, neuroengineering and digital technologies have been increasingly explored to overcome these limitations. Virtual reality (VR) and game-based rehabilitation systems have shown promise in enhancing upper limb motor recovery after stroke by providing immersive, task-oriented, and engaging environments. Meta-analyses suggest that VR- and gaming-based interventions can yield improvements in upper limb function and motor performance comparable to, or greater than, those achieved with conventional therapy [18]. Some VR systems incorporate haptic feedback to simulate textures, object interactions, or contact events, thereby targeting somatosensory as well as motor domains [19]. Despite encouraging results, the widespread clinical adoption of VR- and game-based systems for sensory rehabilitation is limited by their relatively high cost and infrastructure requirements, as well as side effects such as cybersickness, visual discomfort, and cognitive overload, which can be particularly problematic for older persons with stroke [20]. These limitations can lead to reduced tolerance and dropout, despite the potential benefits of the immersive training.

Parallel developments in neuromodulation and haptic interfaces have underscored the importance of coupling sensory feedback with voluntary movement in a closed loop. Theoretical and empirical work in sensorimotor neuroscience indicates that learning and plasticity are enhanced when the nervous system can actively predict and compare the sensory consequences of self-generated actions with incoming feedback [21, 22]. Experimental paradigms using intracortical microstimulation and advanced neuroprosthetic interfaces have demonstrated that artificial tactile and proprioceptive feedback, delivered in tight temporal contingency with movement, can restore elements of touch, improve dexterous control, and enhance embodiment of robotic limbs [21, 23].

Despite these advances, there is still a clear gap in practical, quantitatively controlled rehabilitation protocols that use sensory substitution—such as precisely timed electrotactile feedback—within an active, movement-contingent framework that can be implemented with widely available hardware (e.g. tablets and standard peripheral nerve stimulators) to train somatosensory function in persons with stroke.

Building on the “active touch” framework and prior work on movement-contingent artificial feedback [21, 23], we developed a novel rehabilitation paradigm — the Active Touch Paradigm — that integrates voluntary finger exploration on a touchscreen with precisely timed, contingent electrotactile stimulation. In this paradigm, participants actively scan pairs of virtual textures using the affected index finger. The textures are represented as invisible gratings with different spatial densities, and each crossing of a virtual line by the fingertip triggers an electrotactile pulse delivered to the dorsum of the same finger. By coupling self-generated movement with parametric, behaviorally relevant tactile feedback in real time, the paradigm directly targets disrupted sensorimotor loops while using comparatively simple, clinically accessible hardware. The described setup can also be implemented as a low-cost consumer device, as an add-on for common gadgets.

The primary objective of this pilot randomized controlled study was to evaluate the feasibility and efficacy of the Active Touch Paradigm for improving tactile sensitivity of the affected hand in persons with stroke, as assessed with standardized monofilament thresholds. We hypothesized that participants receiving active, closed-loop electrotactile training would exhibit greater improvements in tactile sensitivity than those receiving standard care without additional structured sensory training. The secondary aims were to explore the impact of the intervention on upper limb motor function and manual dexterity, and to examine potential cross-transfer effects to the untrained limb.

# Methods

Study Design and Participants

This pilot randomized controlled trial evaluated the efficacy of an Active Touch Paradigm for sensory rehabilitation in individuals in the recovery stage after stroke. This study was approved by the Local Ethics Committee at the Federal Center for Brain and Neurotechnologies (Protocol No. 03/07-10-24) and was registered at ClinicalTrials.gov (Identifier: NCT06962397). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. All participants provided written informed consent prior to enrollment.

Adults aged 18–80 years with a history of a single ischemic or hemorrhagic stroke confirmed by neuroimaging and a post-stroke interval of at least 1 month were screened for eligibility. Inclusion criteria were: (1) age 18–80 years; (2) imaging-confirmed ischemic or hemorrhagic stroke; (3) time since stroke onset > 1 month; (4) impaired somatosensation of the affected upper limb, defined by a Fugl-Meyer Sensory subscale score between 3 and 10; (5) preserved cognitive function with Montreal Cognitive Assessment (MoCA; (24) score ≥ 20 ; and (6) Barthel Index ≥ 3.

Exclusion criteria were: (1) severe upper limb paresis (Fugl-Meyer Motor score < 35); (2) clinically significant depression (Hospital Anxiety and Depression Scale – Depression subscale > 11); (3) other major neurological (e.g. Parkinson’s disease, multiple sclerosis) or psychiatric conditions; (4) contraindications to peripheral electrical stimulation (e.g. implanted cardiac pacemaker/defibrillator, uncontrolled epilepsy, skin lesions at the stimulation site); and (5) severe aphasia or cognitive deficits precluding task comprehension.

After screening, 20 eligible participants were enrolled and randomly allocated (1:1) using a computerized random number generator to either: (1) an experimental group (n = 10) receiving Active Touch training plus standard rehabilitation, or (2) a control group (n = 10) receiving standard rehabilitation alone. One additional participant was excluded prior to randomization due to inability to complete baseline assessments.

The experimental group consisted of 10 participants (6 women and 4 men) with a mean age of 66.7 ± 9.97 years. Four participants had a right-hemispheric stroke and six had left-hemispheric stroke. Seven participants had ischemic stroke etiology and three had hemorrhagic stroke.

The control group consisted of 10 participants (4 women and 6 men) with a mean age of 55.7 ± 10.1 years. Seven participants had a right-hemispheric stroke and three had left-hemispheric stroke. Eight participants had ischemic stroke etiology and two had hemorrhagic stroke.

Detailed demographic and clinical characteristics are summarized in Table S1.

Participants in both groups continued their usual physician-prescribed rehabilitation programs throughout the study (e.g. conventional physiotherapy and occupational therapy). Only the experimental group received the additional structured sensory training using the Active Touch Paradigm.

Active Touch Paradigm: Concept and Apparatus

The intervention was based on a closed-loop sensorimotor paradigm in which voluntary finger movement generates contingent tactile feedback via electrotactile stimulation. Participants used the index finger of the affected hand to actively explore the invisible virtual textures present on a touchscreen. The spatial properties of the textures (virtual gratings of different spatial densities) were exclusively conveyed through electrotactile pulses delivered whenever the finger crossed an invisible virtual line.

Hardware

As depicted in Fig. 1 the experimental setup consisted of three main components:

1. Display and input device: A Microsoft Surface Pro 6 tablet with a capacitive touch-sensitive screen (resolution: 2736 × 1824 pixels; refresh rate: 60 Hz) for stimulus presentation and response collection.

2. Electrical stimulator: A MotionStim 8 programmable peripheral nerve stimulator (Medel GmbH, Hamburg, Germany) connected to the tablet via USB. The stimulator delivered symmetric biphasic charge-balanced rectangular pulses with the following parameters:

- Pulse width: 100 µs per phase (200 µs total pulse duration)
- Amplitude: individually calibrated for each participant (range across participants: 2–15 mA), set to elicit a clear tactile sensation while remaining strictly below motor threshold
- Stimulation mode: single-pulse triggering (one pulse per virtual texture line crossing)
- Maximum stimulation frequency was determined by finger velocity and texture density

3. Electrodes: Two self-adhesive surface electrodes (diameter: 20 mm) placed on the dorsum of the index finger of the affected hand, with the cathode positioned on the distal phalanx and the anode on the proximal phalanx.

Software

A custom software application developed in MATLAB R2019b (MathWorks, Natick, MA, USA) controlled all aspects of the experiment. The software implemented the following functions:

1. Texture generation: Creation of binary matrices representing 10 virtual textures with different spatial densities, corresponding to horizontal gratings with systematically varying line spacing. Each virtual texture was defined as a binary 345×345 matrix forming horizontal gratings; “lines” were two pixels thick (two adjacent rows of ones), and the line-to-line spatial period was set by the step size. Six textures were used with periods of 10, 13, 16, 19, 22, and 25 pixels, rendered within a fixed 10 × 10 cm area on the touchscreen (left and right fields of equal size). Given the 10 cm field width, this corresponds to a pixel pitch of 0.29 mm/px, line thickness of ~ 0.58 mm, and physical spatial periods of approximately 2.90, 3.77, 4.64, 5.51, 6.38, and 7.25 mm.

2. Stimulus presentation: Side-by-side display of the outlines of the two rectangular texture areas (left vs. right) on a black background, with the texture lines rendered invisible during active exploration. Two arrow-shaped response buttons were positioned below the exploration areas, see Fig. 1.
3. Real-time position tracking: Continuous monitoring of the participant's finger position on the touchscreen at a sampling rate ≥ 200 Hz (position update interval ≤ 5 ms).
4. Closed-loop stimulation control: Automatic triggering of a single electrotactile pulse via USB command to the MotionStim 8 each time the tracked finger position crossed an active pixel (value = 1) in the virtual texture matrix, creating movement-contingent electrotactile sensory feedback.
5. Feedback delivery: Presentation of visual feedback icons (star for correct, cross for incorrect responses) following each trial, preceded by an auditory cue (900 Hz tone, 50 ms duration) at trial onset.

Baseline Determination of Sensory Threshold

Before each training session, the individual sensory threshold for electrotactile stimulation was determined. The MotionStim 8 was set to deliver single biphasic pulses (pulse width 100 µs per phase) on channel 1, and a sequence of 10 pulses was administered with 0.3 s inter-pulse interval (~ 3.3 Hz). The current amplitude was gradually increased from the minimum setting in small steps until the participant reliably detected all 10 pulses. In all participants, the selected training intensity remained submotor and non-painful.

Experimental Task and Training Protocol

Each trial consisted of an active exploration phase followed by a forced-choice decision. During each trial, two rectangular exploration areas were presented side-by-side on a black background in the upper half of the touchscreen. Each area contained a virtual texture represented by a horizontal grating, with the two textures differing in spatial density (line frequency). During the actual task, the grating lines were invisible to the participant; only the black exploration areas and response arrows were displayed.

Participants were instructed to explore both rectangles using the index finger of the affected hand and to decide which side contained the denser texture (higher spatial frequency). As the finger moved up and

down across the exploration area, each crossing of an invisible virtual line generated an electrotactile pulse delivered to the dorsum of the same finger. Participants could move freely and repeatedly between the two areas without time constraints. When ready to respond, they indicated their choice by pressing one of two on-screen arrows located below the corresponding exploration areas. After each response, visual feedback was presented in the lower part of the screen: a star icon for correct responses and a cross icon for incorrect responses. This feedback was intended to support perceptual learning and maintain engagement.

The experimental group completed ten training sessions on consecutive weekdays over two weeks, with a maximum inter-session gap of three days (weekend break). Each session comprised 60 trials, organized into six blocks of 10 trials. Between blocks, participants were given 2-minute breaks. Total session duration was approximately 15–30 minutes, depending on individual exploration speed and rest duration. Participants in the control group continued their standard rehabilitation program during the same 2-week period but did not receive any additional structured sensory training.

Outcome Measures

All outcome measures were administered at baseline (pre-intervention) and immediately after the intervention period (post-intervention) by the same trained assessor. The post-intervention assessment was performed within a few hours after the final training session in the experimental group, and after the same elapsed number of days in the control group.

Primary outcome.

Tactile Sensitivity Threshold.

Tactile sensitivity was assessed using the Touch-Test Sensory Evaluators (North Coast Medical, USA). Testing was performed in accordance with the methodology described previously [25]. Thresholds were measured at the pads of the index finger (primary site), thumb, and middle finger of the affected hand. The primary outcome was the detection threshold at the trained site only (index finger). The detection threshold was recorded as the evaluator size (North Coast scale); when reported in logarithmic units, log10(mg) values were derived from the evaluator size for comparison across studies.

Secondary outcomes.

*Tactile detection thresholds at the non-trained digits* of the affected hand (thumb and middle finger). In a subset of participants, tactile thresholds were also measured on the hand ipsilateral to the lesion (non-trained hand) to explore potential cross-transfer effects. Due to technical issues, ipsilateral hand data were available only for six participants in the experimental group and nine in the control group.

*Sensorimotor function.* Upper extremity motor and sensorimotor function were assessed with the Fugl-Meyer Assessment for the Upper Extremity (FMA-UE; [26].

*Upper limb functional capacity.* The Action Research Arm Test (ARAT; [27] was used to evaluate grasp, grip, pinch, and gross motor movements.

*Fine motor dexterity.* The Nine-Hole Peg Test (9HPT; [28] assessed manual dexterity and was scored as the time (seconds) required to place and remove all pegs. For the 9HPT, five participants (three in the experimental group and two in the control group) who were unable to complete the test at one or both time points were excluded from the analysis of this outcome.

*Spasticity.* The Modified Ashworth Scale (MAS; [29] was used to rate spasticity of the wrist and finger flexors.

## Sample Size and Power

Sample size and power. An a priori power analysis was performed using G*Power 3.1 for a two-way mixed ANOVA (Group × Time interaction; 2 groups, 2 measurement points). We assumed a medium effect size for the interaction ($f = 0.25$), a two-tailed $\alpha = 0.05$, desired power $(1 - \beta) = 0.80$, a correlation between repeated measurements of $r = 0.80$, and a nonsphericity correction $\varepsilon = 1.0$. Under these assumptions, the required total sample size was 16 participants (8 per group). Anticipating possible drop-outs and aiming for more precise effect-size estimates, we planned to enroll 20 participants (10 per group), which exceeds the a priori requirement and provides adequate power to detect a medium Group × Time effect on the primary outcome. The assumed pre–post correlation of $r = 0.80$ was conservative relative to the empirically observed correlation for the index-finger tactile threshold in our sample ($r = 0.94$), reflecting the expectation that individual rank-ordering of tactile sensitivity would remain largely stable over the 2-week intervention period, with treatment effects superimposed on the top of the high between-subject consistency.

## Statistical Analysis

Statistical analyses were performed using Statistica 64 (TIBCO Software Inc., USA) and verified in Python. Normality was assessed using the Shapiro–Wilk test. For each outcome, a two-way mixed-design ANOVA was conducted with Time (Pre, Post) as a within-subject factor and Group (Experimental, Control) as a between-subject factor. A significant Group × Time interaction was interpreted as evidence of a treatment-specific effect. When an interaction was observed, post-hoc pairwise comparisons were performed (Tukey's test). Effect sizes were reported as partial eta-squared ($\eta^2 p$).

Because several variables deviated from normality, non-parametric sensitivity analyses were also performed: Wilcoxon signed-rank tests for within-group pre–post changes and Mann–Whitney U tests for between-group differences in change scores. For the three tactile sites (thumb, index, middle), Wilcoxon p-values were adjusted using Holm correction for multiple comparisons. All tests were two-tailed with $p < 0.05$. Data are presented as mean ± SD unless stated otherwise.

# Results

Twenty participants completed the study (n = 10 per group). Baseline comparisons between groups showed no significant differences across primary and secondary measures (all Mann-Whitney $p > 0.16$), including sensory function, FMA-UE, ARAT, 9HPT, paresis, MAS, and baseline tactile thresholds (affected and ipsilateral hands).

Sensory Function recovery

The primary outcome was the index-finger detection threshold on the affected hand, expressed as evaluator size (North Coast scale). Mixed RM-ANOVA revealed a significant Group × Time interaction for the index finger, $F(1,18) = 6.903$, $p = 0.0171$, $\eta^2p = 0.277$, with a significant main effect of Time ($F(1,18) = 18.991$, $p = 0.0004$, $\eta^2p = 0.513$) and no main effect of Group ($p = 0.5545$). The experimental group improved from 5.342 ± 1.103 to 4.793 ± 1.302 evaluator size, whereas the control group changed from 4.821 ± 1.163 to 4.685 ± 1.146. The between-group difference in change scores was confirmed by a non-parametric test (Mann-Whitney $p = 0.0131$; $\Delta exp = -0.55$ vs $\Delta ctrl = -0.14$ evaluator size) (Fig. 2, A).

The secondary sensory outcomes showed no significant Group × Time interaction for the thumb (trend: $F(1,18) = 3.882$, $p = 0.0644$, $\eta^2p = 0.177$) or middle finger (interaction $p = 0.427$) (Fig. 2B, C).

Ipsilateral (non-trained) hand thresholds were available only for a subset (six experimental, nine control) and were analyzed descriptively. The largest apparent change was observed for the index finger in the experimental group ($\Delta = -0.493$ evaluator size), compared with a smaller change in controls ($\Delta = -0.148$) (Fig. 2D). Changes for the thumb and the middle finger were small and inconsistent across groups.

The Fugl-Meyer sensory subscale score for the affected hand showed a significant main effect of Time ($F(1,18) = 7.642$, $p = 0.0128$, $\eta^2p = 0.298$), without a Group × Time interaction ($p = 0.369$).

Motor Function Recovery

Participants in both groups underwent a rehabilitation program prescribed by a physician and demonstrated improvements in motor function, as evidenced by the results of assessments using the Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT), and Nine-Hole Peg Test (9HPT). However, factorial repeated-measures ANOVA did not reveal a significant interaction between the factors "group" and "time point."

FMA-UE showed a significant main effect of Time ($F(1,18) = 22.806$, $p = 0.0002$, $\eta^2p = 0.559$) with no interaction ($p = 0.669$). ARAT showed a significant main effect of Time ($F(1,18) = 24.885$, $p = 0.0001$, $\eta^2p = 0.580$) with no interaction ($p = 0.624$) (Fig. 3).

For 9HPT, five participants (three experimental, two control) were excluded due to inability to complete the test; the remaining data showed no interaction ($p = 0.8995$) and no significant main effect of Time ($p = 0.0803$).

No significant changes were observed in scores related to paresis or spasticity scales for either group.

## Discussion

# Summary and connection to the existing studies

This pilot randomized controlled trial demonstrates that a brief, movement-contingent electrotactile training paradigm can selectively improve tactile sensitivity of the trained index finger in individuals with stroke. The primary outcome, the Semmes–Weinstein monofilament threshold at the affected index finger, showed a significant Group × Time interaction with a medium-to-large effect size, whereas no interaction was observed for the thumb or middle finger or for global sensory and motor scales (Fig. 2). This pattern supports the idea that the Active Touch Paradigm induces a site-specific sensory benefit at the trained digit rather than a non-specific improvement in overall upper limb function.

At the group level, the experimental intervention produced a mean improvement of 0.55 evaluator steps at the trained index finger, compared with 0.14 steps in the control group receiving standard rehabilitation alone (Table S2). Nine of ten participants in the experimental group showed some degree of threshold improvement at the index finger, whereas change in the control group was more balanced between improvement and worsening. Although the between-group difference in the proportion of responders did not reach statistical significance in this small sample, the direction and consistency of change are clinically relevant and align with the continuous outcome analysis.

While interpreting the clinical significance of Semmes-Weinstein threshold changes is challenging due to the lack of established minimal clinically important difference MCID for site-specific post-stroke measures and the use of composite sensory scores in trials like SENSe [16] and SENSUPP [30], a meaningful clinical interpretation remains possible. This is facilitated by the established categorical framework of the North Coast Touch-Test classification, which groups filaments into five grades based on force [25]. In this system, the filaments are grouped into five grades based on force: 1.65–2.83 (grade 5, normal sensibility), 3.22–3.61 (grade 4, diminished light touch), 3.84–4.31 (grade 3, diminished protective sensation), 4.56–6.45 (grade 2, loss of protective sensation), and 6.65 (grade 1, deep pressure sensation only). Within this system, an improvement of one full grade represents a categorical transition towards a less impaired sensory state, rather than a fluctuation within a single category. Applying this framework to our data shows that 7 of 10 participants in the experimental group improved by at least one grade at the trained index finger over two weeks, compared to only 2 participants in the control group.

Thus, although the direct comparison to a numerical MCID is not feasible, the magnitude and distribution of the categorical improvements suggest that for a majority of individuals in the experimental group, the intervention induced a change that is clinically meaningful in terms of shifting sensory status.

Our findings complement and extend previous work on post-stroke sensory rehabilitation. Passive protocols such as sensory TENS or tactile stimulation have been reported to enhance sensorimotor

recovery when added to conventional therapy, although effects on cutaneous thresholds are variable [10, 31]. For instance, randomized trials of repetitive sensory stimulation (e.g., RESET) show sensorimotor improvements over sham in subacute stroke [12]. Notably, the effect size reported after 10 sessions of 45-min stimulation is comparable to the effect size observed in our study.

Active sensory retraining paradigms, including those developed by Carey and colleagues and the SENSe [16] and SENSUPP [30] programs, have demonstrated that structured discrimination training can improve touch and proprioception even in the chronic phase, but typically require multiple therapist-guided sessions over several weeks. In contrast, the Active Touch Paradigm used here involved ten sessions of approximately 15–30 minutes over two weeks — substantially shorter in both total dose and calendar duration than most published protocols. This schedule fits within a typical inpatient rehabilitation stay, where the average length of stay in intensive rehabilitation facilities is around 2 weeks, and thus enhances the pragmatic feasibility of implementation.

Despite the lower training dose, the magnitude of improvement at the trained digit in our experimental group appears comparable to, and in some cases larger than, the sensory gains reported in previous upper-limb interventions when expressed in monofilament units or equivalent measures, although direct quantitative comparisons are hampered by heterogeneous outcome metrics. The absence of a Group × Time interaction for FMA-UE, ARAT, 9HPT, and the Fugl–Meyer sensory subscale is consistent with the targeted nature of the intervention. The training focused on a single digit and a single modality—tactile detection—and was not designed to drive broad changes in multi-joint motor coordination or functional task performance. The parallel improvement in motor outcomes in both groups likely reflects ongoing standard rehabilitation, whereas the added electrotactile training selectively enhanced the trained sensory measure.

## Possible mechanisms: electrotactile feedback, tactile exploration, and attention

The Active Touch Paradigm combines three components that may each contribute to the observed sensory gains: (1) peripheral electrotactile stimulation, (2) coordinated with tactile perceptions active exploration of virtual textures, and (3) sustained, task-directed attention to finger sensations within a closed-loop sensorimotor context.

First, peripheral sensory electrical stimulation (SES) alone has been shown to modulate cortical excitability and improve sensorimotor performance after stroke when delivered repetitively to the paretic hand. Several randomized trials of repetitive peripheral sensory stimulation or low-frequency electrical stimulation have reported improvements in motor scores and, in some cases, in sensory function, even when stimulation is applied passively without an explicit discrimination task [12, 32–35]. In our

paradigm, however, stimulation was not delivered as an isolated passive input but was tightly coupled to active texture exploration and decision-making. This movement-contingent, behaviorally relevant pairing may provide stronger Hebbian-like sensorimotor reinforcement than passive stimulation alone and is likely to be more engaging for participants, which may support adherence in repeated training. Although stimulation was applied to the dorsum of the index finger rather than the fingertip where thresholds were tested, several participants reported referred sensations extending toward the pulp. This suggests that patterned stimulation may broaden or reweight sensory representations, even with partial spatial mismatch, particularly when paired with behaviorally relevant tasks [36].

Second, the training required continuous active exploration of textured surfaces on the touchscreen. Perceptual learning frameworks emphasize that active exploration and repeated discrimination tasks sharpen sensory representations, while exploratory movements themselves provide rich tactile stimulation to the trained skin region. In SENSe and SENSUPP, structured, attention-guided sensory retraining improves tactile and proprioceptive function, with some generalization beyond trained stimuli [15, 16, 37, 38]. The Active Touch Paradigm likewise required continuous, goal-directed scanning of virtual textures, so repeated up-and-down movements over the surface likely delivered robust mechanical stimulation to the pulp. This may have reinforced tactile discrimination learning by combining natural tactile input with timely artificial stimulation delivered to the finger dorsum, thereby contributing to the observed improvement in monofilament thresholds.

Third, the paradigm explicitly directed attention to somatosensory input from the affected digit. Closed-loop paradigms link self-generated actions with predictable sensory consequences, a key driver of sensorimotor learning and plasticity [39–41]. In our task, each line crossing triggered an electrotactile pulse with precise temporal contingency, aligning efference copy, sensory prediction, and afferent feedback. The task also required sustained attention to fingertip sensations and included trial-by-trial feedback, which can further enhance perceptual sensitivity and cortical reorganization in somatosensory networks [10, 14, 38]. Beyond local plasticity, short-term tactile training has been shown to improve sustained attention on the Sustained Attention to Response Task, reducing omission errors and mind-wandering [42]. Thus, an improvement in attentional control may be one additional mechanism through which our training enhances the detection and discrimination of near-threshold tactile stimuli. Similar attentional mechanisms have been proposed to underlie the effects of interoceptive training, where repeated, focused attention to bodily sensations strengthens functional connectivity between the anterior insula and cognitive control networks and improves interoceptive accuracy [43, 44]. By analogy, directing attention towards electrotactile and cutaneous input from the affected digit may simultaneously sharpen somatosensory representations and augment domain-general attentional resources that support more reliable detection of tactile stimuli during threshold testing.

Future work should attempt to dissociate the contributions of these components — for example, by comparing the full Active Touch Paradigm with (1) passive electrotactile stimulation without exploration, (2) exploration without stimulation, and (3) attention-matched tasks without tactile engagement—while using larger samples and neurophysiological measures to probe cortical reorganization.

# Limitations and future directions

Several limitations warrant consideration. First, the sample size in this clinical study was modest (n = 10 per group), consistent with the pilot nature of the trial, and effect-size estimates may therefore be imprecise. Second, we assessed the outcomes only immediately after the two-week intervention; follow-up measurements are required to determine the durability of the sensory gains and their impact on everyday hand use. Finally, training was restricted to a single digit on the more-affected hand; explorations of multi-digit and bilateral protocols may reveal whether closed-loop electrotactile feedback can produce broader somatosensory improvements.

## Clinical implications

Despite these limitations, the present pilot trial provides proof-of-concept that a short, movement-contingent electrotactile training protocol implemented with widely available hardware (a tablet computer and a standard peripheral nerve stimulator) can selectively improve tactile sensitivity at a targeted digit in chronic stroke. The intervention is brief, does not require invasive procedures or sophisticated VR equipment, and can be delivered within the time constraints of routine inpatient or outpatient rehabilitation. Importantly, the same closed-loop principle could be translated into a gamified mobile format for home-based self-training, potentially reducing dependence on clinic time and improving long-term adherence through frequent, low-burden practice. Beyond stroke, the combination of active touch, electrotactile feedback, and attentional focus may be relevant for other populations with tactile deficits or for enhancing somatosensory acuity in healthy individuals, including children and older adults to achieve tactile supersensitivity which may be beneficial in a range of professions.

## Conclusions

This pilot randomized controlled trial provides proof-of-concept that a brief, movement-contingent electrotactile training paradigm can selectively improve tactile sensitivity at a trained digit in people in the recovery stage after stroke. Active Touch training produced a medium-to-large Group × Time effect on the Semmes–Weinstein threshold at the affected index fingertip, whereas tactile thresholds at non-trained digits and global sensory and motor scales improved similarly in both groups. This pattern supports a site-specific sensory benefit rather than a non-specific enhancement of overall upper limb function.

The intervention was feasible, well tolerated, and implemented with widely available hardware (tablet computer plus peripheral nerve stimulator), suggesting good pragmatic potential for integration into routine rehabilitation. Future studies should also examine whether multi-digit or bilateral versions of the paradigm can produce broader somatosensory gains and whether combining Active Touch with motor training amplifies functional recovery.

# Abbreviations

9HPT
Nine-Hole Peg Test
ARAT
Action Research Arm Test
FES
Functional electrical stimulation
FMA-UE
Fugl-Meyer Assessment of the Upper Extremity
MAS
Modified Ashworth Scale
RCT
Randomized controlled trial
SES
Sensory electrical stimulation
TENS
Transcutaneous electrical nerve stimulation
VR
Virtual reality

# Declarations

Ethics approval and consent to participate

This study was approved by the Local Ethics Committee at the Federal Center for Brain and Neurotechnologies (Protocol No. 03/07-10-24) and was registered at ClinicalTrials.gov (Identifier: NCT06962397). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. All participants provided written informed consent prior to enrollment.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

MV conceived the study, coordinated data collection, and drafted the manuscript.

AT contributed to study design and statistical analysis.

EI, TI and AK conducted participant assessments and intervention procedures.

GI contributed to clinical supervision and interpretation of rehabilitation outcomes.

AO supervised the project, contributed to methodology and interpretation, and critically revised the manuscript.

All authors read and approved the final manuscript.

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# Figures



**Figure 1**

Microsoft Surface Pro 6 PC hosts the software and displays two exploration areas to the subject. The subject actively explores the virtual texture by moving the index finger up and down and receiving electrical stimulation each time the finger crosses a virtual line.

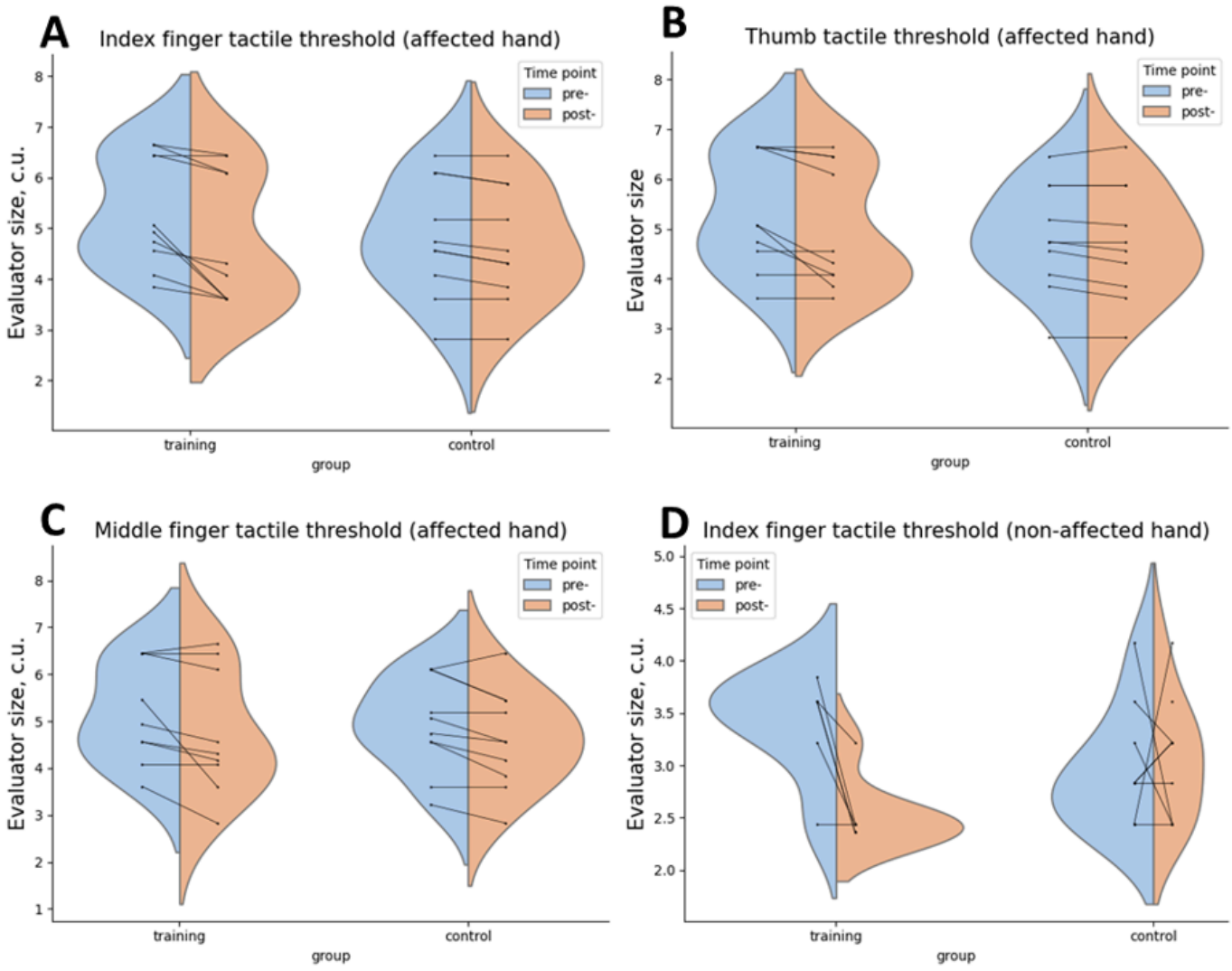



**Figure 2**

Change in tactile sensitivity of the index finger on the affected hand, the primary outcome (A), and the secondary outcomes: thumb of the affected hand (B), middle finger of the affected hand (C) and index finger of the non-affected hand (D). Violin plots illustrate the distribution of baseline (blue) and follow-up (orange) values. Individual data points are depicted as dots, with lines connecting pre- and post-intervention measurements for each participant.

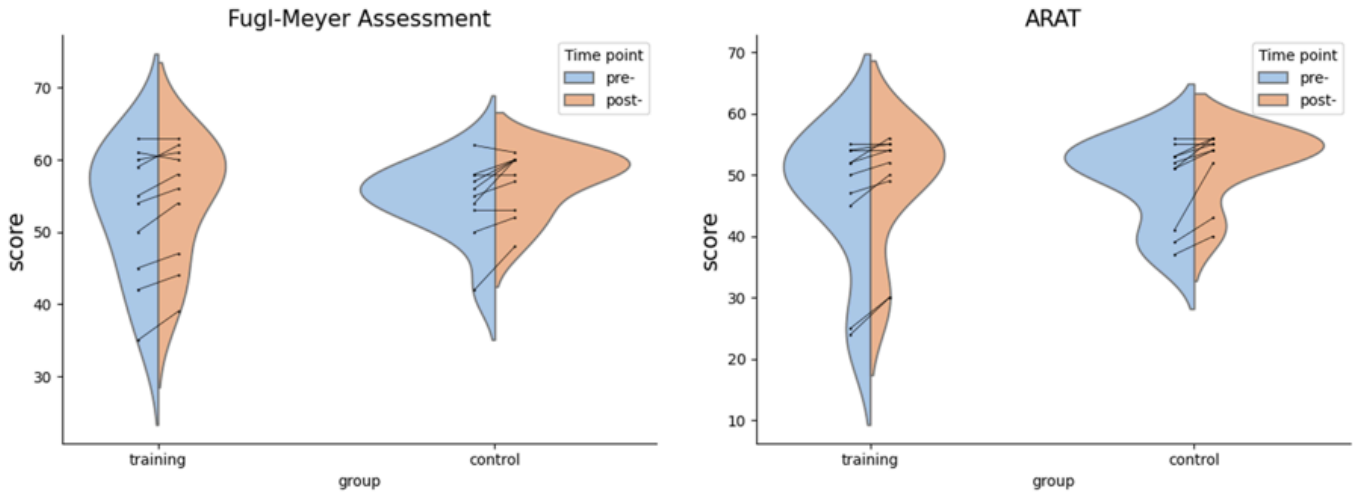



**Figure 3**

Change in Fugl-Meyer (left) and ARAT scores (right). Violin plots illustrate the distribution of baseline (blue) and follow-up (orange) values. Individual data points are depicted as dots, with lines connecting pre- and post-intervention measurements for each participant.

## Supplementary Files

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- TableS1.xlsx
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- TableS3.xlsx