An Instrumented Glove for Restoring Sensorimotor Function of the Hand Through Augmented Sensory Feedback

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***Abstract*— The loss of sensitivity of the upper limb due to neurological injuries severely limits the ability to manipulate objects, hindering personal independence. Non-invasive augmented sensory feedback techniques are used to promote neural plasticity hence to restore the grasping function. This work presents a wearable device for restoring sensorimotor hand functions based on Discrete Event-driven Sensory Control policy. It consists of an instrumented glove that, relying on piezoelectric sensors, delivers short-lasting vibrotactile stimuli synchronously with the relevant mechanical events (i.e., contact and release) of the manipulation. We first performed a feasibility study on healthy participants (20) that showed overall good performances of the device, with touch-event detection accuracy of 96.2% and a response delay of 22 ms. Later, we pilot tested it on two participants with limited sensorimotor functions. When using the device, they improved their hand motor coordination while performing tests for hand motor coordination assessment (i.e., pick and place test, pick and lift test). In particular, they exhibited more coordinated temporal correlations between grip force and load force profiles and enhanced performances when transferring objects, quantitatively proving the effectiveness of the device.**

***Index Terms*— Hand rehabilitation, sensory substitution, wearable technology, haptic interface.**

I. Introduction

PARTIAL or complete loss of sensitivity in the upper limb may cause severe impairments in the ability to perform activities of daily living (ADLs), manipulate objects, and interact with the environment. In fact, sensory information is integrated in the sensorimotor control to ultimately reduce motor errors. This is made possible by the internal models in the cerebellum which are used by the central nervous system (CNS) to predict movements (through the so-called inverse model) and their sensory consequences (forward model) originating from an efferent copy of the motor command [1], [2], [3]. Discrepancies between predicted and actual sensory information, so-called sensory prediction errors, are used to implement corrective actions on the motor command in order to reduce the error on the motor performance rendering it “closed-loop” [4], [5].

In particular, tactile sensory information plays a central role in object manipulation tasks [6]. According to the Discrete Event-driven Sensory Control (DESC) model, the sensory information associated to discrete mechanical events, such as contact, lift-off, replace and release, is used to define sensorimotor control checkpoints and to time the release of motor commands according to the task action phases [7]. The CNS uses these checkpoints for the coordination of movement subgoals during manipulation tasks [4], [8], [9]. Building on this one could state that the focus of the CNS during manipulation tasks is on the changes in the interaction with the environment rather than on continuous sensory information. Fast adaptive fibers on the fingertips are responsible for this behavior. In particular, Meissner endings (FA-I) are sensitive to transient mechanical events of the manipulation, such as contact or break of contact with objects or slipping events [9]. When the intrinsic tactile feedback is lost, due to peripheral or central injury, e.g., stroke, such information is no longer signaled to the brain, leading to a more clumsy and uncoordinated motor control [10], [11].

Stroke is one of the leading causes of disability worldwide [12] and has a profound detrimental impact on the hand dexterity and ability to perform daily activities of those affected [13], [14]. This neurological disorder consists of an interruption of the blood supply to certain brain areas, which can cause tissue necrosis and ultimately lead to motor and sensory impairments [10], [11], [15].

Current post-stroke rehabilitation practices primarily focus on motor training, although impairments in the fine motor manipulation have been associated also to sensory impairments

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Local Ethical Committee of the Scuola Superiore Sant’Anna, Pisa, Italy, under Approval No. 10/2023.

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[16], [17]. For this reason, the restoration of sensory information during rehabilitation practices may promote neural plasticity and motor re-learning, allowing for both short- and long-term benefits [16], [18], [19], [20]. Indeed rehabilitation therapies, which include augmented feedback associated to the interaction with the environment during motor tasks, have shown to compensate for and aid in regaining lost motor functions, especially for the upper limb [16].

With this goal in mind, many researchers investigated the effectiveness of various non-invasive augmented sensory feedback techniques in reinstating lost tactile sensitivity, albeit the results present discrepancies [20]. One of the reasons influencing the effectiveness of augmented feedback might be the chosen paradigm strategy. Specifically, a strategy that is overly complex could hinder the integration of the stimulus into motor control. We believe that delivering augmented feedback following the DESC policy, in particular, delivering short-lasting vibrotactile stimuli synchronously with discrete mechanical events, could facilitate its integration in the motor control loop. In fact, mimicking the way the CNS naturally organizes motor tasks, i.e., delivering sensory information that can be easily integrated to define phases related to manipulation subgoals, improved manipulation performances of healthy participants controlling a supernumerary hand, as well as a participant affected by partial hand amputation [21], [22], [23]. Moreover, transradial amputees benefitted from (and favored) the integration of DESC-like augmented vibrotactile feedback for myoelectric prosthesis control [24].

To leverage the benefits of augmented sensory feedback for rehabilitation, several wearable devices were developed (see the work of Demolder and colleagues for an extensive review [25]). Based on their function, they can be classified in Sensing Devices (SD) and Sensory Feedback Devices (SFD). Among the former, the commercially available Wearable Sensing Gloves feature various sensing technologies to measure the interactions between the hand and the environment [26], [27], [28]. Amongst the various sensors used in literature, the artificial skin, a thin substrate featuring a combination of strain, pressure and temperature sensors and other receptors, could represent a paradigm shift for wearable SDs [29], [30], [31], [32]. This flexible and stretchable electronic sensing substrate can be placed on any surface from which we want to collect a wide spectrum of environmental information. Once the information from the external environment is collected, wearable SFDs can be employed to convey cutaneous sensory cues to sensible districts of the body. SFDs are used to provide amputees or people affected by neurological conditions that led to sensory impairments (e.g., people affected by stroke, spinal cord injury, cerebral palsy, sclerosis, etc.) with artificial sensory feedback [33], [34], [35], [36]. To our knowledge, only few existing devices successfully combined these two aspects together encoding the information recorded by the SDs to deliver augmented sensation through SFDs, mainly for applications in Virtual Reality and teleoperation [37], [38], [39], [40]. Leveraging these promising yet preliminary outcomes, in this work we propose the combination of SDs and SFDs to deliver haptic feedback with the aim of restoring hand sensorimotor functions.

In particular, we developed a novel wearable device which consists of an instrumented glove that delivers discrete vibrotactile stimuli synchronously with contact and release events detected at the fingertips during manipulation tasks. The device is instrumented with piezoelectric sensors that mimic the behavior of fast-adaptive mechanoreceptors of the hand, capable to sense discrete mechanical events [9]. This information is then fed back to the user through short-lasting vibrations (i.e., DESC policy) in a sensitive area of the upper limb (or more generally, of the body) with eccentric-mass actuators. In this paper, after presenting the architecture and basic principles of operation of the device, we assessed its sensitivity and specificity in experiments with healthy participants. Then, we run a pilot test to assess the immediate effect of the device on the motor performance when worn by two volunteers with limited sensorimotor functions of the dominant upper limb.

The device proved capable to identify both contact and release events in tests performed on healthy individuals, with a detection accuracy of 96.2%. Through the pilot test with participants affected by sensorimotor deficits we noticed that both the volunteers improved their hand motor coordination when provided with discrete feedback while performing a task of reaching and lifting an object and a pick and place test, with respect to the performances extracted from the same tests when no feedback was provided. In particular, for the first test this improvement was proved by a temporal correlation between the grip force and load force more similar to the one observed in humans without disabilities. In fact, a lower time delay between the increase of the grip force to stabilize the grasp and the lifting of the object is typical of natural grasping [41]. Concerning the pick and place test, improvements corresponded to a higher number of correct transfers of the fragile object (+17%) or a reduced transfer time (−14%). This suggests that this feedback strategy, which already proved its efficacy in prosthetic users [23], [24], holds potential also in the fields of sensorimotor rehabilitation and assistance for facilitating seamless integration in the neuromotor control.

II. MATERIALS

A. Architecture

We developed a wearable device for sensorimotor hand assistance and rehabilitation. The device consists of an instrumented glove equipped with piezoelectric sensors that detect contact and release events during manipulation tasks. Synchronously with these events, two small actuators are activated by a controller board to deliver vibrational bursts on the skin of the user. After a short calibration procedure, during which the device is connected to a PC, the device can be used as a portable, stand-alone system. The architecture of the device includes three parts: (i) an instrumented glove, (ii) a control unit, and (iii) two vibrotactile actuators.

The **instrumented glove** is based on a commercial fabric glove (Forclaz Trek 500, Decathlon, Fr) equipped with two custom piezoelectric polyvinylidene fluoride-based (PVDF) sensors sewn at the thumb and index fingertips. These sensors are harvested from a commercial piezoelectric sheet (1-1004347-0, TE Connectivity Measurement Specialties, USA), composed by a thin layer of PVDF polymer coated

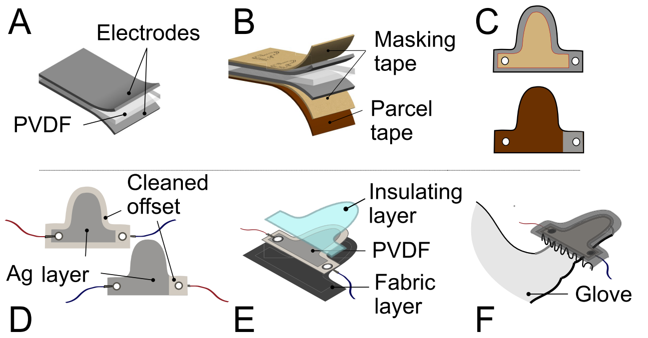


Fig. 1. PVDF sensors manufacturing process. A) PVDF sheet layered structure, B) Masking the sensor with the masking and parcel tape, C) Cutting the sensor in the final shape, D) Cleaning the offset to prevent short circuiting between the electrodes and electrical connections, E) Insulating the sensor to reduce noise due to skin conductivity, F) Sewing the sensor on the fingertips of the glove.

with two conductive silver laminae (Fig 1a). Their low profile (40 μm) and high sensitivity to mechanical deformation makes them an interesting option for the intended application. To manufacture the custom sensors we pursued the following procedure, optimized for increasing the reliability and robustness of the sensors. The piezoelectric sensors were cut out from the sheet and treated to prevent short circuiting between the two silver laminae (i.e., electrodes) (Fig 1b, c, d). They were wired through eyelet connectors, glued to a thin fabric substrate, covered with a layer of electric insulating tape on the exposed surface, and finally sewn externally on the thumb and index fingertips of the glove (Fig 1e, f).

The **control unit** is based on a custom printed circuit board (PCB) with a 16-bit microcontroller (PIC24F16KL401-I/MQ, Microchip Technology Inc.). Raw signals from the PVDF sensors are amplified and sampled with a 10-bit ADC, low-pass filtered (Butterworth, 2nd order, fc: 17 Hz) and processed by means of an event-detection algorithm to recognize contact and release events during object manipulation. The algorithm relies on the piezoelectric nature of the sensors, which upon contact and release events produce positive and negative electric spikes, respectively (Fig 2a). A contact (or release) event is detected if the signal amplitude is larger (or smaller) than an absolute detection threshold (ADT) for at least 60% of a 10 ms observation window or if its time-derivative signal is larger (or smaller) than a specific derivative detection threshold for the entire observation window. To avoid multiple detections, we set a refractory period of 100 ms after each event is detected, during which further events are ignored. Detection threshold values are user-dependent and are determined through an automated calibration procedure performed with a dedicated software application. The board can stream data via a serial communication protocol (RS-232) to a PC, where the application allows for real-time data visualization and storage. Finally, the controller board is powered by a 3.7V LiPo rechargeable battery and enclosed within a plastic case (66 × 63 ×27 mm), that can be secured on the user's forearm with an elastic band.

Finally, two eccentric-mass **vibrotactile actuators** (310-113, Precision Microdrives, UK) are used to deliver haptic cues to the user. They are wired to the controller board and are controlled to deliver short vibration bursts (50-150 ms, 200 Hz, 2.6 g peak-to-peak) synchronously with the detection of contact and release events (Fig 2a).

B. System Calibration

After donning, a calibration procedure - guided by a PC application - is necessary to tune the detection thresholds, so to optimize sensitivity and specificity of the device, i.e., maximize true positives and minimize false positives. During this phase the user is first prompted to perform three stereotypical free movements (FM) of the hand, while avoiding bringing into contact the fingertips with the palm. These movements are flexion/extension of the thumb (FM1), flexion/extension of all the joints of the fingers (FM2), flexion/extension of the metacarpophalangeal joints of the long fingers (FM3). The movements are intended to reproduce configurations that could erroneously trigger the sensors (e.g., maximal stretch of the glove fabric at the fingertips, pinching the sensors between the phalanges) and generate false detections. Then, the PC prompts the user to grasp and lift a small object (45 × 45 ×45 mm, 80 g plastic cube), using the thumb and index digits, three times (Fig 2b). ADTs on the sensor readings are thus determined averaging the maximum value of the signal recorded during FM and lifting movements. Specifically, the following empirical equations were used:

$$\mathrm{ADT_{High}} = \frac{FM_{max} + 0.8PLT_{max}}{2}, \tag{1}$$

$$\mathrm{ADT_{Low}} = \frac{FM_{min} + 0.8PLT_{min}}{2}, \tag{2}$$

where *FMmax* and *FMmin* are the maximum and minimum values of the signal recorded during the execution of the free movements, *PLTmax* and *PLTmin* are the maximum and minimum values of the signals recorded while lifting the cube. Similar equations are used to determine the derivative detection thresholds (DDTs):

$$\mathrm{DDT_{High}} = \frac{D\_FM_{max} + 0.8D\_PLT_{max}}{2}, \tag{3}$$

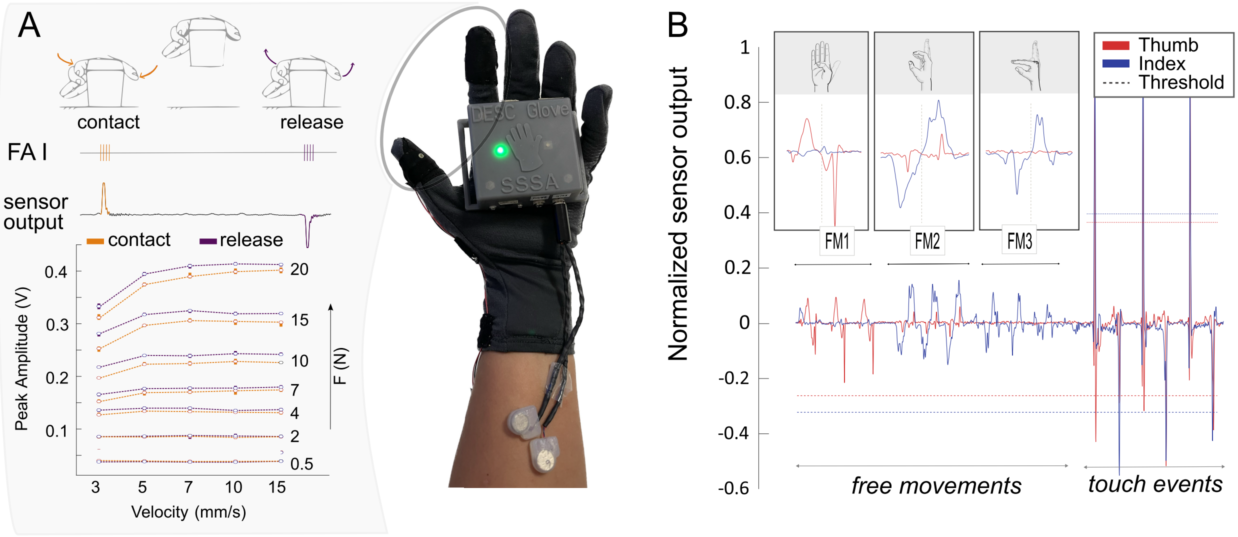
$$\mathrm{DDT_{Low}} = \frac{D\_FM_{min} + 0.8D\_PLT_{min}}{2}. \tag{4}$$

At the end of the calibration procedure the values of the detection thresholds are automatically stored in the microcontroller. After determining the detection thresholds, the vibrators are positioned accordingly with the user, prioritizing the capability of clearly distinguish the stimulus and the comfort of the stimulation. The amplitude and frequency of vibration generated by eccentric-mass motors are not adjustable. Consequently, adjustments were made to the stimulus duration, taking into account that variations within the 50-200 ms range are perceived as modulation of the stimulus intensity [42]. Thus, the vibration is triggered by the detection of the touch event and remains active for the chosen duration, which can be set between 50 and 150 ms.

III. METHODS

A. Participants and Assessment Tests

We conducted two experimental studies including two state-of-art assessment tests to verify the viability of our device.



Load cell

Fig. 2. A) Final version of the device with an insight on the sensor response to transient mechanical events. Such response is coherent with the response of fast adaptive fibers type I (FA I), that fire in case of contact or break of contact with objects (modified from [24]). A bench test characterization was performed through a 3D platform applying and removing 7 loads on the sensor's surface at different rates: the PVDF sensor responded with a single spike for every contact or release event, with an amplitude proportional to the load applied [65]; B) Sensors' signals acquired during a calibration session. It consisted of repeating three times each of the free hand movements (FM1, FM2, FM3) and three touch-and-release task. Free hand movements and the corresponding signals are shown in the top panels on the left. Dashed lines represent the absolute detection thresholds computed through equations 1 and 2.

20 adults with unimpaired hand and arm function and naïve to the purpose of the experiment (Age: 26.8±2.2 years, 11 females in the group, all right-handed) participated in the first study. Two volunteers, S1 (65-year-old man) and S2 (37-year-old woman), with sensory impairment participated in the second study.

S1 lost nearly all perception in the right hand and partially the motor control of the entire upper limb (dominant side) following a brachial plexus injury. The motor impairment primarily concerned shoulder movements, with limited ability to flex or extend the elbow. With respect to the hand function, he could execute a pinch grasp using his thumb and index finger but could not perform a firm power grasp. S2 lost nearly all perception in the right side of her body due to an incomplete posterior lesion of the spinal cord at level C1. S2 had near normal sensitivity at the right shoulder and some diffuse perception that extends distally until the elbow, but she reported that this perception is very distinctly different from perception on her unimpaired left side [43]. S2 reported not to embody upper and lower limb on the right side, and she only managed to recover her ability to walk and to use her right hand after extensive rehabilitation. Her only way of estimating the applied grip force was through visual observation of the discoloration of her fingernail, caused by the proportional compression of the blood vessels in response to the applied pressure. Accordingly, we asked her to paint her fingernails with dark nail polish for the duration of the study.

Informed consent in accordance with the Declaration of Helsinki was obtained before conducting the experiments from each participant. The studies were approved by the local ethical committee of the Scuola Superiore Sant'Anna, Pisa, Italy (Approval No. 10/2023). The methods were carried out in accordance with the approved guidelines.

Two state of art tests were used to evaluate the motor coordination while using the device: the Pick and Place Test (PPT) and the Pick and Lift Test (PLT). The participants performed the PPT and PLT while standing in front of a table.

1) Pick and Place Test (PPT): The PPT measures the participants' ability to regulate grip force during delicate manipulation. The PPT can be likened to the Virtual Eggs Test, initially introduced by Clemente et al. as a modification of the well-known box and blocks test for gross manual dexterity [24]. It resembles a task of picking and repositioning fragile objects without breaking them. Here, $50 \times 50 \times 50$ mm plastic blocks weighing 55 g, were equipped with a magnetic fuse as in [44]. A force applied on the walls exceeding a fixed threshold caused the fuse to break instantaneously, thus collapsing the block, similarly to "breaking an egg". In this study, the participants are asked to transfer, for 35 times, the blocks from one side of a plastic wall (height of 6 cm) to the other, as quickly as possible while also preventing their breakage. To measure the transfer time, participants are instructed to press a button with the same hand used to perform the experiment at the beginning and end of each transfer. The number of broken blocks and the duration of each successful transfer are measured.

2) Pick and Lift Test (PLT): The PLT is a well-established procedure in motor control studies, used to assess the participants' motor coordination and integration of sensorimotor control paradigms [23], [45]. In the PLT, the participant, using only the thumb and index digits and standing in front of a table, is instructed to repeatedly grip, lift, replace and release at a self-selected speed, a test-object. The test-object includes two load cells (SMD2551-012, Strain Measurement Devices, UK) able to measure the grasping force (GF) and a third load cell in a stand, capable to measure the load force (LF) before

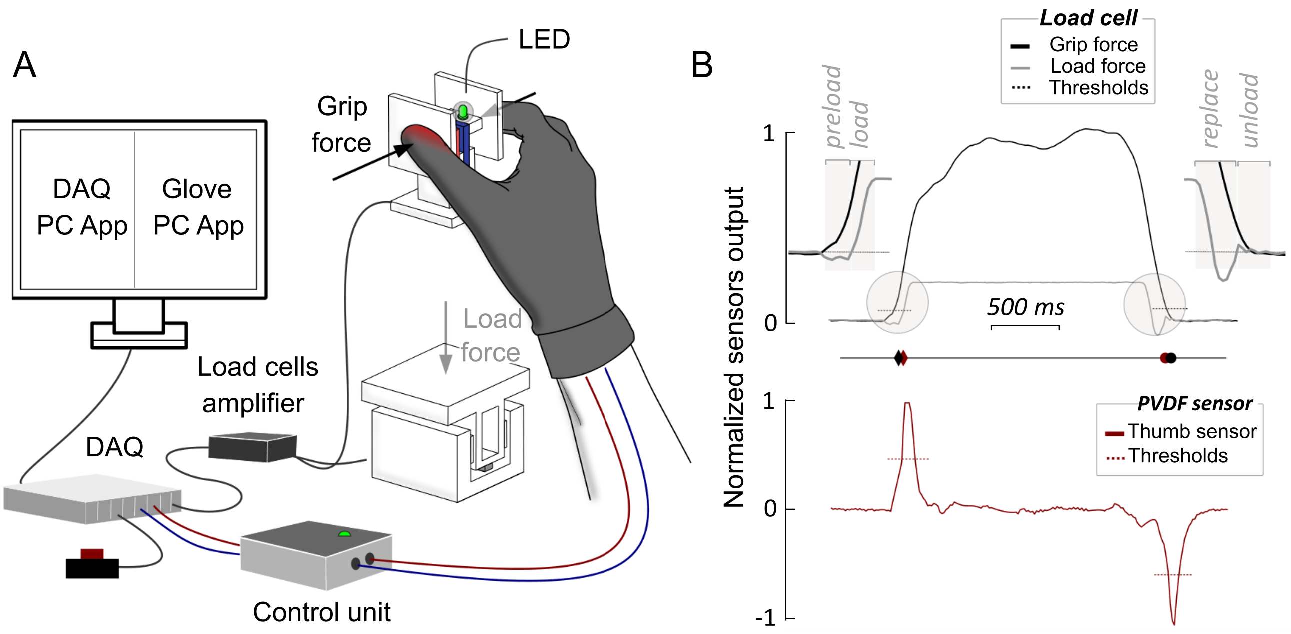


Fig. 3. Experimental setup for Study 1. Representation of the experimental setup to record grip and load forces and glove sensors signals during a pick and lift task; B) Exemplary trial performed by a participant. Load cell and thumb sensor detected an event when their signals crossed the respective detection thresholds.

lift-off [43]. Signals from the test-object are sampled by a data acquisition board (100 Hz rate) and stored to a PC for online visualization and/or offline processing.

B. Study 1 – Technology Validation With Healthy Participants

The first study aimed to validate the technology of the glove by assessing its specificity, sensitivity and response delay in a group of 20 young adults with no sensory or motor disorders, while wearing the instrumented glove (medium size) during specific tasks that did or did not involve touch events. During these tasks signals from the glove and test-object were sampled (100 Hz rate) and stored on a PC for offline analysis.

The specificity of the sensors was inferred by calculating the false positive rate (FPR) during the execution of free movements that did not involve touch events between the fingertips and other parts of the hand. Therefore, participants were asked to perform 30 times each of the three free movements (FMs), and to pay particular attention to prevent self-contacts. The FPR was calculated as follows:

$$\mathrm{FPR}_{finger} = 100\left(\frac{FP_{finger}}{N}\right), \tag{5}$$

where FP represents the false positives, i.e., the number of actual detections of the relative sensor, and N the number of movements. Considering that each FM consisted of two movements (flexion and extension) during which the sensor could produce at least two detections due to fabric stretch and relaxation (Fig 2b, top panel), N was defined as twice the number of the repetitions, i.e., 60.

The sensitivity (rate of correct detections) and response delay were instead inferred by a task which involved touch events. This was a pick and lift task (100 trials) of the test-object described above, used as the ground truth for the contact and release events as detected by the glove (Fig 3). The latter were considered as true positives only if they fell within a time window of ±150 ms around the event detected by the test-object. The true positive rate (TPR) for each sensor and touch event was calculated as the percentage of correct detections over the number of lifts occurred. The response delay was defined as the delay between the identification of the touch event by the load cell and the glove.

C. Study 2 – Pilot Study With Individuals With Sensory Impairment

The second study involved two individuals with sensory and motor impairment in the dominant hand and aimed to infer the immediate effects of the device in motor control and coordination tasks. To this aim the Pick and Place Test (PPT) and the Pick and Lift Test (PLT) were performed. Each test was repeated in three conditions: i) wearing the device with sensory feedback enabled (glove on), ii) wearing the device with sensory feedback disabled (glove off), iii) without the glove (bare hand). The sensory impairment of the participants, assessed with the Semmes-Weinstein Monofilament Test [46], concerned complete sensory deprivation of the thumb (participant unable to perceive any monofilament), and loss of protective sensation in the index finger (thinnest perceived monofilament sized 4.56, equivalent to 0.039 N) for S1, and loss of protective sensation in both the thumb and index (thinnest perceived monofilament sized 5.18, equivalent to 0.15 N) for S2 [47].

The participants wore the glove and the miniature vibrators were placed in sites where the stimulus was clearly perceived. The vibration duration was set to 70 ms for both the participants and remained fixed for the whole experimental session. In particular, for S1 they were located on his dorsal forearm, the most distal point with sufficient residual sensitivity. Contrarily S2, who experienced sensory disorders on the whole upper limb, preferred receiving the stimuli on the thumb and index of the left hand (i.e., the unaffected hand). The status of the device and motors activations were monitored by the experimenter for the whole experimental session through the PC application. The participants familiarized with the device and the PPT; during this time they transferred blocks exhibiting different breaking thresholds, while receiving discrete feedback when touching and releasing them. This familiarization also served to determine the breaking threshold of the block to be used in the PPT. After the familiarization phase the participants performed the PPT and PLT (35 repetitions) in the three conditions in the following order: *glove on*, *glove off*, *bare hand*. The data from the load cells were used to extract two phases from each trial. The preload phase, starting at the first digit contact with the object surfaces to the onset of the LF increase and the load phase, from the onset of the LF increase until the moment of lift off (i.e., when the contact between the test object and the stand was first broken) [9]. For each test condition we extracted the following metrics, which are known to be characteristic of the motor task: the maximum grip force applied during the task and the grip force-load force delay (i.e., the time difference between load force (LF) reaching 50% of the maximum LF and GF reaching the same force) [23]. Due to the observational nature of this study, we did not conduct statistical analysis.

IV. RESULTS

All reported numbers and errors are median (and interquartile ranges, IQR, in brackets).

A. Study 1 – Technology Validation With Healthy Participants

Signals from the glove and load cell were recorded during pick and lift movements and analyzed to extract validation data in terms of sensitivity, specificity and response delay.

The False Positive Rate (FPR) proved 0 (0.8)% for the thumb and 0 (0.69)% for the index (Fig 4a). The True Positive Rate (TPR) for the thumb proved 99 (3.0)% and 98 (4.1)% for contact and release events, respectively; the index sensor detected 99.5 (1.4)% of contacts and 99 (3.5)% of release events (Fig 4b). The response delay of the glove was 40 (25) ms and 20 (35) ms, for contact and release events of the thumb sensor, respectively, and 22.5 (30) ms and 5 (35) ms for contact and release events of the index finger sensor, respectively (Fig 4c).

B. Study 2 – Pilot Study With Individuals With Sensory Impairment

1) Pick and Place Test (PPT): The familiarization procedure proved that the participants were unable to transfer blocks exhibiting a breaking threshold below 2 N, which was thus chosen as the value for executing the test. During the PPT, S1 successfully transferred the blocks in 71.4% of the trials in the *glove on* condition, 65.7% in the *glove off* condition and 54.2% without the glove (Fig 5, S1). He demonstrated a faster execution in transferring the eggs with the *bare hand* than with *glove on*, taking a median of 3.09 (0.27) s and 3.39 (0.16) s, respectively. The median of the transfer time in the *glove off* condition was in between, 3.28 (0.73) s, albeit characterized by a higher variability (Figure 5, S1). Conversely, S2 successfully transferred all the blocks in all the test conditions but proved faster when receiving the feedback (Fig 5, S2). Specifically, she took a median of 3.81 (0.30) s when performing the test in the glove on condition, 4.66 (0.72) s in the glove off and 4.46 (0.80) s with the bare hand. Despite the dark nail polish, S2 exploited visual information when manipulating the fragile objects with the bare hand. In particular, she referred to the lateral deformation of the finger pad when grasping the test object to adjust the grip force.

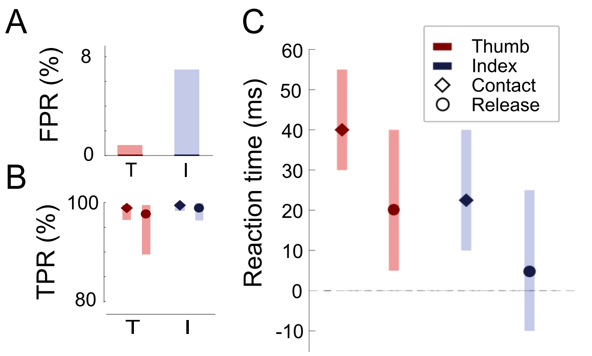


Fig. 4. A) False Positive Rate (FPR) during free-hand movements. B) True Positive Rate (TPR) during pick and lift trials. C) Response delay of the device in terms of event detection delay across all the participants (median values and IQR).

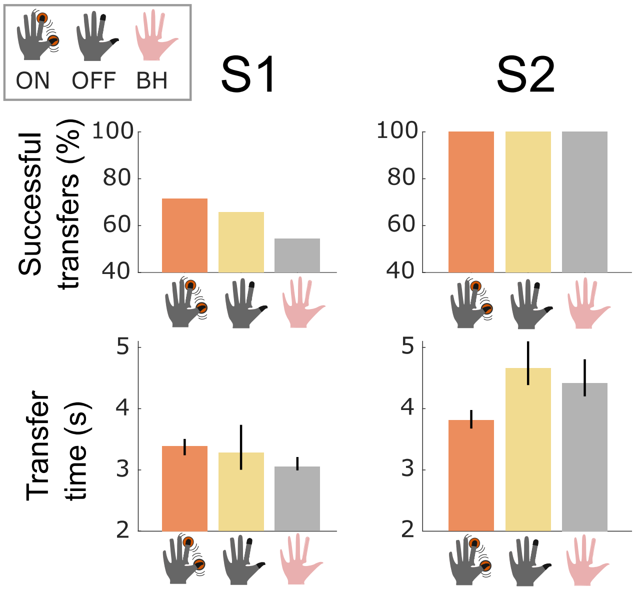


Fig. 5. Pick and Place Test (PPT). Number of test objects successfully transferred and time for each transfer across the experimental conditions for S1 (on the left) and S2 (on the right). ON - glove on condition; OFF - glove off condition, BH - bare hand condition.

2) Pick and Lift Test (PLT): Both the participants showed a greater motor coordination when receiving the feedback, as proven by a GF-LF temporal correlation closer to the one observed in able-bodied humans [41] (Fig 6). Specifically, S1 shortened the GF-LF delay in the *glove on* condition to 50 (20) ms with respect to 80 (50) ms in the *glove off* condition and 70 (40) ms in the *bare hand* one (Fig 6, S1). S2 exhibited a

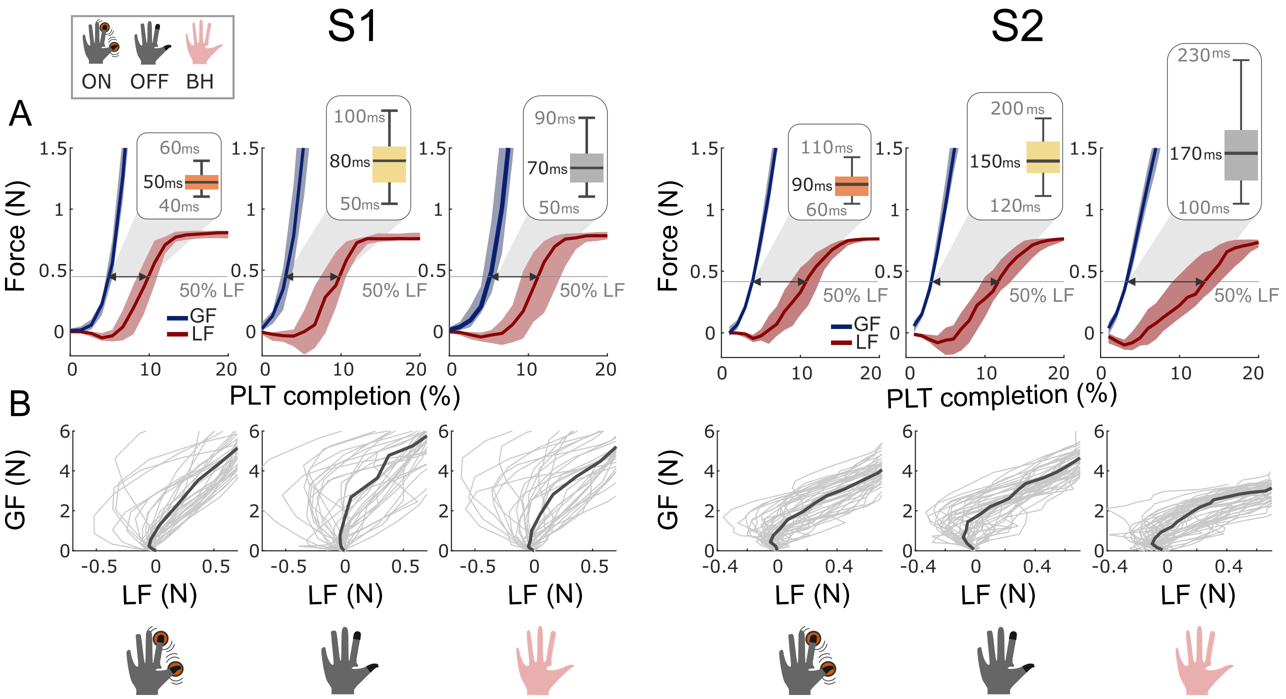


Fig. 6. Pick and Lift Test (PLT). A) Motor coordination during the PLT in the three test conditions for S1 (on the left) and S2 (on the right). The inserts depict the GF-LF delay distributions during the PLT. B) GF vs LF profiles from object contact to lift-off across the conditions for S1 (on the left) and S2 (on the right). ON - glove on condition; OFF - glove off condition, BH - bare hand condition.

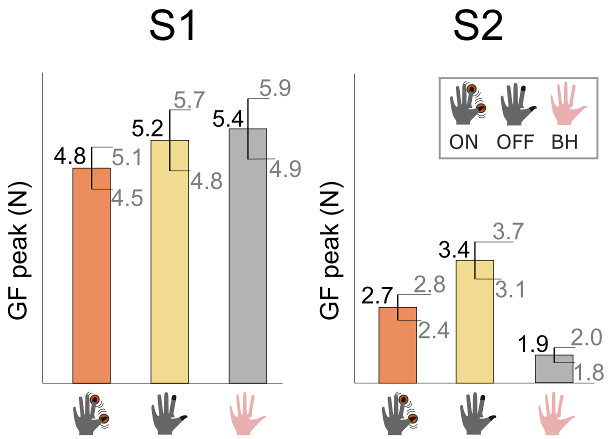


Fig. 7. Pick and Lift Test (PLT). Distribution of grip force peak during pick and lift task across the conditions for S1 (on the left) and of S2 (on the right). ON - glove on condition; OFF - glove off condition, BH - bare hand condition.

reduced GF-LF delay in the *glove on* condition to 90 (50) ms with respect to 150 (80) ms in the *glove off* condition and 170 (130) ms with the bare hand (Fig 6, S2). Finally, S1, in the *glove on* condition applied a lower GF to lift the object [peak of 4.81 (0.67) N] with respect to the *glove off* condition [5.39 (0.97) N] and to the *bare hand* condition [5.61 (1.00) N] (Fig 7, S1). S2 exhibited an opposite trend, applying a lower force when lifting the object with the bare hand (1.92 (0.24) N) compared to when she wore the glove, exhibiting a GF peak of 2.66 (0.40) N in the glove on condition and of 3.39 (0.58) N in the glove off condition (Fig. 7, S2).

V. DISCUSSION

In this work we presented a wearable device that aims at restoring sensorimotor functions by providing augmented sensory feedback during object manipulation. In fact, augmented sensory feedback strategies are known to promote motor learning, reinforcing the internal models responsible for the optimization of motor performances [48], [49]. The sensing ability of our device relies on two PVDF piezoelectric sensors sewn on the thumb and index fingertips of a fabric glove, while two miniature vibrators are used to provide the augmented feedback. Its action is handled by a battery-powered control board worn on a bracelet, running an algorithm capable of interpreting the sensor signals and converting them into vibration cues. Vibrational bursts are delivered to the skin of the user's forearm synchronously with contact and release events, according to the DESC policy [4]. The system relies on passive sensing technology and low-power actuators, resulting in a non-invasive, lightweight, and compact device. Also, beyond the brief initial calibration phase, that in a prospective application could be implemented inside, the glove does not need to be tethered. The system could therefore operate completely stand-alone, a feature that makes it suitable both for hospital and home use.

The small ratio of wrong detections observed in the first study (Fig 4a) was likely caused by imperfect fitting of the glove (the same size was used for all the participants). In fact a too tight glove can cause unintended stretch of the PVDF film, which may trigger a spike response of the sensor, whereas a loose fit may cause relative motions between the glove and the digit and, therefore, false detections when the finger and the glove come to contact with each other. Therefore, we argue that tailoring the glove to the participant's hand size could further improve the performance. With respect to the response delay, sometimes the sensors were able to detect contact events with a lower latency than the load cells, resulting in a negative delay value (Fig 4c). These negative latency values can be explained through the fact that the systems used to detect the events are based on different detection thresholds: a delicate touch could be enough for the glove to sense it but not for the test-object to overcome the threshold. This reactivity allows for a quick delivery of feedback stimuli, providing the user with timely information to be integrated into the motor control. Finally, a slight yet acceptable difference in performance between the two sensors was observed (Fig 4a, b). This could be due to the custom fabrication process of the PVDF sensors, which possibly leads to intrinsic variability of the voltage response of each sensor.

Taken collectively, the outcomes of the Pick and Place Test (PPT) and Pick and Lift Test (PLT) performed by the individuals with sensory impairment suggest immediate integration of the DESC feedback into the motor control, as indicated by the behavioral and functional improvements in the grasping tasks while receiving the sensory feedback (Fig 5, 6, 7). In precision grasping, the coordination of grip and lifting forces is adapted accordingly to the prediction of the friction between the object and the skin [50]. However, when tactile sensory input is deprived, the reliance on predictive feedforward mechanisms typical of natural grasping is compromised, leading to a closed-loop motor control that solely relies on indirect information (i.e., visual feedback) [51]. Experiments involving cutaneous anesthesia have provided additional evidence for the importance of tactile information revealing a disruption of manipulation patterns, in which slips of low-friction surface objects are often compensated by the application of exceeding grasping forces [45], [50], [52].

The outcomes from the PPT performed with the bare hand highlighted that the two study participants, S1 and S2, exhibited different levels of manual dexterity. S1 demonstrated a more rudimentary motor control of the affected hand, a fact confirmed by his statement indicating rare use for activities requiring precise gripping. In contrast, S2 showed to be more aware of her condition, proving able to compensate for the impairment by exploiting unnoticeable visual cues (i.e. the deformation of the fingertip to the applied grip force). In fact, when performing the PPT with the bare hand, S1 successfully transferred half of the blocks, while S2 was able to transfer all of them (Fig. 5).

Regardless of their baseline dexterity, when receiving the DESC feedback, both study participants improved their performance, although in different ways. S1 improved his performance by transferring a greater number of blocks albeit increasing the transfer time, whereas S2 matched the excellent performance of bare hand (in terms of number of successful trials) while significantly reducing the execution time (Fig. 5). This outcome is important per se as it supports the DESC control policy in humans [9], but also poses questions on why the performance improved in different ways. This may be eventually associated with the very different residual functionalities of the two participants and in turn to different control mechanisms involved. The reduced transfer time achieved by S2 in the glove on condition suggests the adoption of a predictive motor control strategy (based on the forward model), as a result of the integration of the vibrational cue into the motor control scheme. It is known that feedforward motor strategies typical of healthy individuals allow to bypass the neural delays that would slow down the motor action [7], [53], ultimately reducing the task completion time. However, the anticipation of the motor action is contingent upon the construction of an internal model in the cerebellum, thus when the motor task is fully assimilated and does not require cognitive effort for its execution [54]. The increased transfer time achieved by S1 in the glove on condition suggests instead the adoption of a reactive (feedback-oriented) motor control strategy, which might be due to the complexity of the task as experienced by S1, taking into account his low residual functionalities. Indeed, challenging tasks require more practice to construct the related internal models, concurrently favoring feedback-oriented behaviors [55], [56], [57]. S1, who likely perceived the task as challenging and prone to failure, more likely exploited the DESC feedback to continuously monitor the progress of the manipulation task (rendering it “closed loop”) instead of adopting a feedforward strategy.

The difference in control strategy did not emerge from the PLT, likely because of the nature of the test. While in the PPT the objects would clearly break, thus giving a direct feedback/sign of failure of the trial, this was not the case in the PLT. The latter did not provide any indication to the experimenter, and as such could not fail, as long as he/she managed to maintain a sufficient grip force. Hence, the PLT might have been implicitly experienced as a less challenging task. This may explain why both participants responded similarly, i.e. adopting a predictive motor control strategy as indicated by the more coordinated lifting patterns – quantitatively assessed by a lower GF-LF delay (Fig 6). In other words, by incorporating the feedback cues into the motor control scheme, they were able to anticipate and adjust their actions. Indeed, because of the long delays in sensorimotor control loops (∼100 ms), dexterous manipulation is possible only by accurate predictions (feed-forward) [58]. The provided vibrational cues served to restore the contact events, which represent crucial sensorimotor control points to compare predicted and actual sensory signals [9]. This fine behavior was not present under the glove off or bare hand conditions, which instead demonstrated uncoordinated lifting patterns, and, for S1, a higher grip forces to maintain an adequate safety margin before slippage (Fig 7, S1), in agreement with studies with people with suppressed sensitivity [45], [52]. This proved not the case for S2 which exploited the visual clue from her finger-pads to apply and adequate GF when performing the task with the bare hand (Fig 7, S2) (a compensation that could not be exploited when wearing the glove). However, a more precise grasp did not translate into a more coordinated one. In fact, the lowest GF showed in the bare hand condition corresponded to the highest GF-LF delay (Fig 6-7, S2).

This study relies on the pivotal role of somatosensory inputs in driving brain plasticity, ultimately promoting motor (re)learning [59]. Indeed, tactile gating mechanisms lead to the suppression of sensory information classified as noise, allowing only the information selected as relevant to be processed [60], [61]. For this reason, we believe that a discrete and concise feedback could be seamlessly integrated in the motor control. To the best of our knowledge, this was the first attempt to provide augmented feedback following the DESC policy (i.e., with time-discrete stimuli rather than in a continuous fashion) to individuals with limited sensorimotor functions. Although only the contact events were provided, they could leverage that information to modulate the GF during the whole task and more generally to enhance hand motor coordination. Hence these findings suggest that DESC feedback was promptly incorporated in the individuals' motor control and support the notion that human manipulation relies on temporally-correlated sensory information related to the completion of sub-tasks [7], [9], [62]. The incorporation of the DESC sensory feedback is even more interesting if considering that the stimulus was provided on the forearm or on the contralateral arm, and thus implied a sensory remapping process without explicit training. In fact, providing stimuli through sensory substitution devices imply an adaptation of the CNS to encode the stimulus and translate it into a proper information [63]. To effectively interpret the information from this new sensory channel, users typically undergo a training phase to familiarize themselves with the device [63], [64]. Likely, the discrete and temporally correlated nature of the DESC feedback facilitated the encoding process, rendering it more intuitive and user-friendly.

Despite the scientific evidence regarding the impact of augmented sensory feedback for motor rehabilitation or assistance [59], a systematic evaluation of the effects of haptic feedback for motor re-learning is still missing [18]. In addition, although promising, these represent preliminary findings derived from two participants. In order to draw consistent and robust conclusions, we aim at assessing the usability and effectiveness of the device among the target user population, i.e., stroke survivors and/or people affected by impaired sensory function of the hand, paving the way for its use in the real-world, such as rehabilitation clinics or users' homes.

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