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Abbass, Yahya; Saleh, Moustafa; Dosen, Strahinja; Valle, Maurizio

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Embedded Electrotactile Feedback System for Hand Prostheses using Matrix Electrode and Electronic Skin

Yahya Abbass, *Student Member, IEEE*, Moustafa Saleh, *Student Member, IEEE*, Strahinja Dosen, *Member, IEEE*, and Maurizio Valle, *Senior Member, IEEE*

***Abstract*— As the technology moves towards more human-like bionic limbs, it is necessary to develop a feedback system that provides active touch feedback to a user of a prosthetic hand. Most of the contemporary sensory substitution methods comprise simple position and force sensors combined with few discrete stimulation units, and hence they are characterized with a limited amount of information that can be transmitted by the feedback. The present study describes a novel system for tactile feedback integrating advanced multipoint sensing (electronic skin) and stimulation (matrix electrodes). The system comprises a flexible sensing array (16 sensors) integrated on the index finger of a Michelangelo prosthetic hand mockup, embedded interface electronics and multichannel stimulator connected to a flexible matrix electrode (24 pads). The developed system conveys contact information (binary detections) to the user. To demonstrate the feasibility, the system was tested in six able-bodied subjects who were asked to recognize static patterns (contact position) with two different spatial resolutions and dynamic movement patterns (i.e., sliding along and/or across the finger) presented on the electronic skin. The experiments demonstrated that the system successfully translated the mechanical interaction into electrotactile profiles, which the subjects could recognize with good performance. The success rates (mean ± standard deviation) for the static patterns were 91 ± 4% and 58 ± 10% for low and high spatial resolution, respectively, while the success rate for sliding touch was 94 ± 3%. These results demonstrate that the developed system is an important step towards a new generation of tactile feedback interfaces that can provide high-bandwidth interfacing between the user and his/her bionic limb. Such systems would allow mimicking spatially distributed natural feedback, thereby facilitating the control and embodiment of the artificial device into the user body scheme.**

***Index Terms*— Sensory feedback system, tactile sensors, electronic skin, electrotactile stimulation, prosthetic hand**

I. Introduction

Upper limb loss leads to substantial disability and thus dramatically reduced quality of life of an amputee. Myoelectrically controlled prosthetic hands have been developed to substitute the functions of the biological hand (e.g. [1]). Such prostheses are controlled by recording electromyography (EMG) signals from the residual limb muscles to estimate user movement intention, which is then converted into commands for the prosthesis [2]. Despite remarkable progress in improving the control, amputees often reject their prosthetic hands [3], [4]. One of the drawbacks of the contemporary prostheses, which might contribute to their rejection, is the lack of somatosensory feedback from the prosthesis to the user; hence, the amputees do not "feel" their bionic limbs. Restoring the missing tactile feedback can have a positive impact on the utility and user experience by improving performance and facilitating the feeling of ownership [5]. A system for feedback restoration comprises the following components [6]: (i) a sensing system for the detection of tactile stimuli; (ii) a readout circuit for data acquisition and the encoding of tactile data into stimulation profiles; and (iii) a stimulation system to deliver the stimulation patterns to the prosthesis user. Preferably, the technical solution should be simple, compact in size, portable, and durable.

Y. Abbass, M. Saleh, and M. Valle are with the Department of Electrical, Electronic, Telecommunications Engineering, and Naval Architecture (DITEN) - University of Genoa, via Opera Pia 11A, 16145, Genova, Italy. (e-mail: yahya.abbass@edu.unige.it, moustafa.saleh@edu.unige.it, maurizio.valle@unige.it)

S. Dosen with the Department of Health Science and Technology, Aalborg University, Aalborg, Denmark (email: sdosen@hst.aau.dk)

To provide artificial tactile feedback, the prosthesis is equipped with sensors measuring the interaction with the environment (e.g., grasping force). Acquired sensor data are translated into stimulation patterns and delivered to the user invasively by stimulating peripheral nerves [7], or non-invasively through electrotactile, mechanotactile, and vibrotactile interfaces [8], [9]. These methods have been extensively described and compared in several recent reviews [8]–[11]. Despite many different approaches that are presented in literature, a common characteristic of these systems is that they typically transmit only one or two global prosthesis variables [12]. Most often [5], the total grasping force is selected as the feedback variable since this is a critical parameter during grasping where an inappropriate force can lead to object slipping or breaking. Sometimes, the feedback also includes hand aperture, which in combination with force allows recognizing object size and stiffness [13], [14]. To provide such artificial exteroceptive and proprioceptive feedback, the prosthesis needs to be endowed with sensors that measure position and force [15]. Typically, the measured sensor information is transmitted to the subject by using only a few stimulation channels, for instance, several electrodes [16], vibration motors [17] and mechanical pushers [18] that provide stimulation to several discrete points along the residual limb. These feedback systems enable the user to feel "global" sensations, e.g. contact, slippage, hand aperture and applied force, and it has been demonstrated that such feedback can indeed improve performance and user experience. Nevertheless, an effective feedback system is still an open challenge as the impact of feedback depends on multiple interacting factors [5]. The aforementioned approaches are limited in the number of sensors and stimulation points, and this substantially limits the amount of information that can be transmitted through the feedback interface. This is in a sharp contrast to the human hand, which is covered with a dense network of tactile mechanoreceptors and hence the natural feedback provides spatially distributed pressure information.

Importantly, advanced sensing solutions that allow capturing spatially distributed mechanical interaction are becoming more common. Several of such sensor systems have been developed for robotic hands and are commercially available. The most relevant for tactile sensing are BioTac, TekscanTM, and DigiTacts. BioTac [19] is a sensorized finger equipped with a matrix of pressure sensors across the fingertip, as well as a vibration and temperature sensor. Electronic skins integrating matrices of sensing elements embedded into flexible structures have been fabricated (e.g., [20]–[25]). Most of these sensors were originally developed in the robotic framework. However, they can be utilized in prosthetics, and some solutions have been already developed specifically for this application [26]–[31].

Since such sensing systems embed a network of sensors, they are attractive solutions for providing an advanced feedback to a prosthesis user. However, a critical question in this approach is how

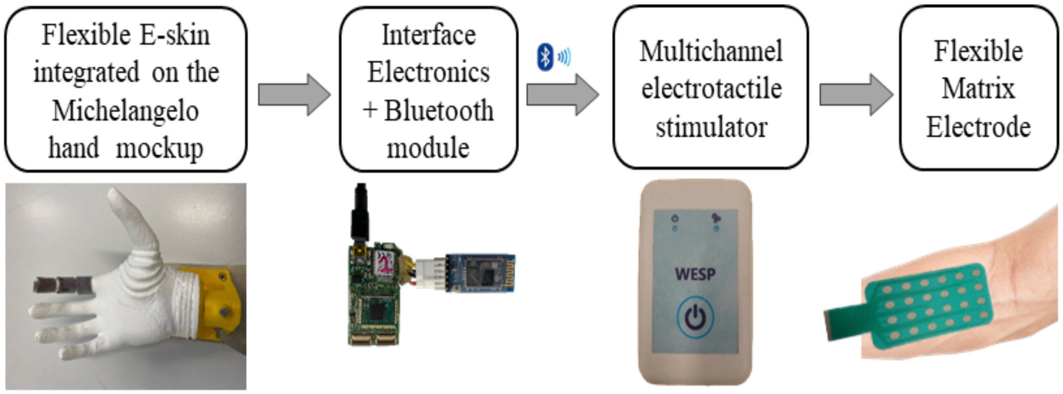

Fig. 1. System Architecture. The system comprises an e-skin with 16 sensors, interface electronics for signal acquisition, and a multichannel stimulator with flexible matrix electrodes integrating 24 electrode pads to deliver the electrotactile stimulation to the subject. The system therefore translates the tactile data recorded by the e-skin into stimulation profiles that are delivered online to the skin of the subject.

to transmit the rich tactile information recorded by an e-skin as the feedback to the user of a prosthesis. Electrotactile stimulation is particularly attractive technology for this application since it is compact and allows printing electrodes in different shape, size and configuration of the conductive pads (stimulation points) [32]. In addition, it is characterized with fast response since there are no moving mechanical elements, which may be particularly important when delivering feedback during dynamic interactions. Finally, it also allows independent modulation of stimulation parameters, namely, intensity and frequency, which enables flexibility in encoding of the tactile information [33], [34]. In our previous work, [35], [36], we have investigated the possibility of communicating tactile information from 64 piezoelectric sensors (PVDF-based sensor array) using matrix electrodes placed on the forearm. However, the skin sensor was not designed for a prosthetic hand and was placed on a table surface. In addition, the electronics and acquisition system was not integrated but implemented on a dedicated PC.

The development of an embedded real-time feedback interface that is capable of multipoint sensing (i.e. sensors all over the hand) and stimulation is an important step towards the clinical application of this approach. Most of the embedded solutions that were presented in the literature are based on a few FSR or strain gauge sensors with either electrotactile [37]–[40], mechanotactile [6], [41], [42], or vibrotactile [43]–[46] stimulation for delivering feedback information (e.g. touch position and force level) to the subject. Similarly, [47] developed a multi-modal sensory feedback system that maps sensory information from five piezoelectric barometric sensors into stimulations through vibrotactile or mechanotactile feedback. Compared to conventional approaches to sensorization of prosthetic hands, which rely on a few sensors (e.g., overall grasping force, contact on the fingertip), the integration of an e-skin with many sensors distributed over the fingers and/or palm combined with surface stimulation through matrix electrodes endows a bionic limb and its user with high fidelity sensing and feedback. Such system can provide prosthesis users with sensations that cannot be restored using conventional methods. For instance, when a prosthetic hand grasps an object, the users can feel spatially distributed sensations that reflect contact surface and texture, as well as movement of an object within and across the hand. Such feedback can increase performance, enable social and passive touch, and promote the feeling of embodiment [48]. Furthermore, the distributed contact and pressure information detected by an e-skin can be used to detect slippage and estimate/control grasp stability (semi-autonomous control [49]). However, the drawbacks of this technology can be increased cost and system complexity. To achieve this functionality, several components need to be developed and connected into an online pipeline. The components have to be compact so that, in the future, they can be integrated into a socket and economical in power consumption (wearable system). Finally, the sensing (e-skin) and stimulation (electrode) interfaces need to be conformable to the curved shape of the hand (prosthesis) and limb (user), respectively. Recently in [50], we demonstrated a preliminary version of an embedded feedback system that transferred tactile data from flexible piezoelectric sensing array onto the forearm of three subjects using discrete electrotactile stimulation. The sensing arrays were placed on the table and tapping on one of the sensing arrays was delivered to the subject in the form of electrotactile patterns through three concentric electrodes.

The present manuscript describes a novel embedded system for tactile feedback based on multipoint sensing and stimulation. The system comprises a flexible piezoelectric sensing array with 16 sensors integrated on the index finger of the Michelangelo prosthetic hand mockup, an embedded electronics and multichannel stimulator connected to a flexible matrix (24 pads) electrode placed on the forearm. In this first version of the prototype, the online feedback delivered contact information (binary detections) from the e-skin to the subjects. The system is compact, portable and thereby suitable for integration into a myoelectric prosthesis. The system increases the amount of tactile information that can be detected and transmitted to the user leading thereby to a rich tactile feedback, which can potentially improve utility and facilitate embodiment. There are many compact solutions for restoring tactile feedback in upper limb prostheses [8]. However, to the best of our knowledge, this is the first solution that integrates all the required components to provide online multichannel feedback from an e-skin. To achieve this, we have developed a new approach of integrating an e-skin onto the curved surfaces of a prosthetic finger. Next, a method was developed to process the tactile data and extract contact information from the e-skin. The data processing method as well as a communication protocol to transmit the processed data to the stimulation unit were implemented within an embedded electronic system. Finally, an experimental assessment was conducted to demonstrate that the developed components properly work together. The experimental assessment demonstrated that the developed system indeed delivered the desired functionality – a timely multipoint electrotactile feedback on the static and dynamic contact patterns, which was easily perceived and interpreted by the subjects. In this manuscript, the system components, including hardware and signal processing are described and the results of the online assessment of the system in able-bodied subjects are reported.

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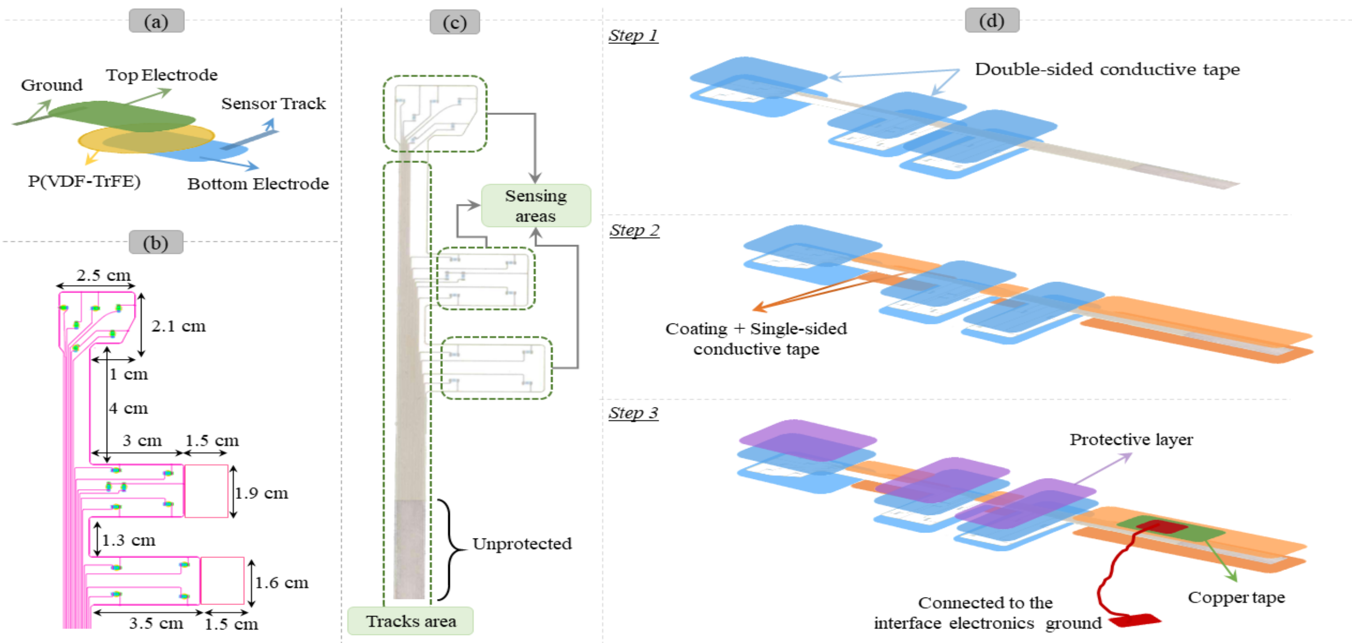

Fig. 2. (a) Single sensors structure, a P(VDF-TrFE) layer sandwiched between two electrodes. (b) Layout and dimension of the sensing array dimensioned to cover the index finger of the Michelangelo hand prosthesis. (c) The sensing array is composed of three sensing areas and a tracks area. (d) Skin patch development process. The sensing array is shielded using conductive tapes and a thin protective layer is used to protect the sensing areas.

The paper is organized as follows: Section II presents the materials and methods. Section III describes the experimental assessment of the developed feedback system. The results related to the assessment of the system are reported in Section IV. Finally, our discussion and conclusive remarks are given in Section V.

II. Materials and Methods

A. System Architecture

The designed embedded system for electrotactile feedback (Fig. 1) includes 1) piezoelectric sensing arrays (electronic skin), 2) an interface electronics, 3) a master Bluetooth module, 4) an electro-tactile stimulator, and 5) a flexible matrix electrode. The e-skin converts mechanical contacts into a set of electrical signals (one signal per sensor). The sensor signals are sampled by the interface electronics, processed and mapped into stimulation patterns using a predefined encoding scheme. More specifically, the signals are filtered and thresholded to detect contact events, and the contact information is used to set the state (on/off) of the corresponding stimulation channels. To this aim, the interface electronics generates appropriate stimulation commands and sends them through the Bluetooth module to the stimulator. The electrotactile stimulation is delivered to the subject through the matrix electrode placed on the subject's forearm. The electrode is placed on the forearm to mimic the envisioned application in prosthetics, in which the interface would be located on the residual limb of a transradial amputee. The feedback pipeline runs in real time and therefore, the tactile interaction (contact information) registered by the electronic skin is translated online into dynamic tactile sensations elicited across the subject's forearm. The block diagram of the overall system is shown in Fig. 1.

1) Tactile sensors Arrays: We have designed fully screen-printed flexible sensor arrays based on P(VDF-TrFE) poly(vinylidene fluoride trifluor-oethylene) piezoelectric polymer sensors, which were fabricated by JOANNEUM RESEARCH [51]. The manufacturing process is based on screen printing ferroelectric sensor arrays based on P(VDF-TrFE) repeated units. Fig. 2.a shows the structure of a single sensor. A bottom electrode is screen-printed on a transparent and flexible (175 μm thick) DIN A4 plastic foil (Melinex® ST 725) substrate. A ferroelectric polymer P(VDF-TrFE) layer (5.1 μm thick) is then screen-printed onto the bottom electrodes, followed by screen printing of the top electrodes (Either PEDOT: PSS or carbon have been used as top electrodes). A UV-curable lacquer layer is then deposited on top for overall sensor protection. Finally, a pooling procedure aligns in the thickness direction of the randomly oriented dipoles contained in the P(VDF-TrFE) crystallites. The sensor technology has been validated previously in [52]. The intrinsic flexibility of sensing arrays together with its wide frequency bandwidth (1 Hz-1 kHz) make it a good candidate as a functional constituent of a flexible electronic skin measuring dynamic contacts.

The aforementioned process was used to fabricate sensing arrays that host multiple sensors (range: 4-16 sensors). A complete set of sensing arrays with different geometries and sensor distribution has been designed to fit the fingers and palm of a Michelangelo prosthetic hand [15]. The fingers sensing arrays are designed to fit easily on the prostheses phalanges, without the need for special disassembly or mechanical manipulation of the device. In the present study, a single array made for the index finger of the prosthesis was integrated into the feedback system. The index finger is most commonly used during grasping and manipulation, and it was therefore covered with the sensors most extensively. Specifically, the sensors were arranged to cover the volar and lateral sides of the fingertip (5 and 2 sensors), middle (2 and 2 sensors) and proximal phalange (2 and 2 sensors), as shown in Fig. 3.a. The sensors on the lateral aspect of the index finger were added to allow contact detection when lateral grasp is used. In this case, an object is grasped between the thumb and the lateral side of the index finger, as when grasping a key. Figure 2.b shows the geometry, sensor distribution, and dimensions of the index finger sensing array while Fig. 2.c depicts the sensing and tracks areas.

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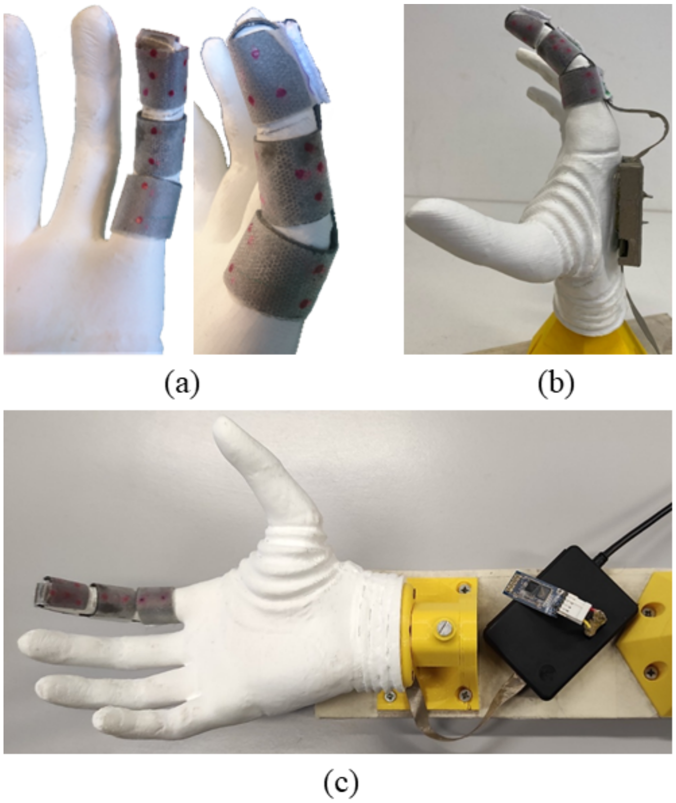

Fig. 3. Sensing system integrated on the Michelangelo hand mockup. (a) The sensing array with 16 sensors attached to the index finger (b) Sensing array connected to a PCB placed inside a shielding box and attached to the back of the hand. (c) A shielded flat cable connects the PCB on the back to the interface electronics, and the interface electronics with Bluetooth module were placed inside a shielding box.

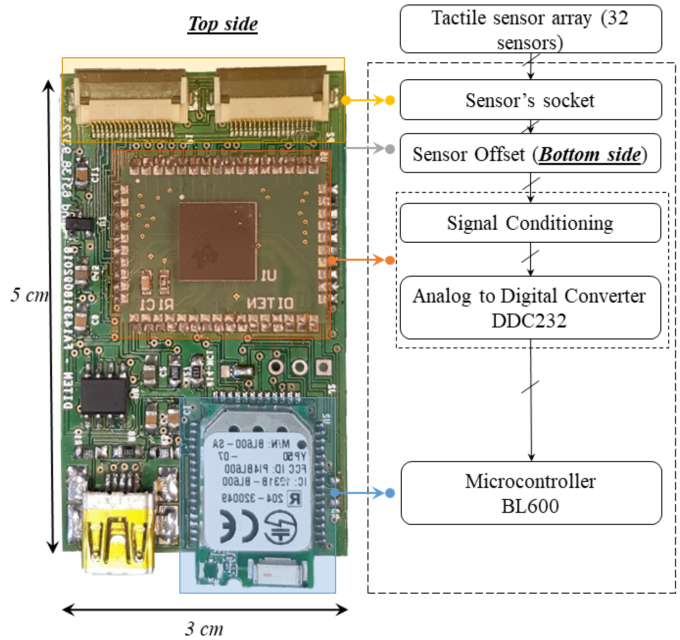

Fig. 4. Interface electronics printed board circuit (left) and its block diagram (right). The module can sample 32 tactile signals, process and transmit them wirelessly with a remote host via a Bluetooth connection. The module also implements the encoding scheme mapping the tactile signals into stimulation profiles and a command protocol to set the stimulation parameters of an electrotactile stimulator.

In order to apply the sensing arrays on the prosthetic fingers, an integration process was invented to protect the skin electrically and mechanically, while allowing it to conform to the shape of the finger. In the present study, the sensing arrays for the index finger have been chosen as a representative example to test the newly developed procedure for the integration of the skin on the hand mockup as well as to demonstrate the online operation of the complete feedback pipeline (Fig. 1). Figure 2.d shows the integration process of the skin on the mockup model of the prosthesis. The integration process was done in three main steps. Since the sensing system might be exposed to external charge especially when the arrangement is based on piezoelectric sensor and charge amplifiers, the sensing areas were first sandwiched between two double-sided electrically conductive tapes (Model tesa 60262, tesa). The conductive tape was used as a shielding layer, which guarantees a minimum sensitivity to noise. The mockup was 3D printed using P.L.A (polylactic acid) plastic with the Fused Deposition Modeling (FDM) technique. The texture of the mockup is semi-rough and not completely soft. For that reason, the skin patch was coupled from the bottom side with a flexible cylindrical shape substrate (PVC of 0.25 mm thickness) using a double-sided adhesive tape (Model 3M 9485, 3M). The resulted structure was then wrapped around the index finger of the mockup. In the second step, a small PCB compromising two FPC sockets was fixed using hot glue to the back of the hand to route sensor signals to the interface electronics. The skin patch was connected to the PCB, and then hot glue was applied to ensure the stability of the tracks-socket connection. An insulating coating (Model PLASTIK 70, KONTAKT CHEMIE) was applied to the unprotected part of the tracks area to protect and insulate the sensor tracks. The tracks area was shielded using single-sided electrically conductive tape (Model tesa 60234, tesa). Both conductive tapes (single-sided and double-sided) are conductive from both sides and hence they were electrically connected once they were coupled to each other. The shielding layers were connected to the ground of the interface electronics (see section II-A.2) using a self-adhesive copper foil tape and a wire (Fig. 2.d). Finally, a thin flexible cylindrical shape protective layer (Art. 5500 Dream, Framisitalia) was added on the top of the sensing area to protect the sensors from damage and increase the lifetime of the integrated sensing system, forming the skin patch. Figure 3 shows the sensing system integrated into the mockup. The PCB on the back of the hand and the interface electronics were placed in small shielded boxes, respectively (see Fig. 3.b and Fig. 3.c, respectively). A shielded FPC cable was used to connect the PCB to the interface electronics. All the materials used in the integration process (i.e. substrate and protective layer) were produced by Smartex, Italy [53] and they are biocompatible.

2) Interface Electronics: Figure 4 shows the Printed Circuit Board (PCB) and the block diagram of the interface electronics design. The circuit is composed of two main off-the-shelf devices: BL600 module (Laird Connectivity, US) for Bluetooth connectivity and DDC232 (Texas Instrument, US) current-input analog-to-digital converter. The PCB also includes (bottom side) digital integrated circuits for power management (i.e. voltage regulator) and a USB data transfer interface (i.e. FTDI232). The design can handle up to 32 sensors through two sockets with 16 input channels each. Both sockets are connected to an offset circuit (bottom side) to adjust the baseline of the bipolar signals generated by the sensors, which allows DDC232 to receive both the positive and negative polarities of the sensor signals. The DDC232 chip comprises multiple current-to-voltage integrators and delta-sigma analog-to-digital converters. The DDC232 is configured to use 16-bit resolution and cover the maximum input charge response. The device architecture features simultaneous sampling of the 32 input channels with a configurable

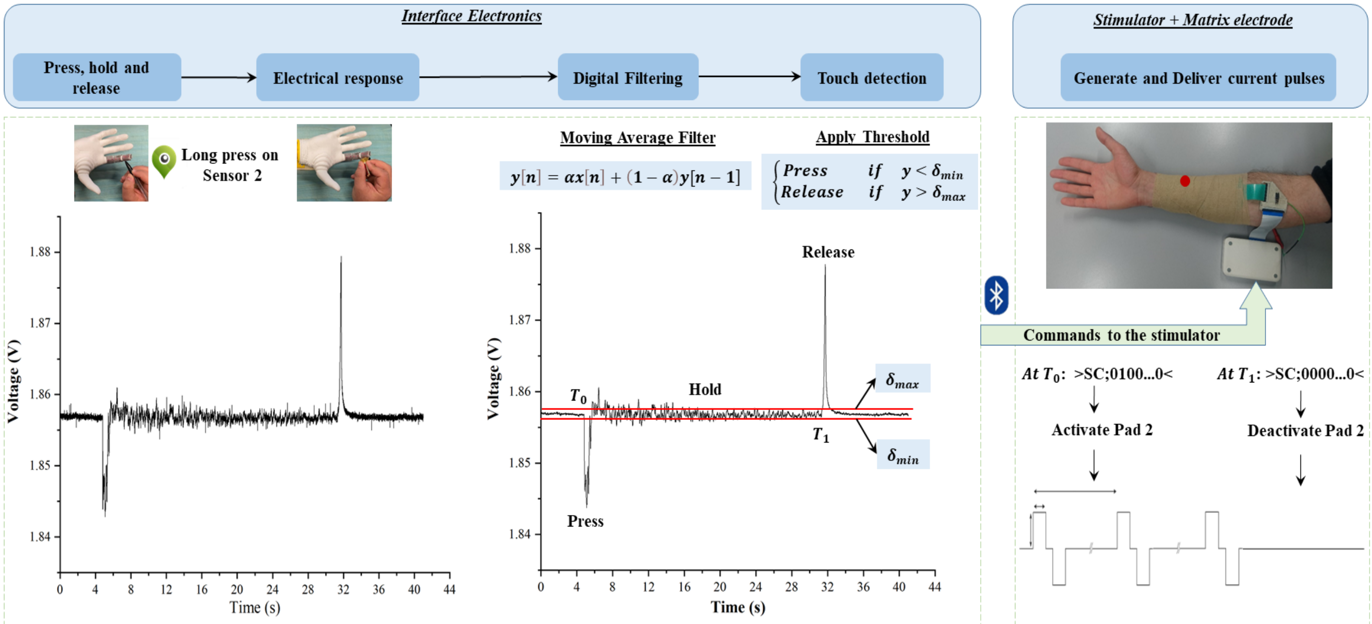

Fig. 5. The online processing pipeline of the embedded feedback system. The left panel shows an electrical response (sensor signals) due to a contact applied to the e-skin by an experimenter using a pen tip (press-hold-release). The exponential moving average filter was applied and then the signal was thresholded to detect press and release (middle panel). Finally, the interface electronics sent stimulation commands to the stimulator to activate or deactivate stimulation at the corresponding channel, thereby eliciting tactile sensations (right panel) over the subject's forearm.

sampling rate of up to 6 kHz. Data acquired by DDC232 are then retrieved by BL600 module via UART. The BL600 contains an ultra-low-power microcontroller based on an ARM Cortex M0 chip that reads, processes, and transmits sensor data. The USB provides power to the PCB and a serial interface to transfer sensor data throughout the system. The interface electronics has been preliminary validated in [54].

In the present study, the firmware for the interface electronics comprised 1) a novel signal processing method to detect contact events, 2) the mapping of the contact information into stimulation parameters, and 3) the communication protocol to transmit the computed parameters to the electrotactile stimulator, as described in section II-C. The interface electronics was configured to sample and process tactile data from 16 sensors at 2K samples/second. The 2 kHz sampling rate was used to capture the full bandwidth of the sensors (see section II-A.1), which is beneficial for detecting the timing of contact events, that are characterized by a steep increase/decrease in the signal. However, the sampling frequency was not optimized in the present study and it might be that similar results could be obtained with lower sampling rates. Importantly, the transmission rate via UART and Bluetooth interface was much lower, since it was event driven – the command was sent to the stimulator only when a contact event (press or release) has been detected (see section II-C).

3) Electrotactile Stimulator: The stimulation block employs a 24-channel programmable battery-powered research prototype stimulation system based on Tecnalia technology of spatio-temporal distribution of pulses [32]. The device generates current-controlled, charge-balanced biphasic pulses with current amplitude in the range of 0-10 mA (0.1 mA step), frequency from 1 to 400 Hz (1 Hz step), and pulse width from 50 to 500 μs (10 μs step). The stimulator is equipped with a BT interface to receive commands controlling the stimulation parameters and the channel states (on/off). In the present study, the stimulator was controlled directly by the interface electronics by implementing the communication protocol in the firmware. The protocol comprised the commands for configuring the role of the stimulation channels (i.e. anode or cathode), modulating the pulse width of each channel and the frequency of all channels, and setting the state (on/off) and amplitude of each channel. Once the feedback system is launched, the interface electronics sends the first four commands to initialize the stimulation parameters and then uses only the channel state and amplitude command to implement the online feedback.

4) Electrodes: In the present study, the stimulator was connected to a biocompatible flexible matrix electrode produced by Tecnalia Serbia. The electrode was made of a polyester layer, Ag/AgCl conductive layer, and an insulation coating covering the conductive leads. It integrated 24 oval units (pads) with a longitudinal radius of 1 cm and a transverse radius of 0.5 cm arranged into a 6×4 grid. The center-to-center distance between the adjacent pads is 2 cm in longitudinal and 1.2 cm in the transverse direction, which is higher than the spatial discrimination threshold on the forearm [55]. The pads on the matrix were used as active pads to elicit sensations, whereas a single self-adhesive electrode placed on the dorsal side of the forearm acted as the common reference. To improve electrode-skin contact, the electrode pads were covered with conductive biocompatible hydrogel (AG725, Axelgaard, DK).

B. Signal processing to detect contact events

Figure 5 depicts the electrical response of one sensor to a press-hold-release contact pattern captured by the interface electronics. As shown in the figure, the sensors capture the dynamic features of the mechanical event by generating two phasic bursts in charge-mode output signals (Fig. 5). The bursts correspond to the press and release events, while in-between the bursts there was almost no response apart from some wiggling. The contact event was indicated with a decrease whereas the release generated an increase in the signal. To reduce the signal noise and therefore detect light touches, an Exponential Moving Average (EMA) digital filter has been implemented in the interface electronics. The EMA filter, selected because it is

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convenient for implementation, is expressed by the equation below [56]:

$$y[n] = \alpha x[n] + (1 - \alpha)y[n - 1]. \tag{1}$$

where $x[n]$ is the current input, $y[n]$ is the current output, and $y[n-1]$ is the previous output; α is a factor used to set the cut-off frequency. The parameter α was set to 0.09, which corresponds to the cut-off of 30 Hz. To detect contact events, the Detection Thresholds (DT) of the 16 sensors were calibrated. To this aim, the interface electronics recorded signals from the skin for approx. 3 s with no mechanical interaction. The DTs were set to the lowest (δ_{min}) and the highest amplitude (δ_{max}) of the filtered signals measured during the 3 s calibration period to detect the press and release events, respectively.

C. Online feedback

Figure 5 illustrates the online processing pipeline of the feedback system. The interface electronics digitizes, acquires, and stores the electrical response of the 16 sensors. The EMA filter (described above) is then applied over the electrical response of all the sensors, and the resulting signals are compared to the thresholds (δ_{min} and δ_{max}) to detect the press and release events. Once the interface electronics detected an event, it created and then wirelessly transmitted appropriate commands to the stimulator. As explained in the next section, the mapping was defined between the e-skin sensors and stimulation channels, so that a contact event activated corresponding stimulation channels while the release event turned off the stimulation on those channel. Hence, the subject felt a localized sensation each time a sensor on the e-skin changed the state (on/off). As an example, Fig. 5 shows the electrical response of sensor 2 to a press-hold-release pattern and the corresponding feedback delivered through the electrode matrix. In response to the press, the command was sent to the stimulator to start the delivery of the electrical pulses through the pad 2 while the release deactivated the pad. The commands were transmitted as text messages, where '>' and '<' indicates the beginning and end of the message, and 'SC' is the message code for changing the channel state (0 and 1 – stop and start stimulation). The stimulation parameters (pulse intensity and frequency) were adjusted beforehand to elicit sensations that were clear and comfortable, as explained in the next section. The total delay from the applied contact to the stimulation is the summation of the delays throughout the different components of the pipeline. The overall delay was measured to be around 32 ms, which means that the response of the system is fast enough to transmit the desired signal without a perceptible delay.

III. EXPERIMENTAL ASSESSMENT

A. Experiments

Three experiments (Table I) were designed to assess if the feedback system can convey static patterns (contact location) with two different spatial resolutions and dynamic patterns in which the contact changes over time (i.e., sliding along and/or across the finger). In the tests, the experimenter touched the e-skin, the system detected the contact, and then transmitted tactile information to the subjects, who were asked to focus on the elicited sensations and interpret the feedback.

- **Group-to-Group experiment (G2G)**: The aim of this assessment was to evaluate if the feedback system can successfully detect and convey to the subject the information on static contacts with low spatial resolution. The sensing areas of the e-skin patch were divided into 6 groups as shown in Fig. 6.a. The 6 groups covered the three phalanges of the index finger from the volar and lateral sides. Similarly, 16 pads in the electrode matrix were selected and organized into 6 groups as shown in Fig. 6.b. The pad groups were chosen to mimic the sensors groups in the number of pads and spatial arrangement. Touch information was transmitted to the subject using spatial coding. Touch applied to one of the sensing groups on the e-skin was mapped into the activation of the corresponding group of pads in the matrix electrode. The sensor group was deemed activated if any of the sensors belonging to the group registered a contact event, and in this case, all pads in the corresponding pad group started stimulating.
- **Sensor-to-Pad experiment (S2P)**: The goal of this experiment was to test the effectiveness of the feedback system in detecting and delivering touch information with higher resolution compared to that used in G2G experiment. In this case, the contact applied to an individual sensor was conveyed to the subject by activating stimulation at the corresponding individual pad as shown in Fig. 6. Hence, the subject was asked to discriminate between 16 different pads that could be activated/deactivated individually in response to contact/release events detected by the e-skin.
- **Sliding patterns experiment (SLP)**: The aim of the test was to evaluate if the system can successfully detect and deliver the information about moving contacts to the subject. The sensor to pad mapping was the same as in S2P experiment. The sliding movement applied on a sequence of sensors was conveyed to the subject by activating the corresponding sequence of pads in real-time (see Fig. 6.b). The movement patterns included sliding along the volar and lateral aspects of the index finger, and transversally, across each phalange.

B. Setup and Protocol

Six healthy subjects (male, age 28 ± 4 years) participated in the three experiments described in section III-A. All experiments were approved by the local Ethical committee of the Specialized Hospital for Rehabilitation and Orthopedic Prosthetics (approval number 1172). Before starting, the subjects signed an informed consent form.

Figure 7 shows the experimental setup used in all the experiments. The subjects were seated comfortably on a chair in front of a monitor used for visualization. The forearm of the dominant arm was placed on the table surface and the matrix electrode was then positioned on the volar side of the subject's forearm. The electrode was covered with a medical bandage to prevent movement and improve contact. Figure 7.b shows the view from the subject's perspective. The sensorized Michelangelo hand mockup was mounted on a support and placed so that the subject could not see the hand nor the experimenter interacting with the hand (see Fig. 7.a). The interface electronics was connected to a host PC through a USB and paired with the stimulator through the Bluetooth. Two screen monitors were used during the

TABLE I
SUMMARY OF PERFORMED EXPERIMENTS

Name	Description	Touch patterns
G2G	Spatial coding with six classes (static pads)	G1, G2, G3, G4, G5, G6
S2P	Spatial coding with sixteen classes (static pads)	Sensor 1 (S1), Sensor 2 (S2), . . . , Sensor 16 (S16)
SLP	Spatial coding with five classes (dynamic patterns)	Distal, Middle, Proximal, Lateral, Medial sliding movement

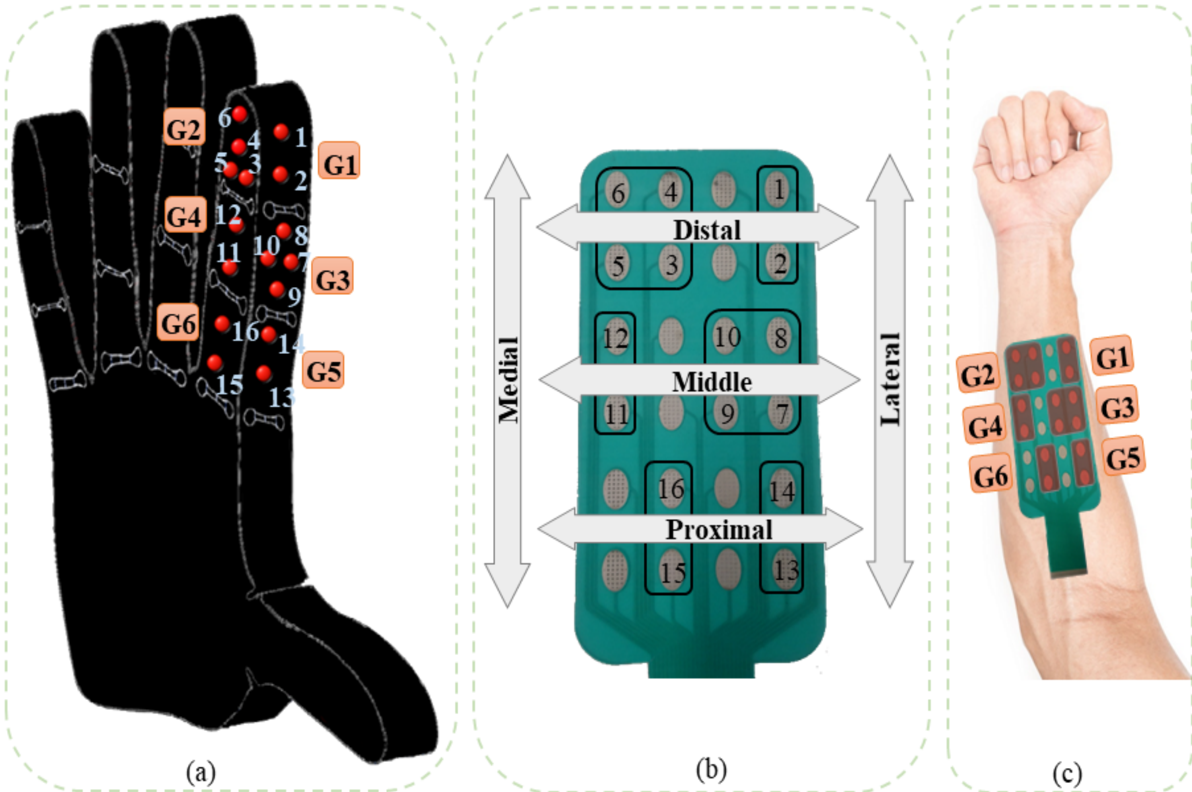

Fig. 6. (a) Sensor distribution within the electronic skin placed on the index finger of the Michelangelo mockup. The sensors are numbered and each sensor is associated to a stimulation pad on a matrix electrode placed on the subject's forearm as shown in (c). The sensor and pads were also grouped into six corresponding groups (G1-6, boxes in (b) and (c)) where G1 corresponds to Group 1 and G6 corresponds to Group 6. (b) Three experiments were conducted to assess the subject's ability to perceive and interpret the feedback: 1- touch on a group of sensors (low spatial resolution), 2- touch on individual sensors (full spatial resolution), and 3- dynamic touch (i.e. sliding across medial, lateral, distal, middle, and proximal lines in two directions).

experiments, one positioned just behind the prosthesis and oriented towards the subject and the second oriented towards the experimenter. A LabVIEW software was developed on the host PC to visualize the activity of the sensors and the electrode pads. The software was used by the experimenter to monitor the tests and as the visual feedback to the subject during training, as explained below. Prior to the experiments, the Sensation Thresholds (ST) was determined for each of the 16 pads using the methods of limits by varying the pulse amplitude [57]. During the rest of the experiment, the pulse amplitude was set to 1.5×ST, which ensured that the sensations elicited by the feedback were clear and comfortable. The amplitudes were additionally fine-tuned by the experimenter until the subject reported that the perceived intensity was similar for all the pads. The pulse rate and pulse width were common to all the pads and set to 50 Hz and 140 μs, respectively.

As explained before, the aim of the experiments was to assess the subject's ability to identify the contact patterns applied to the e-skin, captured by the integrated sensing system and delivered to the subject through electrotactile stimulation via electrode matrix. Each test started with an introductory phase, in which the subject was presented with an explanation of the working principles of the sensory feedback system and the feedback mapping. The same experimental protocol was followed in the three tests (G2G, S2P and SLP) comprised of familiarization, reinforced learning, and validation phase. In all phases, each touch pattern (i.e. activation of a group of sensors, individual sensor activation, or sliding movement) was presented 5 times to the subject.

- Phase 1: Familiarization
  In the familiarization phase, the subjects received online visual feedback on the screen monitor showing the applied touch pattern (sensor activity) and the corresponding stimulation pattern (pad activity). The subject was asked to use the visual feedback to build a mental mapping between the experienced sensation and the visual description (i.e. touched sensors, group of sensors, or sequence of sensors).
- Phase 2: Reinforced learning
  In the reinforced learning phase, online visual feedback was removed, the contact patterns were randomly applied, and the subjects were asked to guess the applied patterns. The experimenter then provided visual and verbal feedback on the correct answer. Specifically, the experimenter said "correct" if the subject successfully guessed the active pattern or "incorrect" otherwise. In the latter case, the correct answer was shown to the subject on the computer screen.
- Phase 3: Validation
  During this phase, the protocol was the same as during the reinforced learning, however, no feedback on the correct answer was given to the subject. The validation phase was the main part of the experiment and the results from this phase were used to assess the performance, while the previous two phases were used as the training.

An additional experiment (Delay-Exp) has been implemented to measure the noticeable delay in the feedback system. The aim was to demonstrate that the feedback pipeline operates significantly below the delay that can be registered by the subject, ensuring thereby that visual and tactile feedback are perceived as essentially synchronous.

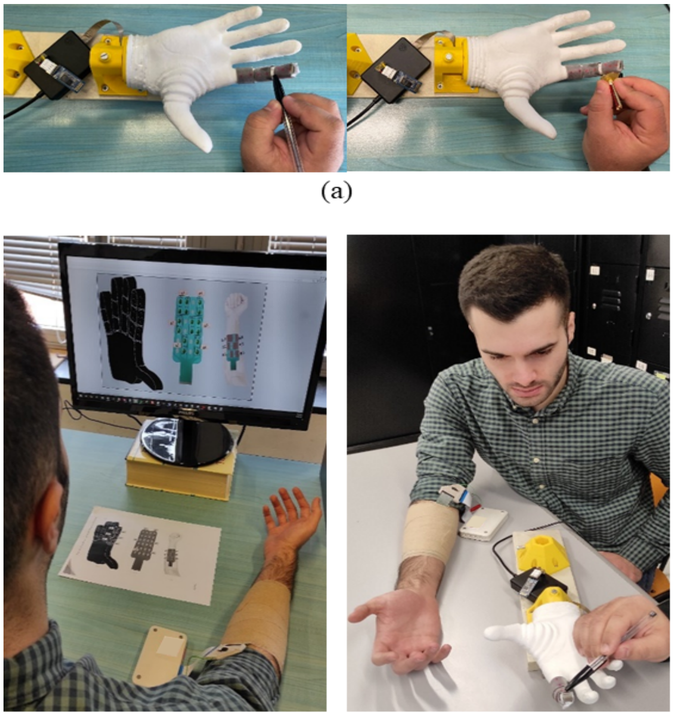

Fig. 7. Experimental setup. (a) Experimenter interacting with the sensing system, (b) Subject received electrotactile feedback through a matrix electrode placed on the right forearm and covered with a medical bandage. The subject received visual feedback shown on the computer screen only during the familiarization phase. (c) In an additional experiment, the setup was used to measure the acceptable touch-stimulation delay. In this test, the subjects received the tactile feedback while looking at the experimenter touching the hand, and they were asked to report when the delay (intentionally added in the system) between tactile and visual feedback became noticeable.

Table I summarizes the description of the experiment and Fig. 7.c shows the experimental setup used to measure the delay detectable by the subject. The subject wearing the electrode connected to the stimulator was seated on a chair in front of the sensorized Michelangelo hand mockup. During the experiment, the delay between the contact time and the activation of the stimulation was gradually increased in steps of 10 ms by the experimenter. This was done by introducing a delay in the command transmission in the firmware of the interface electronics. The subject was asked to report if he could perceive the delay between the moment when the experimenter touched one of the sensors and the start of the electrotactile stimulation. The subjects therefore compared the correspondence between the timing of the visual and tactile feedback. The experiment terminated once the subject reported that he perceived the added delay. Each of the three spatial discrimination experiments lasted approximately half an hour, whereas the delay test took approximately 10 min. A complete experimental session (setup and tests) lasted around 1 hour.

C. Data Analysis

The main outcome measure in all experiments was the success rate (SR) defined as the percent of correctly recognized stimuli, namely, groups in G2G, individual sensors in S2P and sliding movements in SLP, where the latter included both movement type (distal, middle, proximal, lateral and medial sliding) and direction (from top to bottom, left to right and vice versa). In the S2P test, the group level SR was also computed and compared to that achieved in G2G. In this case, the recognition was deemed correct if the subject guessed the sensor that was possibly wrong but still belonged to the same group as the actually activated sensor. This assessment was performed to test if the group level recognition was impacted by the higher spatial resolution of the feedback. The following marginal SRs were computed in the SLP experiment (in addition to the overall SR): 1) the marginal SR for sliding line recognition regardless of the direction, and 2) the marginal SR for the sliding direction regardless of the line type. The SRs were computed per subject for each touch modality (i.e. contacted sensors, group of sensors, or sequence of sensors) and they were then averaged to obtain the overall mean and standard deviation. The results were reported as mean ± standard deviation in the text and figures. The performance was also presented in the form of confusion matrices to identify prevalent mistakes.

The Friedman test was applied to assess statistically significant differences at the level of the group followed by Tukey's honestly significant difference test for post hoc pairwise comparison. The threshold for the statistical significance was adopted at $p < 0.05$, and the statistical analysis was conducted in OriginPro 2018 (OriginLab, US).

IV. Results

The average SRs from all the experiments are summarized in Table II and the confusion matrices are provided in Fig. 8. The subjects were able to correctly recognize the touched group of pads (test G2G) with a high success rate (SR of 91.25 ± 3.97%). The confusion matrix demonstrates a dominant diagonal line standing for a correct group recognition. From the pattern of misrecognitions in the matrix, it seems that it was easier for the subjects to discriminate between the groups along the transversal axis compared to those along the longitudinal axis. When the subjects made an error, they pointed to a directly neighboring group placed distally or proximally with respect to the correct group (G2 to G4, G4 to G6 etc.), see the second parallel diagonals above and below the main diagonal. Contrary to recognizing the groups, the recognition of the individual pads was not an easy task for the subjects. The overall SR from experiment S2P was 57.9 ± 10.1%. Nevertheless, this SR is still approximately 9 times higher than the chance level (i.e., 1 out of 16 or 6%). The confusion matrix characterizing the transmission of touch on a single sensor (i.e. S2P experiment) exhibited high diagonal values for sensors mapped to pads on the border of the electrode (e.g., pads 13, 15) compared to lower diagonal values for the middle pads (e.g., pads 9, 10). Importantly, the mistakes were typically confined to adjacent pads, and within the same groups of pads. Indeed, when the group level SR was computed from the single pad results, the performance was high ($\sim$ 80%, Table II) although still significantly lower than in a dedicated G2G test ($\sim$ 91%, Table II) and the difference was statistically significant ($p < 0.05$). The mean SR for each group in the S2P experiment is presented in Fig. 9.b. There is tendency for a drop in performance for groups 3 and 4, which are located on the middle phalange; however, the difference was not statistically significant.

The confusion matrix reported in Fig. 8 (Top right) describes the overall SR obtained in experiment SLP. The features of the dynamic

TABLE II
SUMMARY RESULTS (MEAN ± STAND DEV) OF EXPERIMENTS

Test		SR ± standard deviation [%]
G2G		91.25 ± 3.97
S2P	Pads	57 ± 10.1
	group	80.11 ± 9.03
SLP	Line	94 ± 3.57
	Direction	97.95 ± 3

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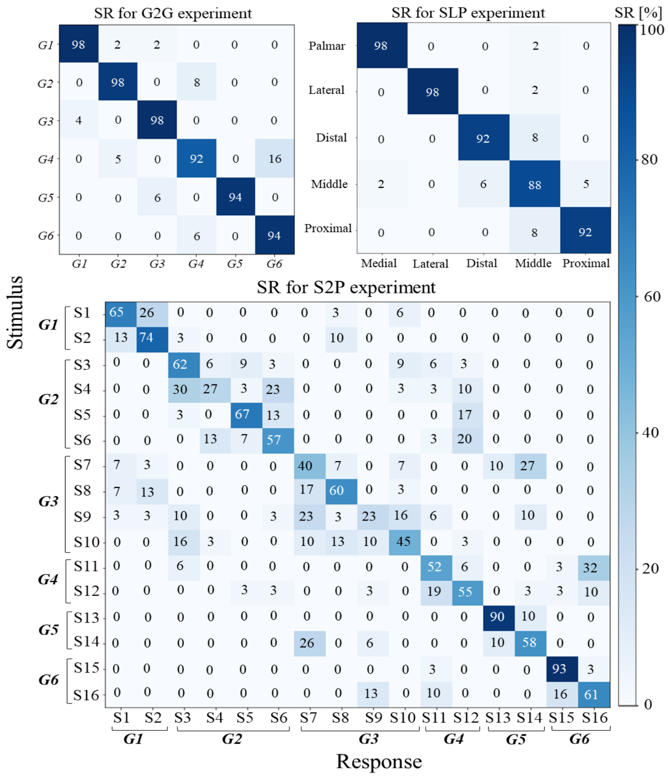

Fig. 8. Confusion matrices for the G2G (Top left) and S2P (Bottom) and SLP experiments (Top right). The results demonstrate a good recognition of 6 classes in G2G experiment, 16 classes in S2P experiment, and 5 classes in SLP experiment (well-focused diagonal line. The confusion matrix of S2P experiment demonstrates the superior performance in recognizing pads on the borders.

patterns (SLP experiment) were recognized with a high success rate. The SR for recognizing the sliding movement (distal, middle, proximal, medial, and lateral) was 94 ± 3.57%. The subjects made most errors when discriminating the transversal lines (Distal, Middle, and Proximal), in particular middle, while Lateral and Medial lines were recognized almost perfectly. The sliding direction was easy to discriminate (97.95 ± 3%). Figure 9.b shows mean SR for each sliding movement in SLP. The bars reflect the trends from the confusion matrix (e.g., lower mean SR for the middle line) but the difference was not statistically significant.

The sensory feedback system operates with a nominal delay between contact time and activation of stimulation of around 32 ms. This delay was not perceived by any of the 6 subjects. The results of the Delay-Exp established that the average detectable delay was 258 ± 49 ms.

V. Discussion and Conclusion

A novel tactile feedback system was developed to transmit mechanical information from a multipoint tactile sensor (e-skin) to the human subject using multichannel electrotactile stimulation delivered through the matrix electrodes placed on the subject's forearm. The system was evaluated by using it to detect mechanical interaction with the e-skin, capture contact events and translate them into spatial profiles of stimulation, which conveyed online tactile feedback to the subjects. We have tested the ability of the subjects to perceive such feedback and estimate the properties characterizing dynamic (sliding line) and static (touch position) patterns of interaction with the e-skin. To the best of our knowledge, this is the first development integrating an advanced tactile sensor with multipoint sensing elements and an electrotactile stimulation unit with a flexible matrix of electrodes into an embedded system for online transmission of tactile data from artificial to the human skin (forearm). As shown in the experiments, such a system allows providing spatially distributed tactile feedback that thereby mimics the natural feedback provided by the limbs (distributed touch).

The power consumption of the interface electronics is 300 mW. When supplied with a single 2 Ah Lithium polymer battery with a voltage of 3.7 V, the battery lifetime expectancy is 22 h of working time, and this includes continuous sampling and processing of tactile signals and sending of commands to the stimulator when contact events are detected. Similarly, the rechargeable battery of the stimulator has a lifetime of 4 h when stimulating constantly. However, considering that the stimulation will be delivered only occasionally, when there is an interaction between the hand and an object, the expected lifetime is substantially longer. The system is therefore economical in terms of power consumption and can provide a long-term usage (> 8 h, the duration of a working day). Importantly, the developed feedback system is modular and other Bluetooth-enabled stimulators could replace the device used in the present study. This would require a change in the firmware of the interface electronics to implement the appropriate communication protocol and possibly remapping/grouping of the pads in case of different number of stimulation channels. In particular, a recently presented system [58] would be an interesting option as it allows simultaneous stimulation and EMG recording, hence a single compact unit that provides both feedback and prosthesis control, respectively. The current interface electronics includes 32 channels, of which 16 have been used in the present experiment. Therefore, 16 additional channels can be exploited to add more sensing arrays placed on other

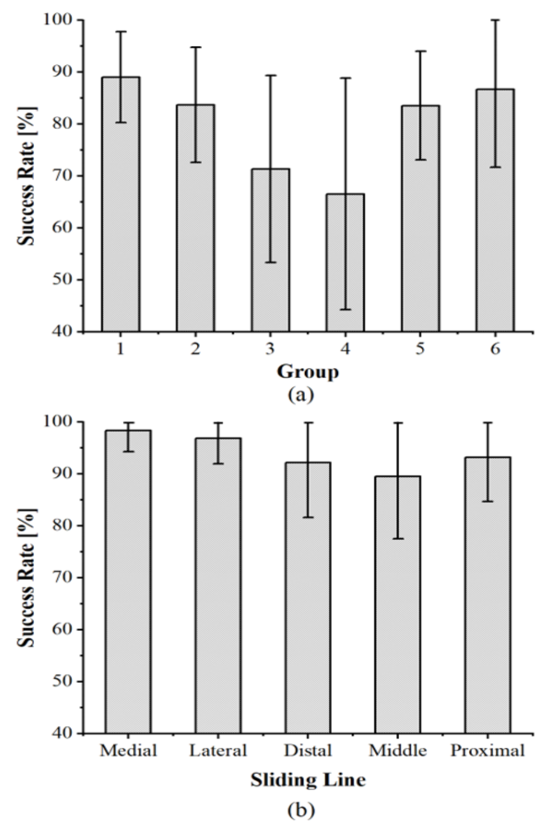

Fig. 9. The overall success rate of recognizing tactile patterns: (a) sensor group in experiment S2P, (b) sliding movements in experiment SLP.

fingers.

The conducted tests have demonstrated that the system indeed provided timely feedback that could be successfully perceived and interpreted by the subjects. The implemented feedback pipeline relies on simple processing, namely, filtering and thresholding, to detect contact and release events, and control the stimulation of the associated pads of the matrix electrode. In all the tests, the feedback was generated by an experimenter interacting with the skin. Such setup activated all components of the feedback pipeline (Fig. 1): sensing, tactile signal processing, wireless transmission, and stimulation. Therefore, the experiments demonstrated that the e-skin was successfully integrated on the mockup and that the pipeline operated properly. In addition, the results were obtained with interaction patterns that included natural variability due to slight variations in the way experimenter touched the skin (e.g., inconsistent timing, different pad activations). The subjects recognized the activation of the six groups of sensors easily and reliably. Importantly, even such low-resolution feedback is functionally relevant since it demonstrates that the subjects can perceive the contact with all relevant finger areas, i.e., volar and lateral aspect of each phalange of the index finger. Such sensorization can facilitate both palmar (pinch) and lateral grasping. In addition, the system detected mechanical interaction, computed and transmitted the online feedback fast enough to allow the subjects to perceive contact information that was dynamically moving across the finger. Consequently, they recognized both location and direction of the dynamic movements with no difficulties. Recognizing the dynamic stimuli might assist in slip detection and prevention [59], as well as in promoting the feeling of embodiment (e.g., the perception of passive touch [48]). The success rate when recognizing individual pads was significantly lower despite the distance between the pads was higher than the spatial discrimination threshold. Nevertheless, this is not surprising considering that the subjects needed to discriminate between 16 randomly stimulated locations spread across a relatively small area of the forearm, while receiving only a brief training. Nevertheless, the mistakes were still confined to the neighboring pads and within the same pad group (finger aspect). The present experiment demonstrated the feasibility of such high-resolution feedback, and it is to be expected that the success rates in this case will increase with prolonged training [32].

The ability of human subjects to identify the position of electrotactile stimuli delivered through the matrix electrode has been investigated in earlier studies [60], [61]. It was found that subjects had more difficulties to discriminate between the groups along transversal compared to the longitudinal axis (Fig. 8 (Top left)), which is in accordance with the results of the present experiment. For the high-resolution feedback, the success rate was variable across pads. The subjects could still recognize some specific sensors quite reliably (Fig. 8 (Bottom)), for instance those located on the border of the electrode, and especially in the corners of the electrode matrix.

The test employed in the dynamic experiment (SLP) are similar to those used to assess the ability of the human subjects to identify the line and direction of motion over the skin to obtain insights into normal human sensory processing [62]. In the present study, while applying a sliding stimulus to the e-skin, the experimenter would occasionally activate sensors and electrodes that did not belong to the target line. This is a likely reason for the worse performance in recognizing the transversal lines with respect to the longitudinal lines since the latter contain higher number of sensors that are also more closely spaced. Hence, the perception of feedback was in this case less affected by an occasional deviation. Moving tactile stimuli can be a particularly effective method for information transmission to the user, because mechanoreceptors respond stronger to this type of stimuli compared to simple static patterns [63]. For example, such perception can be the basis for the haptic exploration of the environment [64], as when the subject tries to assess the texture of an object by relying on artificial tactile stimulation [65]. In this case, the tactile feedback would arise as an interaction between the movements of the user and the objects with which the user interacts.

The response time in communicating sensations has not been widely reported when examining the performance of a sensory feedback system. A healthy nervous system can take approximately 14-25 ms to deliver tactile information to the brain [66]. Some sensory feedback systems were developed with a latency compared to the one of the healthy nervous system. Two sensory feedback systems that are based on FSR sensors and electrotactile [40] or vibrotactile [67] stimulation are capable of delivering tactile information within 15 ms. Authors in [68] used tension sensors integrated on the finger of a robotic hand to measure the applied force. The system can deliver tactile information with a delay of 0.03-0.4 sec. The majority of the aforementioned systems operate with a delay comparable to that of the natural feedback, but they considered simple position and force sensors combined with discrete stimulation channels. The system presented in this study delivers tactile information coming from a multipoint sensing array, which is then wirelessly transmitted to a multipoint stimulation array within a delay of 32 ms. The delay experiment (Delay-Exp) estimated that an extra delay of 250 ms could be added on top of the existing system latency before the subjects noticed the discrepancy between visual and tactile feedback. Therefore, the developed system has a sufficient latency margin to implement more advanced data processing and encoding. The noticeable delay obtained in the present study is larger than what is reported in the recent work [69], however, that study used invasive stimulation and the subjects self-administrated the touch (instead of the experimenter).

In this first study with the developed embedded system, the processing was simple and the information transmitted by the feedback was limited to contact events. As demonstrated in the present experiment, this information can nevertheless lead to diverse patterns of tactile sensations that can be functionally relevant. The next step in this research is to extract further information from the tactile data, e.g., the contact pressure. The sensing array is based on piezoelectric sensors that register only the transient events, but the steady state information could still be extracted by a suitable processing, for instance, from the amplitude of the contact peak. The magnitude of the estimated pressure could be then transmitted to the subject by modulating the intensity of stimulation (in addition to the active pad, as in the present study). In addition, the present assessment considered only a single active pad at a time (static or dynamic), while it would be interesting to investigate if the subjects would be able to detect multiple points of contact. The latter tactile pattern arises during normal human grasping where multiple areas of the finger form contact with an object.

The present study has described the system and demonstrated the feasibility by testing it in able-bodied subjects, while the next step is to assess the utility of the proposed system in a functionally relevant application. To this aim, the sensing arrays will be used to cover a myoelectric prosthetic hand in order to test the closed-loop system during functional tasks. In this scenario, the feedback will be delivered to the residual limb of a prosthesis user, including amputee subjects, in whom the skin sensitivity might depend on the condition of the residual limb (e.g., scar tissue). Nevertheless, this can be addressed by a custom design of the stimulation matrix that can be printed in arbitrary shapes, sizes and pad configurations. Importantly, the developed feedback system is compact and hence suitable for integration in a prosthetic socket. In addition, in the present study, the sensors were produced to fit the layout of the

Michelangelo hand but the technology is flexible enough to cover an arbitrary prosthesis. Endowing a prosthetic hand with such sensing and stimulation interface would enable high-bandwidth connection between the user and his/her bionic limb, especially if the system would include a full set of sensing arrays that covers both fingers and palm of the prosthetic hand (as proposed in [70]). The provided high-density feedback could increase the utility of the device as well as facilitate the feeling of embodiment.

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Yahya Abbass (YA) (GS'18) received a B.S. degree in Electronic and an M.Sc. degree in Signal, Telcome, Speech, and Image in 2016 and 2018, respectively, from the Faculty of Science, Lebanese University. From June to August 2018 he was an Internship at ULCO University France. Currently, he is a PhD student in Science and Technology for Electronic and Telecommunication Engineering at the Department of Naval, Electrical, Electronic, and Telecommunications Engineering (DITEN) of the University of Genoa. His main research interest includes Deep Learning, integrated sensing systems, electronic tactile sensors, and feedback systems in prosthetics.

Moustafa Saleh (MS) Moustafa Saleh received his M.S. degree in Signal, Telecommunication, Image and Speech at the Lebanese University in 2014. Currently, he received his Ph.D. degree at the Department of Electric, Electronic, Telecommunication engineering and Naval architecture (DITEN) at the University of Genoa, in joint supervision with Lebanese University. His research interests include the development of interface electronics for electronic skin systems, embedded machine learning and FPGA implementation.

Strahinja Dosen (SD) received the Diploma of Engineering in electrical engineering and the M.Sc. degree in biomedical engineering in 2000 and 2004, respectively, from the Faculty of Technical Sciences, University of Novi Sad, Serbia, and the Ph.D. degree in biomedical engineering from the Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark, in 2008. Until 2011, Dr.Dosen was an Assistant Professor at the same Department. Between 2011 and 2017, he was working as a Research Scientist at the Institute for Neurorehabilitation Systems, University Medical Center Gottingen (UMG), Germany. Currently, he is an Associate Professor at the Department of Health Science and Technology, Aalborg University, Denmark, where he leads a research group on Neurorehabilitation Systems. His main research interest is in the closed-loop control of movements and assistive systems, including human-machine interfacing, control of bionic limbs and rehabilitation robotics, artificial sensory feedback, and functional electrical stimulation. He is a member of the IEEE Engineering in Medicine and Biology Society.

Maurizio Valle (MV) (SM'16) Maurizio Valle (MV) received the M.S. degree in Electronic Engineering in 1985 and the Ph.D. degree in Electronics and Computer Science in 1990 from the University of Genova, Italy. In 1992 he joined the University of Genova, first as an assistant and in 2007 as an associate professor. From December 2019, MV is full professor of Electronics at the Department of Electrical, Electronic and Telecommunications Engineering and Naval Architecture, University of Genova where he leads the Connected Objects, Smart Materials, Integrated Circuits – COSMIC laboratory. MV has been and is in charge of many research contracts and projects funded at local, national and European levels and by Italian and foreign companies. Professor Valle is co-author of more than 200 papers on international scientific journals and conference proceedings and of the book: Robotic Tactile Sensing Technologies and System, Springer Science+Business Media, Dordrecht, pp. 1–248, 2013 (ISBN: 978-94007-0578-4). He is IEEE senior member and member of the IEEE CAS Society. His research interests include bio-medical circuits and systems, electronic/artificial sensitive skin, tactile sensing systems for prosthetics and robotics, neuromorphic touch sensors, electronic and microelectronic systems.