A wearable pneumatic platform to automatically assess tactile sensitivity

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***Abstract*—Sensory deficits caused by neurological disorders, *i.e.*, loss of tactile sensitivity and/or limb proprioception, hinder object manipulation and precise movements, and ultimately lead to a significant slow-down in motor rehabilitation. Although sensory rehabilitation has been catching on more and more, current procedures for evaluating tactile sensitivity are still inefficient in terms of equipment portability, test execution time, and specific training required for healthcare personnel. While some automated tactile stimulation platforms have been developed for other applications, robotic systems designed to evaluate residual tactile sensitivity are still largely under-explored. Here we propose a hand-wearable, pneumatically-driven device, which exploits an air chamber to transmit contact forces to the user's fingertip by means of sliding pin, which can then be used to assess tactile sensitivity in a quantitative and reproducible manner. We tested the proposed platform on five healthy participants, and obtained pressure perception thresholds in the order of 0.01 bar, with a median of ~ 0.03 bar, which showed a good correlation ($\rho = 0.8441$) with the Semmes-Weinstein test. Although these results are preliminary, they suggest the potential of the proposed device as a complementary assessment tool of tactile sensitivity.**

***Index Terms*—Design and development in rehabilitation robotics, Wearable robotic systems, Integrated diagnostic and therapeutic systems**

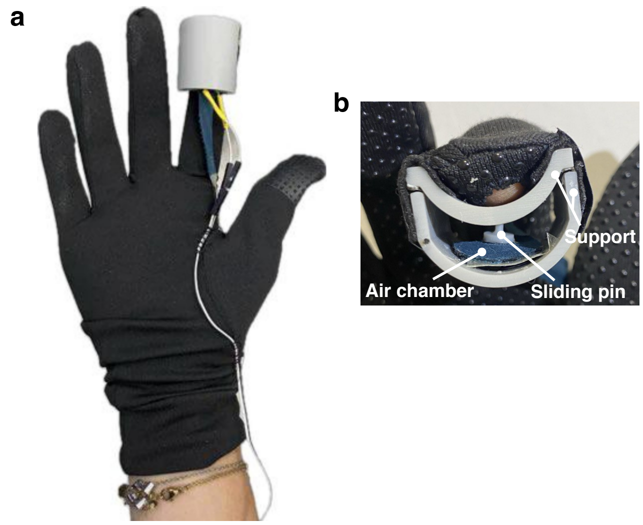

Fig. 1. a) The developed fingertip module, mounted on a fabric glove and worn by a user. b) Upper view of the fingertip module: a custom support hosts an air chamber, which is attached to a sliding pin.

I. Introduction

Neurological disorders, such as stroke, spinal cord injury, multiple sclerosis, and other neurodegenerative diseases, lead to motor impairments: reduction in voluntary motor control, anomalous muscular contractions, worsening of motor coordination, muscle weakness, and longer reaction times, among the others [1]. However, sensory deficits, *i.e.*, loss of tactile sensitivity and/or limb proprioception, may also arise. For instance, 85% of post-stroke patients suffer from some form of reduced tactile or proprioceptive sensitivity [2].

In turn, a chronic loss of sensitivity hinders the execution of fine and complex movements [3], such as object manipulation and precision movements [1, 2, 3], thus significantly hampering the overall progress in motor rehabilitation [4]. While restoration of muscle strength and motor coordination is paramount, rehabilitation strategies should then also focus on somatosensory recovery. In this regard, next to motor rehabilitation therapy, also sensory rehabilitation – where patient's discrimination of tactile stimulations is evaluated and trained – has been catching on more and more in recent years [3]. However, following clinical focus groups, we believe that current procedures for evaluating tactile function – Semmes-Weinstein monofilament test, two-points acuity, JVP domes – are not optimized. Although they are virtually widespread, limited equipment portability, long test execution time, and specific training required for healthcare personnel hamper their efficiency and thus their application. While some automated tactile stimulation platforms have been developed for other applications (such as tactile stimulation during MRI studies [5, 6] and augmented feedback in virtual reality [7, 8]), robotic systems designed to evaluate residual tactile sensitivity after a brain lesion still lay uncharted.

In this study, we report on the development of a hand-wearable, pneumatically-driven device (shown in Fig. 1a), designed to evaluate residual tactile sensitivity in a streamlined fashion. The system is made of a fabric glove endowed with a fingertip stimulation module, which hosts a pneumatic

This work was co-funded by INAIL (the italian National Workers' Compensation Authority) under the HANDeVAL project (G.A. PR23-SV-P1). The work of L.C. was co-funded by the European Union (ERC, MUSE, G.A. 101116249). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

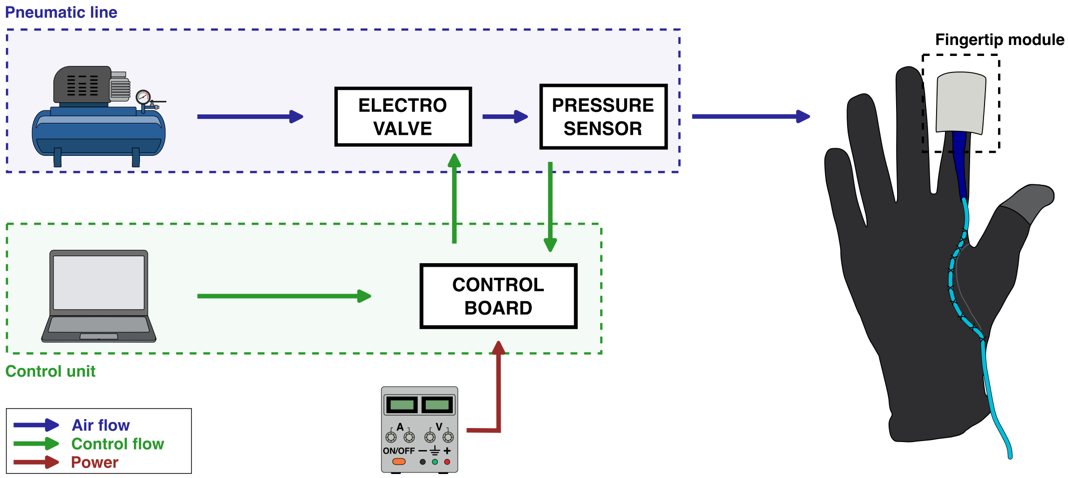

Fig. 2. Schematic of the proposed platform. A PC sends control inputs to a control board, powered by an external supply, which operates the inlet electrovalve connected to an external air compressor. According to the set target, the control board regulates the pressure of the fingertip module by controlling in closed loop the air flow from the inlet electrovalve.

chamber that, upon pressurization, transmits a contact force to the user by means of a sliding pin (Fig. 1b), which can be used to assess their tactile sensitivity in a quantitative and reproducible manner. After a characterization of the relationship between chamber's pressure and exerted force, we tested the proposed platform on five healthy participants to compare its performances against the Semmes-Weinstein monofilament test, which is regarded as the gold standard in assessing tactile sensitivity [9, 10].

The remainder of this paper is organized as follows. In Section 2, we outline the architecture of the device and report its manufacturing steps. In Section 3, we describe the workbench characterization procedure of the device as well as the experimental protocol for tests on healthy participants. In Section 4, we report the device characterization curve and discuss the results of tactile sensitivity tests, comparing them with the Semmes-Weinstein test. Finally, in Section 5 we draw our conclusions, highlighting some limitations of the proposed device and outlining possible future directions.

II. Device Architecture

Our device consists of a wearable fabric glove endowed with a fingertip stimulation module, which is composed of an inflatable air chamber, a retractable sliding pin placed on top of it, and a 3D-printed custom support to house them (see Fig. 1b). Upon pressurization, the air chamber inflates and pushes the pin in contact with the user's fingertip, thus transmitting a contact force that can be controlled by modulating the pressure of the system. In this way, it is possible to administer a reproducible stimulation to infer the tactile sensitivity of the user.

The full system is composed of a pneumatic line (from an air source to the chamber), the fingertip stimulation module (support, chamber and sliding pin), and a control unit (a microcontroller and a PC) connected to an external power supply (see Fig. 2). A detailed description is given in the remaining part of this section.

A. Pneumatic Line

The pneumatic line comprises a commercial air compressor integrated with a pressurized air reservoir, two solenoidal electrovalves to regulate inlet and outlet flows, a custom air chamber and a pressure sensor. We used a proportional valve (PVQ13-5L-08-M5-A, SMC, Japan), controlled in pulse-width modulation (PWM), to regulate the inlet air flow and in turn the inner pressure in a continous way, while we adopted an ON/OFF valve (VZ110-5MOZ-M5-Q, SMC, Japan) for the exhaust line.

B. Fingertip Stimulation Module

The air chamber was designed with an oval shape, to better adapt to a fingertip, and realized using a commercial polyester fabric coated in thermoplastic polyurethane (TPU), to have an airtight yet flexible material that allows quick inflation-deflation, while minimizing distal encumbrance and weight. Two layers of the TPU-coated fabric, spaced by an insulation layer cut in the desired chamber profile, were heat-sealed using a heat-press (TC7 SMART, Secabo, Germany), running at 140 °C for 20 seconds, in order to form an airtight bladder (see Fig. 3a). The excess material was then cut out, and a plastic tube of 2 mm in diameter was inserted in the chamber and fixed using superglue and sodium bicarbonate.

The chamber was then embedded in a commercial fabric glove at the level of the right index fingertip, by means of a custom 3D-printed support fastened with an elastic band: the air chamber is housed inside the support, and a custom-made pin is placed on top of it (see Fig. 3b). The side of the support in contact with the skin presents a central through-hole, which allows sliding motion of the pin: upon actuation of the chamber, the pin slides through the hole and comes into contact with the user's skin. Finally, to avoid pre-stressing the target skin area with a continuous contact pressure, the surface of the support was grooved around the through-hole and, to allow a direct contact between the skin and the pin, a portion of the glove fabric was cut out.

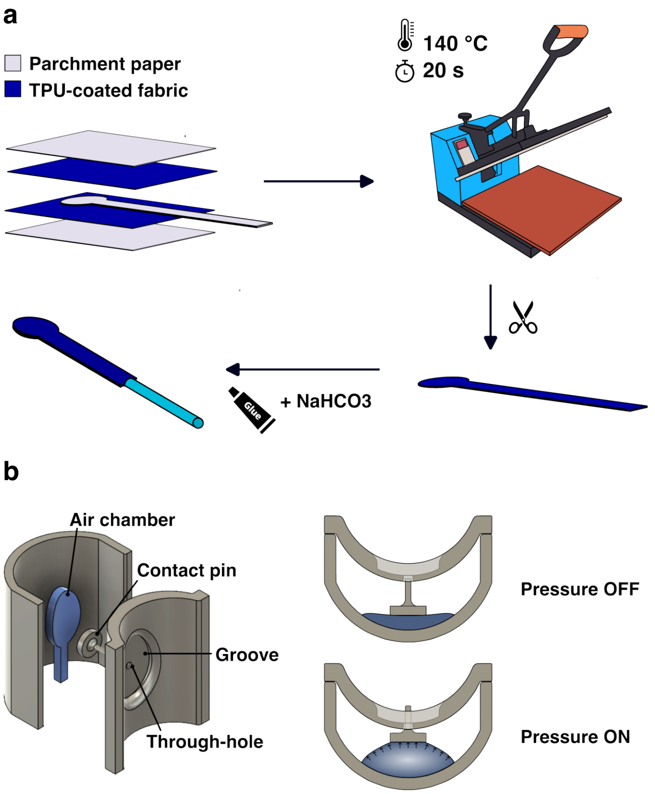

Fig. 3. a) Schematic of the fabrication process of the air chamber. Layers in the heat-press were arranged as follows: parchment paper as an insulation layer, first TPU-coated fabric layer, a piece of parchment paper shaped like the chamber profile, second TPU-coated fabric layer, and a last layer of parchment paper. After the heat treatment, the desired profile was cut from the bonded layers. Finally, a plastic tube was inserted and glued into the elongated portion of the chamber. b) CAD of the custom support, printed in a photoresistive resin. Upon pressurization, the air chamber pushes the pin that slides through the support and comes into contact with the skin.

C. Control Unit

A commercial board (UNO R3, Arduino, Italy) was used to monitor and control the inner pressure of the air chamber in closed-loop, implementing a PID controller. The chamber pressure is read with an absolute pressure sensor (ELVH-150A-HAND, Amphenol All Sensors, US) and the difference between the read value and a target one, set via software, is fed to a PID function; finally, the output of the PID is used as the duty cycle value of the PWM voltage signal that drives the inlet proportional valve, thus closing the control loop.

Based on the literature [11], we modeled the air chamber with a third-order transfer function and fitted its parameters according to the system's response to a chirp signal. Specifically, the proportional inlet valve received as input a PWM signal with duty cycle D given by

$$D(t) = 0.5 + 0.5 \sin\left(2\pi \left(f_0 + \frac{f_1 - f_0}{T} t\right) t\right) , \quad (1)$$

that is, an up-chirp where $f_0 = 0.001\,\mathrm{Hz}$ is the initial frequency, $f_1 = 50\,\mathrm{Hz}$ is the final one, and $T = 30\,\mathrm{s}$ is the duration of the signal. The pressure output corresponding to the chirp input was then imported in MATLAB 2023a (The MathWorks, US), and the System Identification Toolbox was used to determine a third-order transfer function. Finally, using the obtained model for the air chamber, PID parameters were tuned by means of the PID Tuner app in MATLAB ($P = 149.28$, $I = 300$, $D = 9.17$).

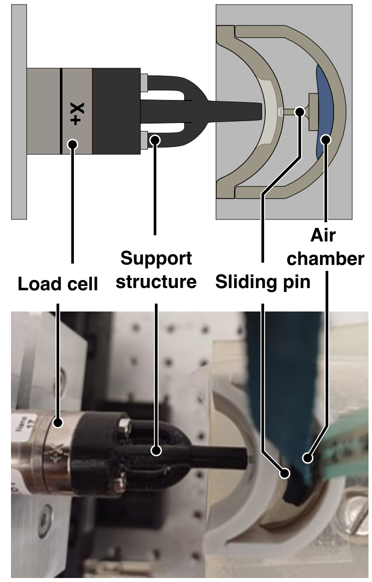

Fig. 4. Experimental setup for the pressure-force characterization of the system. A 3D-printed support was mounted on a load cell and interfaced with the sliding pin in order to measure the force exerted upon pressurization.

III. Experimental Validation

A. Device Characterization

We characterized the relationship between the air chamber's inner pressure and the contact force exerted by the pin using a load cell (Nano17, ATI Industrial Automation, US). The fingertip module was positioned in front of the load cell, so that the through-hole was centered with it. Upon pressurization of the air chamber, the pin slid and came into contact with a custom 3D support mounted on the load cell, which read the exerted force (see Fig. 4). We measured this force 5 times for each of 20 inner pressures, ranging from 0.1 to $1.3\,\mathrm{bar}$.

B. Tests on Healthy Participants

To have a preliminary validation of our device, we recruited five healthy participants (24-29 yrs, 4 males and 1 female). Experiments were conducted under the Declaration of Helsinki and the guidelines of the Ethics Committee of the Scuola Superiore Sant'Anna (Approval No. 10/2023).

At the beginning of the experimental session, we assessed the participant's tactile sensitivity at the right index fingertip by administering the Semmes-Weinstein monofilament test, expressed in gram-force (gf) [9, 10]. We then used our platform to measure their tactile sensitivity in terms of amplitude perception threshold, that is, the minimum perceivable stimulus upon indentation of their fingertip, according to the following experimental protocol.

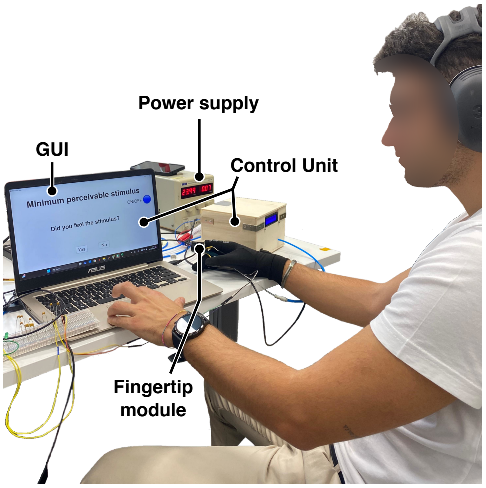

Fig. 5. Example of an experimental session with the proposed device.

Experimental Protocol: Participants were asked to wear the device on their right hand, and the fingertip module was mounted on their index. Additionally, participants were asked to wear a noise-canceling headset during the experiments, to avoid biases due to the noise produced by electrovalves. Tests followed a Two-Interval Forced Choice (2-IFC) procedure. Each trial was made of three phases: a first stimulation window, a short interval, and a second stimulation window. Participants received an actual tactile stimulus in one of the two windows, randomly chosen, and no stimulation (null stimulus) in the other one; they were then asked to indicate in which of the two windows they had perceived a tactile event (see Fig. 5), by means of a custom MATLAB GUI adapted from [12]. The amplitude of the following stimulation was then adaptively modified by means of a Stochastic Approximation Staircase (SAS) algorithm. After 50 trials, the perception threshold was selected as the stimulus amplitude adjusted for the hypothetical 51^{st} trial [13].

IV. Results and Discussion

A. Force-Pressure Calibration Curve

The force-pressure curve obtained from the load cell characterization (see Fig. 6) was highly linear ($\rho = 0.9986$) and had low variability (average IQR $= 0.0116$). This result suggests that the device is capable of exerting a normal contact force in a reliable manner without noticeable non-linearities, despite the presence of the soft air chamber, a characteristic that is particularly desirable for the automatic control of the system.

B. Comparison of Sensitivity Thresholds

Sensitivities measured with the monofilament test ranged from 0.02 to 0.07 gf, with a median of 0.04 gf (IQR 0.04-0.04); pressure perception thresholds obtained with our device were in the order of 0.01 bar, with a median of 0.034 bar (IQR 0.031-0.068) (see Table I and Fig. 7 for complete results). Although not statistically significant ($p > 0.07$), results of the two tests showed a high correlation

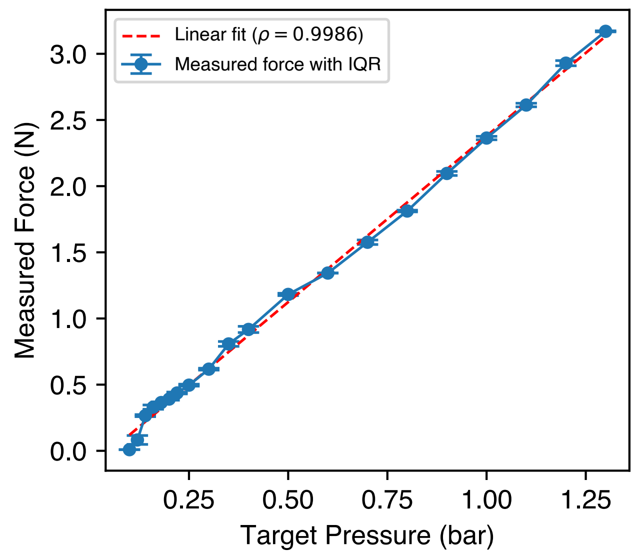

Fig. 6. Pressure-force characterization curve (median with interquartile range, IQR, blue curve) with its linear fitting ($\rho = 0.9986$, red dashed curve).

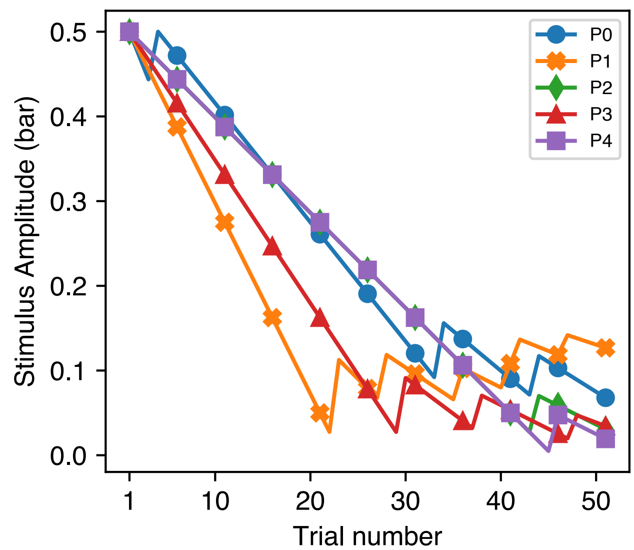

Fig. 7. Staircase stimulation curves of the five participants, where the amplitude adjusted for the hypothetical 51^{st} stimulus is selected as the threshold.

TABLE I
Sensitivity Thresholds Comparison

Participant	Semmes-Weinstein (gf)	Device (bar)
P0	0.04	0.07
P1	0.07	0.13
P2	0.02	0.03
P3	0.04	0.03
P4	0.04	0.02
Median	**0.04**	**0.03**

($\rho = 0.8441$); the unexplained variance could be due to the intrinsic differences in their psychophysics. Specifically, the monofilament test involves a single ascending method of limits where, for the lowest-force filaments ($< 1.4\,\mathrm{gf}$), it is possible to perform up to three stimulations before proceeding to the next filament. Therefore, it is sufficient to perceive only one out of three consecutive stimulations to declare the investigated force as the sensitivity threshold. On the other hand, we implemented an adaptive staircase method to estimate the threshold above which the user has a probability to correctly identify the stimulus ≥ 0.85 [13].

Additionally, the monofilament test has an intrinsic subjective component: to leverage the buckling of the filament, the examiner should approach its critical load in a quasi-static fashion. Since it is not possible to accurately control the speed of indentation, the level of exerted force could cross the critical load, effectively exerting a force higher than intended. Moreover, a higher stimulation rate could elicit different recruitments of mechanoreceptors: the Semmes-Weinstein test, which consists in tapping the participant's fingertip, could excite mainly "fast-adapting" mechanoreceptors, while our device, based on a pneumatic actuation system that exhibits a slower dynamics, could recruit mainly "slow-adapting" ones, characterized by a lower sensitivity [14].

Finally, the prototype nature of the device plays a role, too: at low inner pressures, friction could hamper sliding motion of the pin, making it fail to properly contact the user's skin.

V. Conclusions and Outlook

We developed a wearable pneumatically-driven device for the assessment of tactile sensitivity, which exploits a small air chamber to transmit a indentation force to the user's fingertip. The proposed platform can be used to assess the tactile perception threshold of the user in an automated and repeatable fashion, at a controllable rate and intensity.

Experimental results on five healthy participants showed an overall satisfying performance and suggested the potential of the device as a complementary clinical assessment tool. However, this preliminary investigation also highlighted some limitations to be addressed in future work: increasing the portability of the system, optimizing the fingertip module, and using a direct force measurement as a feedback signal.

In future studies, we aim to increase the number of participants, the number of stimulation modules to target other areas of the hand that can be addressed with the monofilament test, as well as to adapt the device to assess tactile acuity, possibly increasing the number of pins on the same location.

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