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Design and Psychophysical Evaluation of a Tactile Pulse Display for Teleoperated Artery Palpation

L. Santos-Carreras, K. Leuenberger, P. Rétornaz, R. Gassert and H. Bleuler

Abstract— **During traditional open procedures, surgeons directly palpate tissues before dissecting them. In this way, they can avoid the accidental damage of hidden arteries that can lead to fatal hemorrhage. New Minimally Invasive Surgical (MIS) techniques progressively decreased the instrument access into the patient's body to reduce scars and side effects. The major drawback of these procedures is that they do not permit surgeons to perform direct tactile exploration of internal tissues. Surgeons have to rely on preoperative images and anatomical knowledge to avoid artery locations. However, the exact artery position changes depending on the patient and his posture. Hence, it is of primary importance to assist surgeons with technology that can guide them during the surgical procedure. This paper presents the design and evaluation of a tactile display that reproduces pulse-like feedback on the surgeon's fingertip. The display bandwidth and performance of the ad-hoc control unit were assessed with encouraging results. In addition, the outcome of two psychophysical studies carried out in this work validate the usability of the display in terms of user perception.**

I. INTRODUCTION

Laparoscopy is currently the most established procedure in minimally invasive surgery (MIS). However, more recent techniques such as SIL (Single Incision Laparoscopy) and NOTES (Natural Orifice Translumenal Endoscopic Surgery) are gaining interest and application in the medical community [1]. These clinical techniques have the same advantages as classical MIS procedures such as faster recovery, shorter hospitalization and lower post operative pain. In addition, they improve the cosmetic result, which has been found to be a determining factor for patients [2]. Since the access to the abdominal cavity of the patient is being progressively reduced, new instruments such as; laparoscopic tools, endoscopes or surgical robots, access the patient while the surgeon's hands remain outside the body. Therefore, haptic feedback during the surgical procedure is greatly reduced in laparoscopic interventions [3], and lost in most current robotic surgical systems as they do not provide force or tactile feedback [4].

The sense of touch has been an essential tool for surgeons while performing open surgery, providing crucial information on the applied forces, tissue properties and vessel/organ arrangement. During MIS, surgeons perform delicate dissections relying mostly on visual feedback. It has previously been shown that visual cues can convey crude haptic information, such as visual changes of the tissue or signs of force on the robot end effector, inferred through deformations of the tissue and tool. However, it is doubtful that visual cues alone give reliable information about tissue properties [5]. Moreover, surgeons must continuously focus on the screen to effectively interpret visual cues, which could result in an overload of this modality, or reduced focus on the other modalities.

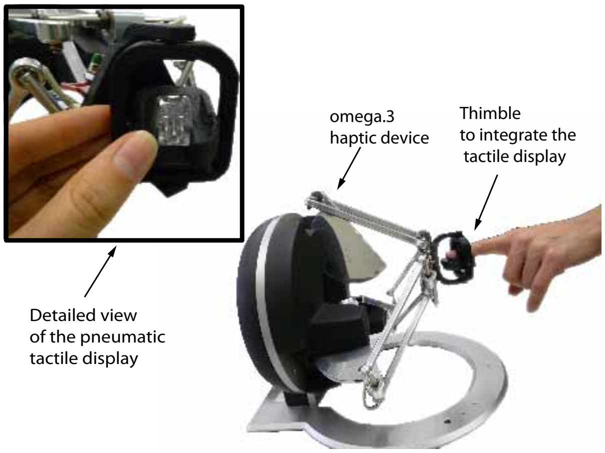

Fig. 1. Haptic workstation providing both kinesthetic and tactile feedback during teleoperated artery palpation (*omega.3* device from *Force Dimension*, Nyon, Switzerland).

The lack of haptic information prevents surgeons from performing organ palpation to localize hidden anatomical structures. During surgical procedures, palpation is often carried out in order to determine the position of arteries. This task is regularly performed to locate needle insertion sites for regional anaesthesia, or to prevent accidental rupture of arteries. The absence of haptic feedback introduced by the new surgical trend inspired our research on a device that could allow surgeons to perform palpation during teleoperated surgery (Fig. 1).

Restoring the surgeons sense of touch through tactile feedback is a challenging task that has seen increasing effort in the last two decades. However, technical developments on tactile devices are still basic and have rarely been integrated with kinesthetic feedback devices [6].

Much effort has been made in the last years to develop new tactile sensors allowing to find hidden anatomical structures beneath opaque tissues such as tumors and arteries. Different techniques such as arrays of capacitive sensor elements [7][8], arrays of resistive sensors [9], ultrasonic probes [10]

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and piezoelectric based sensors [11], can be used to measure such tactile properties inside of patient's body. The resulting tactile information should be represented in an intuitive and useful manner. Overloading by useless information has to be avoided in the OR (Operating Room). The exponential growth in the number of physiological variables that are generally conveyed through the visual and auditory displays of the OR, increase the cognitive load on the clinician [12]. This audio-visual overload motivates providing this information over other modalities, in this case specifically haptics (including tactile and kinesthetic feedback), as this is the sense that is aimed to be restored.

Currently, the majority of telepalpation systems represent the measured tactile information visually [6][7][11]. According to our knowledge, only two research groups, Culjat *et al.* and Ottermo *et al.* employed a tactile display to represent tactile information, employing pneumatic balloons and DC motors for the actuation [13][8]. Although these devices look promising, they are usually intended to reproduce several types of tactile features at the same time (multi-purpose displays), which is excessively challenging for current technology and thus, the tactile sensation conveyed is generally not realistic.

The proposed tactile display is used in an OR and must comply with safety requirements for conventional OR instruments. This constraint implies that many of the standard actuation methods used in tactile displays (electro-reohological fluids [14], DC motors [8], piezoelectric actuators [15][16] and shape memory alloys [17]) are not applicable.

Since it is assumed that the surgeon will hold a tool through the display, which needs a certain pressure, the force produced by the actuators of the display should be, at least, of similar magnitude. In addition, the tactile display should be compact and light to be integrated into the surgical workstation. Consequently, displays based on pneumatic actuation are preferred due to their OR compatibility, light weight and because they can realistically simulate artery pulsation. Moreover, the majority of ORs normally feature a pressurized air access point.

This paper presents the fabrication of a pneumatic tactile pulse display and its technical and psychophysical evaluation. A thimble has been designed to attach the pulse display to the endpoint of a commercial force feedback device, integrating both tactile and kinesthetic information in an intuitive way (Fig. 1). This setup will allow the assessment of the kinesthetic-tactile feedback benefits on this specific task. A virtual test-bed, will be used to measured user's performance during a palpation task under different feedback conditions. The final application scenario of this kinesthetic-tactile feedback device is the master console of a teleoperated robotic surgical system.

II. MATERIALS AND METHODS

A. Moulding of the tactile display

The dimensions of the display were chosen according to the anthropometric data for the fingertip, (i.e. a fingertip breadth of 22 mm corresponding to the $95\%^{ile}$ of the population) [18]. In addition, a key issue for the design consisted in minimizing the size and mass of the display to obtain a good dynamic performance of the force feedback interface. The final dimensions were of $22 \times 14 \times 11$ mm.

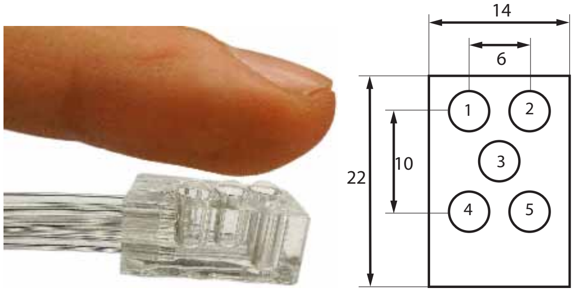

Fig. 2. a) Tactile pulse display rendering a diagonal line. b) Balloon arrangement (distances in mm).

The use of pneumatic actuators limits the actuator density on the display. Therefore, the optimal actuator arrangement is a major issue of the display design. Culjat *et al.* used a 3×2 matrix with $1.5 - 4$ mm of diameter balloons [19]. However, it is important to highlight that in this application, the tactile display will not be used to display textures but to display local pulse. Therefore, providing the artery orientation relative to the tactile sensor is more important than representing its exact shape, which is generally known.

In previous psychophysical studies with pneumatic tactile displays, it was found that a minimum distance between actuators of 4 mm should be guaranteed to allow discrimination between two stimuli on the fingertip [20]. Consequently, and also taking the display size into account, a $2 - 1 - 2$ configuration is assumed to be ideal since diagonal, vertical and horizontal lines can be represented by actuating different groups of balloons (Fig. 2).

The proposed tactile pulse display was fabricated from Polydimethylsiloxane (PDMS) (*Sylgard* 184, Dow Corning) often used for micro fluidic applications. The tactile array consists of five air chambers in a silicone block, covered by a 300 μm thin film of the same material. When pressure is applied at the input of the air chamber, the thin membrane is inflated to a balloon-like shape.

Since spin coating procedures result in non-uniform films [19], the production of the thin silicone film was realized using an injection molding procedure which guarantees a uniform surface. Both the silicone block and the film were manufactured using acrylic molds in combination with aluminum pins to realize the air channels and chambers (Fig. 3).

The two PDMS parts were bonded using a layer of uncured PDMS, which has been shown to be one of the strongest bonding techniques for PDMS [21][22]. The resulting connection proved to be very durable, supporting pressures up to 3 bar.

B. Control unit development

The task of the pressure control unit used in this device is to distribute a global input pressure of 1 bar to the

Fig. 3. Acrylic molds for tactile display fabrication.

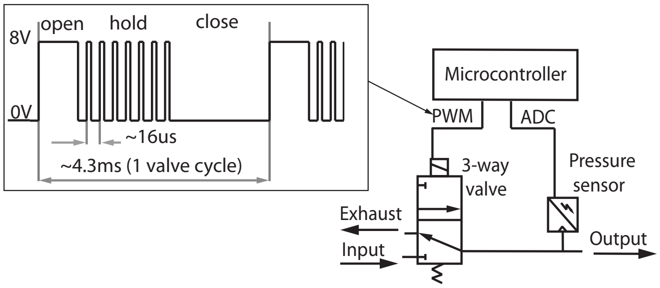

Fig. 5. Pressure control unit and optimized command signal to reduce valve switching time.

five balloons and regulate the pressure in each balloon independently between 0 and 3 bar.

Other solutions actuated through electromagnetic pressure regulators or proportional valves were discarded based on cost, complexity and volume criteria. The proposed control scheme for each balloon is composed of a one 3-way solenoid valve regulated by a PWM signal, and a pressure sensor. The selected valves (Parker X-Valves), require low power (less than 1 Watt), are very compact and can be directly mounted on the PCB.

1) Electronic design: The control unit consists of two printed circuit boards (Fig. 4). The first one includes the microcontroller, power, Bluetooth-USB communication and programmer, while the second one contains the valve specific circuitry. A Digital Signal Controller (DSC) (dsPIC33FJ128MC706) was chosen as microcontroller. The communication with the computer is performed over the UART (Universal Asynchronous Receiver/Transmitter), and then converted to Bluetooth or USB connection. Each valve is driven using a MOSFET (IRLML2402) that can support continuous currents up to 1.2 A, thus guaranteeing the required power (1 W).

Integrated pressure sensors (MPX5100) are used in order to monitor the pressure inside each balloon and close the feedback loop. This sensor returns a voltage within the range of $0.2 - 4.7$ V that is linearly dependent on pressure. However, the analog to digital converter (ADC) of the microcontroller, works within the range of $0 - 3.3$ V. Therefore, the sensor signal is scaled down by a factor of 0.7 by adding a voltage divider and thereafter passed through a lowpass filter to remove high-frequency components and prevent aliasing in the digital domain. The exact pressure (P) in mbar can be calculated from the ADC input (ADC_{in}) in the following way:

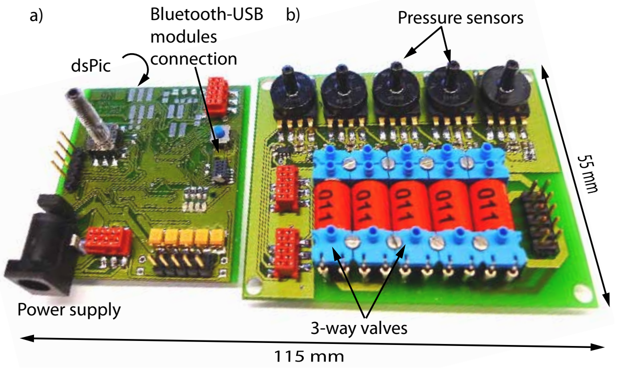

Fig. 4. Control unit PCBs: a) power electronics, MCU, programmer, and bluetooth communication with the computer, b) specific pressure control circuitry and electromagnetic valves.

$$P\,[\text{mbar}] = (\text{ADC}_{in} - P_{off}) \cdot \frac{\text{ADC}_{FSO}}{\text{ADC}_{res}} \cdot \frac{R_1 + R_2}{R_2} \cdot \frac{1}{S} \quad (1)$$

where ADC_{FSO} is the full scale output on the ADC (3.3 V), ADC_{res} is ADC resolution (12 bit), P_{off} is the pressure sensor offset (0.2 V), R_1 and R_2 are the divider resistors values and S is the sensitivity of the sensor (4.5 mV/mbar).

2) Firmware : An important part of the pressure regulation is implemented on the microcontroller firmware. The nominal opening time of the chosen valves is quite high (around 20 ms). For this reason, the opening time is reduced down to 0.3 ms by using a higher control voltage at the beginning of each opening cycle. The valve is powered through a transistor that can be switch using a PWM signal with a frequency high enough to keep the current flowing through the solenoid, in this case 60 kHz. This signal allows modulating the mean valve voltage from 7 V to 3.3 (Fig. 5).

To regulate the air flow through the valve, the ratio of the durations of the hold and close phases are changed. This is achieved by modulating the pulse width of the 60 kHz signal at a lower frequency (230 Hz). Taking into account the delays introduced by the valve when opening and closing (0.3 ms and 2.5 ms respectively), the effective resolution of the pressure regulator (CtrlRes) can be obtained as:

$$\text{CtrlRes} = 60\text{kHz} \cdot \left(\frac{1}{0.23\text{kHz}} - 2.5\text{ms} - 0.3\text{ms} \right) \simeq 92 \quad (2)$$

Consequently, the air flow through the valves can be controlled to 92 different levels. This part of the firmware replaces complicated electronics that would require two different voltage sources, several transistors, timer ICs and additional circuitry. The software solution allows easy timing adjustments and results in a smaller, less sophisticated and cost-efficient circuit board.

As can be seen in Fig. 6, non-linearities were observed during valve opening due to the solenoid inertia. Therefore, a conventional PID is not suitable to control the air pressure

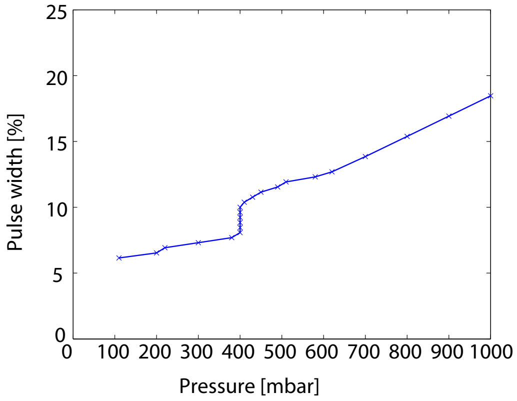

Fig. 6. Pressure output with respect to the PWM signal sent to the valve. Please note the non-linearity produced at 400 mbar

with sufficient precision. Stable and accurate control could only be achieved for either low or high pressures, but never both with the same PID settings producing either insufficient or unstable outputs for the rest of the pressure range (Fig. 7).

By determining the relationship between control output and the resulting pressure, a feedforward model was implemented to support the PID controller. Pressure was measured for different pulse widths of the valve control signal, analyzed and then linearized in two regions to generate the feedforward command (Fig. 8). Feedforward control was combined with feedback control because a second loop is required to track setpoint changes and to suppress the unmeasured disturbances that are always present in any real system. In the most ideal situation, feedforward control should entirely eliminate the effect of the measured disturbance on the output. As can be seen in Fig. 7, even when there are modeling errors, the feedforward control reduces the effect of the measured disturbance on the output better than that achievable by using a PID alone.

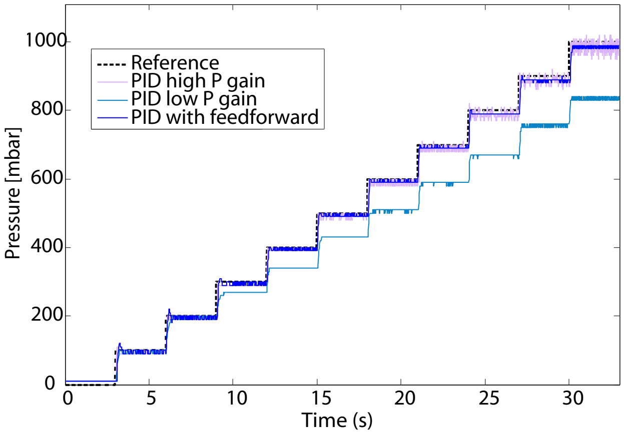

Fig. 7. Pressure output for different control approaches over the working range of the display. Note that when a simple PID is applied, the output produced cannot follow the reference signal properly for both high and low pressures due to the non linearity found produced around 400 mbar

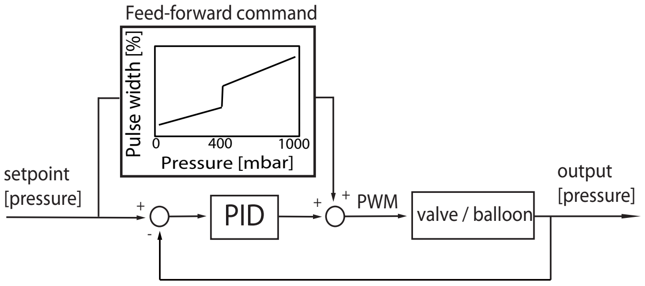

Fig. 8. Linearization of pressure response in two regions ($0 - 399$ mbar and $400 - 1000$ mbar) to implement the feedforward model.

III. DISPLAY CHARACTERIZATION

A. Deformation versus pressure

The tactile pulse display was characterized using a pressure regulator (FESTO MPPES-3-1/4-6-010). The pressure inside the balloons was controlled over a range of $0 - 2$ bar in steps of 0.2 bar and the corresponding deflection was measured for each pressure value. Results showed that balloons deformation is approximately linear for pressures up to 1 bar and that the deformations are uniform for all the balloons as it can be seen in Fig. 9. The non-uniform deformation of the 4 mm diameter balloons that was reported in [19], was solved in the present design thanks to the the new method used to produce the silicone film.

B. Display bandwidth

The major drawback of using 3-way valves instead of pressure regulators is the resulting vibrations caused by the PWM control of the solenoid. Vibrations are transmitted to the surface of the tactile display and can thus be perceived by the user. To overcome this problem the output of each valve is filtered by an adjustable flow limiting resistance that squeezes the transmission tubes. However, this method also reduces the responsiveness of the balloons, lowering the bandwidth by a factor of almost ten as shown in Fig. 10. This does not represent a drawback as the highest frequencies used to display a pulse-like signal are generally below 5 Hz.

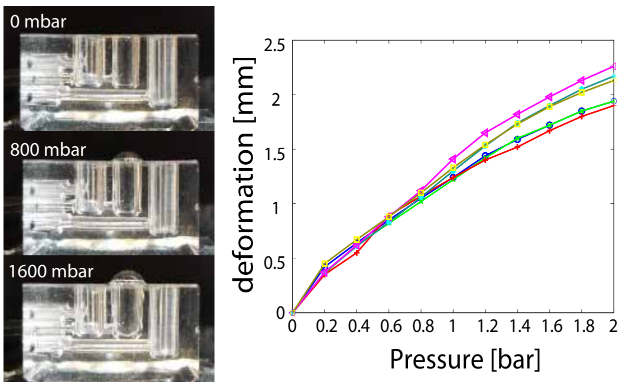

Fig. 9. Balloon deformation for several pressures and deformation plotted against pneumatic pressure. Note that the pressure/deformation ratio can be considered as linear up to about 1 bar.

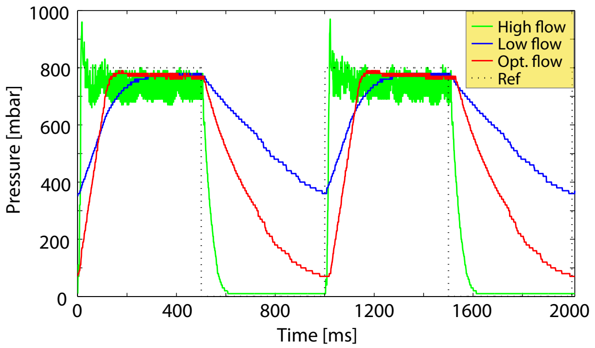

Fig. 10. Pressure plot for a 1Hz square reference signal with three different pneumatic resistances to filter output vibration.

IV. PSYCHOPHYSICAL EXPERIMENTS AND RESULTS

Two psychophysical experiments were conducted with 14 subjects each. The subject group consisted of four women and ten men, aged between 22-38 years, nine of them were right handed and five left handed. None of the subjects had prior experience with tactile displays.

A. Magnitude estimation

A psychophysical ratio scaling method called *magnitude estimation* was performed to determine the mathematical relation between the physical stimuli presented to subjects (balloons pressure) and the human tactual sensory experience. This experiment represents a fast and quantitative way of assessing sensations. During this experiment, subjects were required to assign a number accordingly with the magnitude of the sensation produce by each presented stimuli.

1) Experiment protocol: Only one balloon in the center of the array was used during this test. The number of pressure levels was kept low, using only seven levels, to allow subjects to easily compare the feeling produced by the different stimuli. For each inflation level, the balloon was actuated to simulate six heart beats at a rate of 1.25 Hz. The different pressure levels were presented in a random order and were repeated five times, resulting in a total of 35 trials per subject. After six pulsations, subjects scored the magnitude of the presented stimulus. In order to avoid biasing the results, neither a scale nor a reference pressure level was given, as it is generally recommended for this kind of experiments [23]. Therefore, subjects were free to assign the number that best matched the perceived magnitude of the stimuli.

2) Results: To establish a function showing how intense the different pressure levels were perceived (psychophysical magnitude function), the data from fourteen subjects were combined by calculating the geometric mean and then plotted against the real stimulus value (Fig. 11). The geometric mean indicates the central tendency of the set of measurements and is computed as follows:

$$\text{Geometric mean} = 10^{\frac{\sum \log X}{N}}, \qquad (3)$$

where X is a score value and N is the number of scores.

According to Fig. 11, the resulting function is almost linear, with a positive slope and does not present any saturation. Consequently, the perception of balloon pressure can be taken as proportional to the input pressure, which ranges from 0 to 1000 mbar corresponding to a deformation of $0-1.4$ mm. The fact that no saturation is observed indicates that in terms of psychophysics, the input pressure could be increased to expand the working range. However, technically this might be only feasible to a certain extent due to the mechanical limits of the display. It should be pointed out that most of the subjects were able to distinguish from four to six different levels which is consistent with the number of five levels reported by Culjat *et al.* in [19].

B. Pattern identification

A second experiment was carried out to evaluate the display performance in terms of spatial representation. During this experiment, the number of correct answers while identifying different patterns was evaluated for three different balloon pressures.

1) Experiment protocol: This experiment follows a factorial design with three different factors: pressure (3 levels), pattern (6 types) and subject (14). The six patterns used in the experiments are shown in Fig. 12. As in the previous experiment, each balloon was actuated simulating six heart beats at a rate of 1.25 Hz. The patterns were presented in a random order and at three different pressure levels (200 mbar, 400 mbar and 900 mbar). Each pattern-pressure combination was repeated five times, resulting in a total of 90 trials per subject. During the experiments, subjects had a sheet in front of them with the numbered possible patterns (Fig. 12). Then they were asked to identify the pattern as soon as they were sure about their answer. Subjects were aware that time was measured. However, it was pointed out that correctness was more important than response time. If the subject did not provide an answer, this was considered as a wrong answer.

2) Results: An analysis of variance (ANOVA) was performed with the aforementioned factors: subject, pattern and pressure level. The results are summarized in Table I. The subject factor as well as the pressure factor had a highly significant effect on all measurements ($P < 0.001$). Pattern factor presented a lower influence ($P < 0.025$).

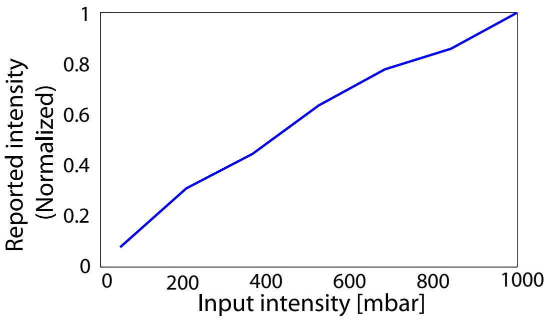

Fig. 11. Magnitude estimation as a function of balloon pressure on the tactile display.

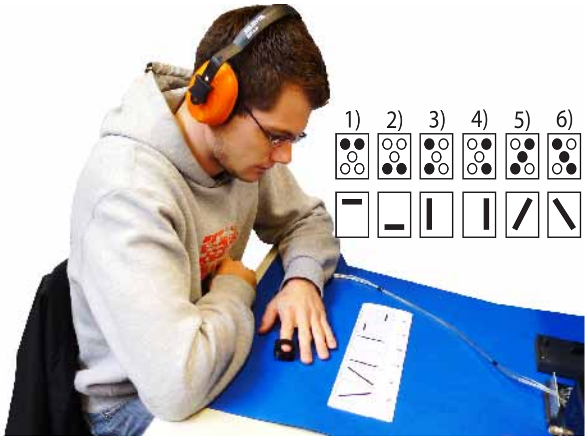

Fig. 12. Experimental protocol for pattern identification experiment.

TABLE I

ANOVA RESULTS FOR PATTERN IDENTIFICATION TEST.

Parameter	Subject	Pressure	Pattern	Interaction
Correctness	P<0.001	P<0.001	P<0.025	P>0.05
Resp. time	P<0.001	P<0.001	P<0.025	P>0.05

Mean values for correctness and response time are shown in Fig. 13. 96.3% of the presented patterns were correctly identified. Regarding the results at different pressure levels, 92.6% of the patterns presented at a pressure of 200 mbar were identified, 98.8% at 400 mbar and 97.4% at 900 mbar. A Bonferroni t-test for multiple comparisons was performed to determine if there were significant differences in user correctness and response time for different pressure levels. As it is shown in Fig. 13 pressure above 400 mbars significantly improved pattern recognition and decreased response time. No significant improvement was found for higher pressures in terms of correctness. Nevertheless, when the pattern was rendered at 900 mbar the response time was significantly reduced. We assume that there is no improvement in answer correctness for pressures above 400 mbar because the detection threshold might already be overcome at 400 mbar. According to Stevens *et al.*, the minimal detectable indentation that can be differentiated from a uniform plane [24] is at 0.2 mm. In this case, due to the smooth edges of the balloons the threshold might be higher. For this reason, the patterns displayed at pressures below 400 mbar are not easily identified. As can be seen in the Fig. 9, at 400 mbar the produced deformation is around 0.5 mm but when the balloon is in contact with the fingertip the deformation slightly decrease. Pressures above this threshold do not provide the users any additional information. However, the subjects were more confident with their answers at 900 mbar, thus lowering their response time and improving their speed-accuracy results.

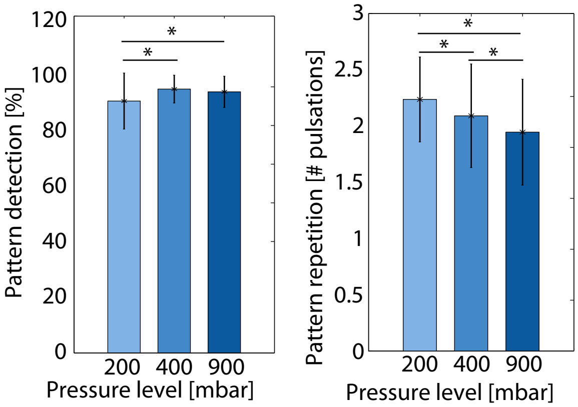

Fig. 13. Mean values of answer correctness of pattern identification and number of pulses per answer. Lines with stars above, connect mean values that are significantly different for a corrected significance level $\alpha_B < 0.01667$. Pressure higher than 400 mbar seems to enhance pattern perception, thus speeding up the identification and increasing the number of correct answers.

V. CONCLUSIONS AND FUTURE WORKS

A. *Conclusions*

A novel tactile pulse display was developed in order to restore tactile feedback during teleoperated surgery, allowing surgeons to localize hidden arteries. The proposed device provides notable flexibility, a simple manufacturing process, and cost-efficiency. In addition, an ad-hoc control unit was developed resulting in a compact, portable and multi-platform overall system. The performance of the PDMS block, in terms of output displacement related to pressure input, fulfills all the initial requirements. Moreover, characterization of the control-unit showed that the bandwidth for an optimal operation, without undesired vibrations, is high enough to display a pulse-like stimulus. The manufacturing process of the PDMS block is not expensive and could be simplified by using a mold-injection to fabricate both the main block and the thin elastic film. For this reason the display could be realized as single use unit.

The function obtained with the magnitude estimation experiment is nearly linear meaning that user's sensation can be considered as proportional to the input pressure. Furthermore, the function is free of saturation guaranteeing optimal performance at any pressure within the working range. Besides, this function can be used to control the device, directly commanding the required level of user perception.

A second psychophysical experiment was performed in order to evaluate system performance in terms of spatial representation. The outcome of this test clearly shows that patterns are accurately identified, with an average of 96.3% of correct answers. It was observed that pressures of 400 mbar and above enhance the user's perception of the stimulus.

B. *Future Work*

The integration of this tactile pulse display into the master console of a robotic surgical system represents a potential application. No studies on the benefit of tactile displays in palpation tasks have been reported so far. This type of investigation will be valuable for the extraction of tactile display design guidelines and surgical application scenarios of such systems. Performance assessment of a palpation task in a virtual scenario, in which tactile information is represented visually and/or tactily, will be soon performed in this direction. Thereafter, the goal will be to perform additional teleoperation experiments with a remote palpation instrument, which will convey tactile information from a tactile sensor located inside the patients body to the surgeons fingertips.

VI. ACKNOWLEDGMENTS

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