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End-of-instrument Stiffness Perception Device Based on Sensory Augmentation for Laparoscopic Surgery

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INTRODUCTION

Laparoscopic surgery brings a lot of advantages for the patient [1] counterbalanced by an increased difficulty for the surgeon, caused in part by limitations in perception [2]. On the one hand, the visual perception is degraded (loss of depth perception, reduced field of view, etc.), on the other hand, due, among other, to the friction of the trocar, the stiffness of the abdominal wall and the lever effect, the haptic perception of forces is also highly degraded [3]. Since both haptic and visual sensory modalities are degraded, the overall force perception, resulting in the integration of both, is insufficient [4]. It leads to tissue damages [5], application of excessive force [6] and poor palpation precision (in terms of hardness and size discrimination for instance) [7].

Therefore, it appears of great interest to reconstitute pertinent information to the surgeon, to improve the perception of forces. We propose here to use sensory augmentation to assist the degraded natural haptic feedback with a sensory substitution approach to reconstitute the effort measured at the tool-tip. This feedback has to respect several constraints. First, it should not interfere with the rest of the operating room. We therefore opt for the tactile modality so as not to increase the load on the already highly solicited auditory and visual modalities [8]. In particular, a tactile feedback based on tangential skin deformation – skin stretch – appears as a suitable candidate; Indeed, it has been suggested [9] that as it is the same sensory channel as for the perception of an effort, it should then be intuitive with no increase of the cognitive load. Finally, in order to avoid disrupting the medical gesture, we decide to apply the skin deformation feedback on the arm instead of the fingertip, as usually done in teleoperation [10] or haptic interaction with virtual environments [9].

To summarize, the present paper focuses on sensory augmentation based on tangential skin deformation on the arm to reconstitute the force applied at the end of the instrument to the surgeon. The design of a first prototype and a pilot study aiming at experimentally assessing the validity of the proposed approach in a 1-Dof context, focusing only on the axial force, are presented hereinafter.

MATERIALS AND METHODS

A. Prototype: Design & Control

We developed a skin-stretch wristband, shown in Fig. 1, in order to evaluate the proposed feedback strategy. The

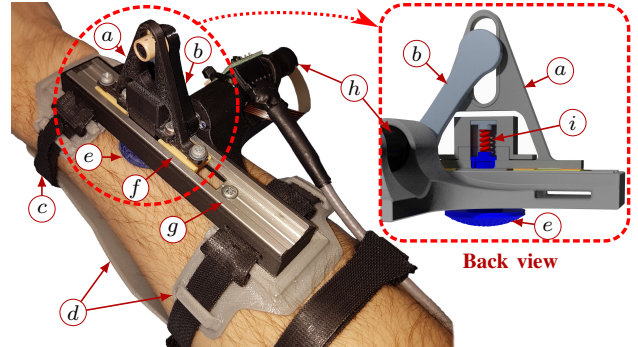


Fig. 1. Skin-stretch wristband: (a) slider, (b) crank, (c) hook-and-loop fasteners, (d) soft TPU pads, (e) factor, (f) low-friction carriage, (g) guide rail, (h) motor, (i) compression spring

device consists of a 1DoF mechanism based on the Scotch-Yoke variant of the crank-slider, as this variant is more reliable, decreases the dimensional requirements [11] and presents less friction [12]. The element in contact with the skin providing the friction-induced skin-stretch is the blue 25 mm diameter spherical convex factor. It is made out of high friction silicone to avoid slippage and it is connected to the slider with a spring-based mechanism to ensure the contact with the skin along the normal direction. The slider, hence the factor, features a stroke of ± 30 mm from the center position. The wristband is positioned and maintained on the arm using soft TPU pads strapped together. All the control and instrumentation signals are connected to a single board computer, running a real-time controller. The latter is performing the position control of the motor and acquiring the force measured by a 6-axis F/T sensor.

The amount of skin stretch to be applied is determined similarly to [9], [10] as follows:

$$x = r_{ss}f, \quad (1)$$

where x [m] is the desired displacement of the factor, r_{ss} [m/N] is the skin stretch ratio and f [N] is the force to be rendered. The desired displacement of the factor is then converted into a desired motor angle using the kinematic model.

B. Protocol: Design & Experimental Setup

We performed an experimental pilot study in order to evaluate our approach and compare it to a visual feedback and no feedback, in a stiffness discrimination palpation task, mimicking a laparoscopic surgery context. A total

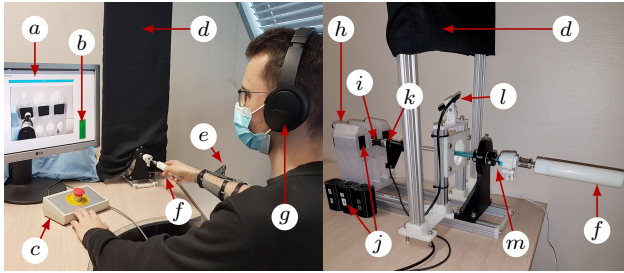


Fig. 2. Experimental setup of the pilot study

Left: (a) view of the scene, (b) force gauge, (c) emergency stop, (d) opaque sheet, (e) wristband, (f) tool, (g) noise-canceling headphone
 Right: (h) stiffness sample holder, (i) spherical palpation probe, (j) stiffness samples, (k) F/T sensor, (l) camera, (m) fulcrum + trocar

of 5 subjects between the ages of 24 and 32 participated in this study, which was performed in accordance with the ethical principles provided by the declaration of Helsinki.

The experimental setup is presented in Fig. 2. The participant is holding a palpation tool inserted in a medical trocar, itself placed in a fulcrum. The end of the instrument consists of a 8mm spherical probe, mounted on a 6 axis F/T sensor, allowing to measure the applied efforts. However, only the force along the tool axis is considered here. Three stiffness samples are placed in a sample holder. The vision of the scene, blocked by an opaque black sheet, is transferred on a screen.

The elementary task is a palpation task in which the participant is presented with three stiffness samples where one, the *odd-one-out*, is stiffer than the other two, the *references*, which are identical. The samples are masked on the screen when the tool-tip is in contact, so as not to influence the perception. The subject is given 15s to identify the stiffest sample.

This elementary task (ET) is performed under three experimental conditions: “*natural*” where there is no additional feedback than the distorted natural haptic feedback, “*visual*” where a gauge whose filling is proportional to the applied effort is displayed on the screen, “*skin stretch*” where the proposed feedback is applied.

For each experimental condition, there is one experimental block subdivided into two parts: a training part of 7 ET and a main part of 21 ET. The main part is composed of three difficulty levels (*easy*, *medium*, *hard*), with 7 ET per level. An increase in difficulty is characterized by a decrease in the difference in stiffness between the *reference* and the *odd-one-out*.

RESULTS

The performance in term of stiffness discrimination precision is evaluated using the success rate, that is, the percentage of correct identification of the stiffest sample. Fig 3 shows the success rate for all participants, for every difficulty level under each experimental condition.

These preliminary results seems to indicate that the participants are performing better with a feedback than with no feedback. Furthermore, if the *visual* and *skin-stretch* feedback appear to perform similarly for the *easy* level, it seems that, as the difficulty increases, the *skin-stretch* feedback is detaching from the *visual* feedback and yields a better success rate.

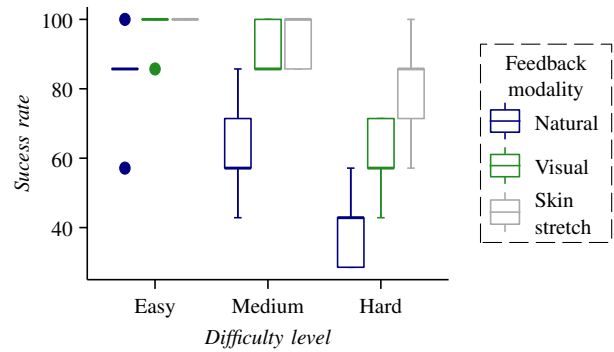


Fig. 3. Results in term of success rate for all participants

CONCLUSION AND DISCUSSION

This paper proposed a feedback modality based on tangential skin-stretch on the arm in order to improve the degraded perception of forces in laparoscopic surgery. The accent was put on the design of a prototype and on a pilot study that showed promising results, confirming the interest of the presented approach.

A complete study is therefore required and will be conducted in future work to confirm the emerging trend from these preliminary results using statistical tests on a larger population. The impact on the cognitive load also needs to be addressed to verify the assumptions established in introduction.

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