Sensory subtraction in robot-assisted surgery: fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction

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Abstract—This study presents a novel approach to force feedback in robot-assisted surgery. It consists of substituting haptic stimuli, composed of a kinesthetic component and a skin deformation, with cutaneous stimuli only. The force generated can then be thought as a subtraction between the complete haptic interaction, cutaneous and kinesthetic, and the kinesthetic part of it. For this reason, we refer to this approach as sensory subtraction. Sensory subtraction aims at outperforming other non-kinesthetic feedback techniques in teleoperation (e.g., sensory substitution) while guaranteeing the stability and safety of the system. We tested the proposed approach in a challenging 7-DoF bimanual teleoperation task, similar to the Peg Board experiment of the da Vinci Skills Simulator. Sensory subtraction showed improved performance in terms of completion time, force exerted and total displacement of the rings with respect to two popular sensory substitution techniques. Moreover, it guaranteed a stable interaction in the presence of a communication delay in the haptic loop.

Index Terms—Haptic interfaces, Telerobotics, Surgery, Telemedicine, Biomedical engineering

I. INTRODUCTION

TELEOPERATED robot-assisted surgical systems can greatly improve the accuracy and safety of medical procedures. They can filter out high-frequency signals, such as surgical tremors [1], or scale down clinician’s movements to enhance their accuracy [2]. Moreover, they may also increase the comfort of clinicians in the operating theatre, since the control interface can be always positioned in a way convenient for the operator to control. Teleoperated robotic systems are composed of a slave robot, which interacts with the given environment, and a master system, operated by a human. The slave robot is in charge of resembling the movement of the clinician who, in turn, needs to observe the environment the robot is interacting with. If the clinician receives sufficient information about the slave system and the remote environment, he will feel as if he is actually present at the remote site: this condition is referred to as telepresence [3], [4]. Achieving it is mainly a matter of technology. A human operator, in fact, upon reflection, knows where he really is, despite the use of any kind of machine, but, if the slave system transmits sufficient information, displayed in a rather natural way, the illusion of telepresence can be compelling [4]. The primary tool to attain this objective is providing a transparent implementation of the teleoperation system, which can be defined as the correspondence between the master and slave positions (kinematic correspondence) and forces [5]. A convincing illusion of telepresence can be achieved through different types of information, which flow from the remote scenario to the human operator. They are usually a combination of visual, auditory and haptic stimuli. Visual and auditory feedback are already employed in commercial robotic surgery systems (e.g. the da Vinci Si Surgical System[1]), while it is not common to find commercially-available devices implementing haptic force feedback. Two of the few examples

1Intuitive Surgical, Sunnyvale, CA, USA.
are the DLR MiroSurge and the Sense robotic catheter system.

However, haptic force is widely considered to be a valuable navigation tool during teleoperated surgical procedures. It allows to detect local mechanical properties of the tissue being penetrated and distinguish between expected and abnormal resistance due, for example, to the unexpected presence of vessels. Force feedback has been shown to enhance operators’ performance in teleoperation in terms of completion time of a given task, accuracy, peak and mean applied force. In surgery, improved performance when providing force feedback was demonstrated for telerobotic catheter insertion, suturing simulation, cardiothoracic procedures, cell injection systems, and fine microneedle positioning. Other studies have linked the lack of significant haptic feedback to increased intraoperative injury in minimally invasive surgery operations and endoscopic surgical operations. Moreover, haptic feedback can be also employed to augment the surgical environment, providing additional valuable information to the operator, such as navigation cues or tool contact accelerations. Nakao et al., for example, presented a haptic navigation method which allows surgeons to avoid collision with forbidden regions by employing haptic feedback through a 2D master manipulator, and McMahan et al. developed a sensing and actuating device for the da Vinci S Surgical System to provide auditory and vibrotactile feedback of tool contact accelerations.

In addition to transparency, another important goal in teleoperation with force feedback is stability. The kinesthetic part of the haptic interaction can, in fact, lead to undesired oscillations of the system, which may be unsafe for both the clinician and the patient being operated on. Stability of haptic systems can be significantly affected by communication latency in the teleoperation loop, hard contacts, stiff control settings, and many other destabilizing factors which dramatically reduce the effectiveness of haptic force feedback in teleoperation. In this respect, passivity has been exploited as the main tool for providing a sufficient condition for stable teleoperation in several controller design approaches, such as time domain passivity control, energy bounding algorithm and passive set position modulation. However, control techniques guarantee the stability of the system at the price of a temporary loss of transparency, which could lead to degraded performance. Moreover, in cases of serious failures of the actuators, the teleoperation loop can experience problems that cannot be managed by control and can lead to an abrupt change in the behaviour of the remote robot. For this reason, feedback approaches that disregard kinesthetic feedback are lately gaining great interest, especially in fields where safety is paramount, e.g. robotic surgery.

A popular non-kinesthetic approach to provide information about forces exerted at the slave side is sensory substitution. It consists of substituting kinesthetic force with alternative forms of feedback, such as vibrotactile, auditory, and/or visual feedback. In this case, since no kinesthetic force is fed back to the operator, the haptic loop becomes intrinsically stable and no bilateral controller is thus needed.

However, these stimuli are often very different from the ones being substituted (e.g. a beep sound instead of force feedback) and they may show worse performance than that achieved employing unaltered force feedback. Similarly to sensory substitution, Prattichizzo et al. presented a feedback approach that substituted haptic force feedback with cutaneous feedback only. Results showed higher transparency levels than that obtained compared to other conventional sensory substitution techniques. The authors named this technique sensory subtraction, since the force provided (i.e., cutaneous stimuli only) can be thought as a subtraction between the complete haptic interaction, consisting of cutaneous and kinesthetic components, and the kinesthetic part of it. However, the study presented by Prattichizzo et al. only considered a 1-DoF teleoperation task, carried out in a virtual environment.

In this paper we exploited the idea of sensory subtraction in a challenging medical scenario: a bimanual 7 degrees-of-freedom (DoF) teleoperation task, very similar to the Peg Board module of the da Vinci Skills Simulator (see Fig. 1). The master system was composed of two 7-DoF haptic interfaces, used together with four wearable cutaneous devices. The task consisted of inserting four rings in two different pegs. Performance were compared while providing (1) complete haptic force feedback through a couple of haptic interfaces, (2) cutaneous force feedback through four cutaneous devices,

Fig. 2. Two fingertip skin deformation devices employed in sensory subtraction.

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2Intuitive Surgical, Sunnyvale, CA, USA, and Mimic Technologies, Seattle, WA, USA.

3Hansen Medical, Mountain View, CA, USA.
The paper is organized as follows: Sec. II introduces the idea of sensory subtraction, together with the cutaneous devices employed in this work. Sec. III and IV evaluate the sensory subtraction approach in two paradigmatic 7-DoF bimanual experiments. Both are discussed in Sec. V. Lastly, Sec. VI addresses concluding remarks and perspectives of the work.

II. SENSORY SUBTRACTION: A NOVEL APPROACH TO FORCE REFLECTION IN TELEOPERATION

General-purpose commercial haptic interfaces can be classified as either ground-based devices (force reflecting joysticks and linkage-based devices) or body-based devices (gloves, suits, exoskeletal devices). The former are solidly connected to the “world”, while the latter are attached to the body of the user. Most of the well-known grounded haptic devices, such as the Omega\(^4\) or the Phantom\(^5\) provide kinesthetic force feedback to the users\(^6\). However, these devices also provide cutaneous stimuli to the fingertips, if we assume that the interaction with the remote environment is mediated by a stylus, a ball, or any other tool fixed on the haptic interface\(^7\),\(^28\). For this very reason we can consider the haptic force feedback provided by grounded haptic devices as perceived by the operator through two different channels: cutaneous and kinesthetic\(^7\),\(^31\),\(^32\),\(^28\). Cutaneous stimuli are sensed by pressure receptors in the skin and they are useful to recognize the local properties of objects such as shape, edges, embossings and recessed features. This is possible, principally, thanks to a direct measure of intensity and direction of contact forces, and to the encoding of the force spatial distribution over the fingertip\(^31\),\(^33\). On the other hand, kinesthesia provides the user with information about the relative position of neighbouring parts of the body, mainly by means of sensory organs in muscles\(^34\) and joints\(^32\).

The sensory subtraction approach, first introduced in\(^7\), consists of substituting this haptic force with cutaneous stimuli only, provided by custom fingertip skin deformation devices. The first device developed for this purpose is the 3-DoF wearable cutaneous interface presented by Prattichizzo et al.\(^27\) and shown in Fig. 2a. It consists of two platforms: one is placed on the back of the finger and supports three small electrical motors; the other one is in contact with the volar skin surface of the fingertip. The two parts are connected by three wires. The motors, by controlling the length of the wires, move the platform towards the user’s fingertip, generating a force that simulates the contact with an arbitrary surface. Three force sensors are placed near to the platform vertices, in contact with the finger, so that they measured the three components of the cutaneous force applied to the fingertip.

An improved version of the same device has been employed by Pacchierotti et al.\(^28\), and it is here shown in Fig. 2b and 2c. It is similar to the one mentioned above, but shows higher accuracy. It consists again of two platforms connected by three wires. Three small electrical motors, equipped with position encoders, control the length of the wires, moving the mobile platform towards the fingertip. One force sensor is placed at the platform’s centre, in contact with the finger, so that it measures the component of the cutaneous force perpendicular to the volar skin surface of the fingertip.

In this work we will employ a customized version of the cutaneous device employed by Pacchierotti et al.\(^29\). The force sensor has been removed, and the two platforms have been reshaped to make it easier to use together with the 7-DoF haptic interfaces.

III. 7-DOF BIMANUAL PEG BOARD EXPERIMENT

In order to evaluate the feasibility of sensory subtraction in a challenging teleoperation scenario, a 7-DoF bimanual peg board experiment was carried out.

A. Experimental setup

Fig. 3 shows the experimental setup. The master system was composed of two Omega 7 haptic interfaces and four cutaneous devices. The Omega 7 is a grounded haptic interface with 7 DoF, four active (translation and gripper) and three passive (wrist). The cutaneous devices are the ones presented

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\(^4\)Force Dimension, Nyon, Switzerland.
\(^5\)Sensible group,Geomagic, 3D Systems, Rock Hill, SC, USA.
in Sec. II and were worn as shown in Fig. 3b, i.e. on the thumb and index finger of both hands. The slave system was composed of two virtual surgical pliers, directly controlled by the master interfaces. The pliers accurately resembled fingers’ motion on the Omega devices. Users were able to move and rotate the pliers in the 3-D space and control their gripping force. The virtual environment consisted of four rings, two green and two red, and two pegs, one green and one red (see Fig. 3c). The rings weighed 30 g and had a minor radius of 3 cm, a major radius of 5 cm, and a height of 1 cm. The pegs were fixed to the ground and had a base diameter of 4 cm and a height of 10 cm. A spring $k_0 = 40 \text{ N/m}$ was used to model the contact force between the proxies and the objects, according to the god-object model [35]. The virtual environment was built using CHAI 3D, an open-source set of C++ libraries for computer haptics and interactive real-time simulation. The haptic interfaces were controlled using the Haptik Library [36].

The task consisted of lifting, one by one, the rings from the ground with one pair of pliers, handing them to the other pair and inserting them into the peg of the corresponding color. An insertion was considered valid only when the ring was inserted in the correct peg. As already mentioned, the task resembles the Peg Board experiment proposed in the da Vinci Skills Simulator. The task started when the user grasped a ring for the very first time and ended when all the rings were inserted into the pegs.

**B. Force feedback conditions**

Each participant made sixteen trials of the aforementioned peg board task, with four randomized repetitions of each force feedback modality considered:

- complete haptic force feedback provided by the Omega 7 haptic interfaces (modality H),
- cutaneous force feedback provided by the cutaneous devices (modality C), i.e. the sensory subtraction approach,
- visual feedback in substitution of force feedback, provided by changing color brightness of the ring being grasped (modality V),
- auditory feedback in substitution of force feedback, provided by changing the repetition frequency of a stereo beep tone (modality A).

In all the considered modalities the Omega 7 devices were in charge of controlling the movements of the surgical pliers by tracking position and orientation of the operator’s hands. The virtual environment then computed the interaction forces, and the controller provided force feedback to the user through either the haptic devices, cutaneous devices or a substitution (visual or audio) modality (see Fig. 4).

Haptic force feedback (modality H) was provided through the Omega 7 haptic interfaces, which are able to render grip and translation forces in the 3-D space. As mentioned before, the force provided by this type of grounded devices is composed of two components, cutaneous and kinesthetic.

Cutaneous force feedback (modality C) was provided by four prototypes of the custom cutaneous device presented in Sec. II. Since they did not embed any force sensor, no direct measurement of the applied cutaneous stimuli was available. This force was thus estimated according to the fingertip model employed in [27], which considers a linear relationship between resultant wrench at the fingertip and device’s platform displacement. In other terms, we assumed device’s platform configuration $\xi = [p_x, p_y, p_z, \alpha, \beta, \gamma]^T \in \mathbb{R}^6$ to be proportional to the wrench $w_p = [f_p^T, m_p^T]^T \in \mathbb{R}^6$ applied to the mobile platform

$$\xi = K^{-1}w_p,$$  

where $K \in \mathbb{R}^{6 \times 6}$ is the fingertip stiffness matrix. An isotropic elastic behaviour was then considered, so that the stiffness value was the same for all the elements of the diagonal matrix: $K = kI$, $k = 0.5 \text{ N/mm}$ [37].

Sensory substitution by visual feedback (modality V) was employed to provide the operator with information about how much grasping force was applied to a ring: the more force was

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6A video of the experiment can be download at [http://goo.gl/Wc6WYB](http://goo.gl/Wc6WYB)
TABLE I
ANOVA RESULTS FOR THE PEG BOARD EXPERIMENT (CONFIDENCE INTERVAL OF 95%).

<table>
<thead>
<tr>
<th>Measure considered</th>
<th>df (BG)</th>
<th>df (WG)</th>
<th>F value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion time</td>
<td>3</td>
<td>18.760</td>
<td>34.158</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Contact forces</td>
<td>3</td>
<td>19.166</td>
<td>49.847</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Rings’ displacement</td>
<td>3</td>
<td>3</td>
<td>64.939</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

applied, the brighter the ring appeared. As shown in Fig. 3c, the rings were presented in two colors, red and green. Colors were rendered using the RGB color model, and their perceived brightness was evaluated as indicated in [38], i.e.

\[ p_b(r,g,b) = \sqrt{0.241 \cdot r^2 + 0.691 \cdot g^2 + 0.068 \cdot b^2}, \]

where \( r, g, \) and \( b \in [0,255] \) indicate the red, green and blue components of the color, respectively. Brightness of the ring being manipulated was then computed as a function of the grip force \( f_h \), expressed in Newtons,

\[ p_b(r,g,b) = 8 \| f_h \| + 85, \]

with

\[ g = b = 0 \quad \text{for red rings, and} \]
\[ r = b = 0 \quad \text{for green rings.} \]

Sensory substitution by auditory feedback (modality A) was also employed to provide the operator with information about how much grasping force was applied to the rings. A series of stereo beep sounds were used: the more force was applied, the higher the frequency\(^7\) of the series of beeps sounds. The pair of pliers controlled by the operator’s right hand produced a sound on the right earphone, while the other pair produced a sound on the left one, making it very easy for the operator to understand which tool was applying force. The series of beep sounds can be seen as a pulse wave, with a fixed pulse duration \( \tau_a = 0.05 \text{ s} \) (the duration of a single beep), and a period, expressed in seconds, of

\[ T_a = \begin{cases} 
1.2 - \frac{\| f_h \|}{5} & \text{if } \| f_h \| \leq 5, \\
0.2 & \text{if } \| f_h \| > 5,
\end{cases} \]

where \( f_h \) indicates again the grip force applied to the object, expressed in Newtons. The operator, therefore, hears the beeps getting closer to each other while the force exerted increases. It is worth highlighting that in modalities C, V and A the Omega 7 were only used to track the position of the fingers and did not provide any force feedback.

\(^7\)Note that we refer to the frequency of repetitions of the beeps, e.g. beeps per seconds.

Fig. 5. 7-DoF bimanual peg board experiment. Completion time, contact forces, and rings’ displacement (mean is plotted) for the haptic (H), cutaneous (C), visual (V) and auditory (A) modalities. Lower values of this metrics indicate higher performances in completing the given peg board task. P-values of Post-Hoc group comparisons are reported when a statistical difference is present (confidence interval of 95%).

C. Subjects

Ten participants took part in the experiment. Five of them had previous experience with haptic interfaces, but only two have tried cutaneous devices before. None of the participants reported any deficiencies in their perception abilities. Subjects were asked to complete the task as soon as possible. Participants were informed about the procedure before the beginning of the experiment, and a 10-minute familiarization period was provided to make them acquainted with the experimental setup.

D. Results

In order to evaluate the performance of the considered feedback modalities, we recorded (1) the time needed to complete the task, (2) the forces generated by the contact between
the pliers and the rings and (3) the total displacement of the rings. Data resulting from different repetitions of the same feedback modality, performed by the same subject, were averaged before comparison with other modalities’ data.

Fig. 5a shows the average time elapsed between the instant the user grasps the object for the very first time and the instant she/he completes the peg board task. Fig. 5b reports the average grip forces generated between the two pairs of pliers and the rings along the direction of actuation of the Omega’s gripper, i.e. the one perpendicular to the object surface. Only data with non-zero forces were considered. Fig. 5c shows the sum of the rings’ displacements, averaged over the subjects. Finally, Fig. 6 reports the grip forces exerted on the rings by the pliers for a representative run.

In order to evaluate the performance of sensory subtraction, both with respect to the ideal case H and to the other popular sensory substitution techniques V and A, we tested the three metrics for differences among the four feedback conditions considered. All the data passed the Shapiro-Wilk normality test. Only data regarding objects displacement passed the Levene’s homogeneity test. For this reason, means were tested using a one-way ANOVA and Tukey HSD post-hoc test for data about rings’ displacement, and a Welch ANOVA and Games-Howell post-hoc test for data regarding completion time and grip forces. The tests revealed no significant difference between the visual and auditory modalities (V and A) for all the considered metrics, while it revealed a significant difference between the other modalities. Details on the statistical analysis are reported in Table IV and Fig. 5.

IV. 7-DOF BIMANUAL PEG BOARD EXPERIMENT WITH COMMUNICATION DELAY

A second experiment was then carried out. It considered the same task, performed by the same ten subjects, with the same experimental setup and feedback modalities. However, this time we introduced a communication delay of 20 ms between the master and slave systems. Time delays, if no countermeasures are taken, are known to bring teleoperation systems with force reflection close to an unstable behaviour, i.e. undesired oscillations [41]. In order to evaluate the performance of the considered feedback modalities, we again recorded (1) the time needed to complete the task, (2) the forces generated by the contact between the pliers and the rings, and (3) the total displacement of the rings. Data resulting from different repetitions of the same feedback modality, performed by the same subject, were again averaged before comparison with other modalities’ data.

A. Results

As for the first experiment, Fig. 7a shows the average task’s completion time, Fig. 7b the average grip forces generated between the pliers and the rings, and Fig. 7c the sum of

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8Measuring the average of intensities of the contact forces is a widely-used approach to evaluate energy expenditure during the grasp [39].

9Data in this and in the following statistical tests were transformed, if necessary [40].
the rings’ displacements, averaged over the subjects. Fig. 8 reports the grip forces exerted on the rings by the pliers for a representative run. In order to evaluate the performance of sensory subtraction, both with respect to the ideal case H and to the other popular sensory substitution techniques V and A, we again tested the three metrics for differences among the four feedback conditions considered. All the data passed the Shapiro-Wilk normality test. All the data, except the ones regarding completion time, passed the Levene’s homogeneity test. For this reason, means were tested using a one-way ANOVA and Tukey HSD post-hoc test for data about rings’ displacement and grip forces, and a Welch ANOVA and Games-Howell post-hoc test for data regarding completion time. The tests revealed no significant difference between the visual and auditory modalities (V and A) for all the considered metrics, no significant difference between cutaneous and haptic modalities (C and H) for what regards the gripping force, and no significant difference between visual and haptic modality (V and H) for what regards completion time. It then revealed a significant difference between the modalities in all the other cases. Details on the statistical analysis are reported in Table II and Fig. 7.

We then performed an additional analysis to compare performance between this experiment and the one without communication delay (see Sec. III-D). We tested the means of each feedback modality across the two experiments, for the three metrics considered, e.g. haptic feedback with delay VS cutaneous feedback without delay, cutaneous feedback with delay VS cutaneous feedback without delay, etc. In order to determine whether the performance observed here can be considered equivalent to that registered in the first experiment, we used the two one-sided t-test (TOST). The null hypothesis of the TOST states that the mean values of two groups are different by a certain amount θ (or larger). Then, in order to test for equivalence, the 90% confidence intervals for the difference between the two groups are evaluated. The null hypothesis that the groups differ by at least θ is rejected if the limits of the interval fall outside the ±θ bounds. Conversely, comparability is demonstrated when the bounds of the 90% confidence interval of the mean difference fall entirely within the ±θ bounds. The design of equivalence tests can be quite tricky since the acceptance criterion θ has to be defined on the basis of prior knowledge of the measurement. For a sample data set of n independent measurements with standard deviation s, for instance, θ must be for sure greater than s/√n, otherwise the test may fail simply because of imprecision, rather than because of a true difference. However, it must also be less than any specifications or standards that the testing is challenging, or the test becomes too easy and will thus not adequately discriminate. In this work we evaluated θ as suggested in [43], where the authors provide a useful step-by-step process for performing equivalence testing with commonly available computational software packages.

We ran twelve TOST equality tests to compare, across the two experiments, three metrics in four feedback modalities. The tests revealed statistical equivalence for cutaneous (C) and auditory (A) feedback in all the metrics and for visual feedback (V) for what regards completion time only. However, visual feedback in the other two metrics (displacement and
forces) was very close to equality. In fact, running a new TOST with $\theta_{w} = 1.5 \theta$ made modality V equivalent across the two experiments for all the metrics, as we expected. Haptic force feedback (H) did not pass the TOST equality tests in any metric. We thus ran a paired t-test to check haptic feedback data (H) for differences across the two experiments. Results revealed a significant difference between the data in all the considered metrics ($p < 0.001$ for completion time, grip force, and rings’ displacement).

V. DISCUSSION

We tested four feedback modalities in two different experimental scenarios, the second of which introduces a 20 ms communication delay in the teleoperation loop.

Results of the first experiment (no delay) are reported in Sec. III-D and Fig. 5. Subjects, while receiving haptic force feedback (H), showed better performance than while receiving any other form of stimuli (C, V, or A). Moreover, sensory subtraction (C) yielded to significant better results than employing auditory or visual feedback in substitution of haptic feedback (A and V). The two latter modalities showed no significant differences between each other. These considerations are valid for all the metrics considered: completion time, grip force, and rings’ displacement.

In order to validate the stability properties of sensory subtraction, we carried out an additional experiment, in which we introduced a communication delay of 20 ms between the master and slave systems. Results are reported in Sec. IV-A and Fig. 7. Sensory subtraction (C) and the substitution modalities (A and V) showed a behaviour similar to the one registered before (when no delay was present), while haptic force feedback showed highly degraded performance. The occurrence of such a degraded behaviour is well-known in the literature and was reported here to highlight the intrinsic stability of sensory subtraction.

From these results we can conclude that sensory subtraction may be a valid replacement for sensory substitution techniques in teleoperation. Moreover, it may also be a valid replacement to complete haptic feedback in those scenarios where safety is paramount, e.g. robotic surgery. Sensory subtraction, in fact, guarantees the intrinsic stability of the system. On the other hand, stability of teleoperation systems with haptic feedback can be significantly affected by various destabilizing factors (e.g. time delays in the teleoperation loop), which may compromise the safety of both the patient and the clinician.

The results hereby registered are in agreement with previous results in the literature. Prattichizzo et al. performed four experiments of teleoperated needle insertion in 1-DoF and found sensory subtraction to perform better than sensory substitution with visual feedback [7]. Pacchierotti et al. developed two custom devices to provide cutaneous stimuli in teleoperation [10], [44]. Both of them were attached to the end-effector of grounded haptic interfaces, such as the one employed here, and showed performances comparable to the ones presented

\footnote{A video of this second experiment, focusing on the unstable behaviour of the haptic modality, can be downloaded at \url{http://goo.gl/4T51Tw}.}
in this work. However, all the aforementioned papers agree that haptic force feedback, when no oscillations arise, perform significantly better than any substitutive modality.

VI. CONCLUSIONS AND FUTURE WORKS

In this work we presented a novel approach to force feedback in robot-assisted surgery, which we called sensory subtraction. It was first introduced by Prattichizzo et al. and consists of substituting haptic stimuli, composed of a kinesthetic component and a skin deformation, with cutaneous stimuli only.

The force generated can be thus thought as a subtraction between the complete haptic interaction and the kinesthetic part of it. For this reason we refer to this approach as sensory subtraction and not sensory substitution.

We evaluated the sensory subtraction approach in a challenging 7-DoF bimanual teleoperation task, similar to the Peg Board tasks proposed in the da Vinci Skills Simulator. We compared sensory subtraction with complete haptic feedback, i.e. force feedback provided by a grounded interface, and two popular sensory substitution techniques, i.e. visual and auditory feedback in substitution of force feedback. Sensory subtraction outperformed the two sensory substitution techniques but, as expected, performed worse than providing complete haptic feedback. However, sensory subtraction guaranteed the intrinsic stability of the teleoperation system and kept the system stable even in the presence of a communication delay in the teleoperation loop. Haptic force feedback, on the other hand, showed highly degraded performance in the presence of such a delay.

Although sensory subtraction seems very promising, haptic force feedback, when no oscillations arise, still showed better performance in all the metrics considered. Moreover, surgeons may not be totally positive about the idea of wearing four fingertip devices while operating. And finally, the force sensed through this kind of cutaneous devices is upper bounded by the sensing capabilities of human cutaneous receptors. Work is in progress to design new cutaneous displays with better dynamic performance and better wearability. Furthermore, new experiments, aiming at evaluating system performance while interacting with a real environment, will be performed in the next future. Finally, work is in progress to validate the approach with more subjects.

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