Vibrotactile stimuli for augmented haptic feedback in robot-assisted surgery

Adrian Ramos Peon*
Dept. of Information Engineering and Mathematics,
University of Siena
Dept. of Advanced Robotics,
Istituto Italiano di Tecnologia

Claudio Pacchierotti†
Dept. of Information Engineering and Mathematics,
University of Siena
Dept. of Advanced Robotics,
Istituto Italiano di Tecnologia

Domenico Prattichizzo‡
Dept. of Information Engineering and Mathematics,
University of Siena
Dept. of Advanced Robotics,
Istituto Italiano di Tecnologia

Abstract

This paper introduces a new approach to haptic feedback during teleoperated robot-assisted surgery. Haptic feedback allows to display to the surgeon the local mechanical properties of the tissue being manipulated, as well as additional information, such as navigation cues. However, when the same end-effector is used to present multiple types of information, there is the risk of confusing the sources of force feedback signals provided to the operator.

The objective of this work is to study how to efficiently combine remote tissue sensing and haptic guidance, in order to make the surgeon aware of the source of the stimuli. We propose to use vibrotactile feedback to render navigation cues and kinesthetic feedback to reproduce the mechanical properties of the tissue. The viability of this approach is validated with two experiments where vibrotactile-guided navigation achieves promising performance and allows users to easily disambiguate forces due to the action of guiding constraints and forces due to the interaction with the remote tissue.

1 Introduction

Advances in teleoperation and robot-assisted surgery have had a large impact in the medical field, and opened a lot of promising opportunities in the operating room. In a teleoperation scenario, a skilled surgeon can benefit from the accuracy of robots while performing surgery [25]. The robot follows the surgeon's commands, and the latter must be able to observe the environment with which the former is interacting by means of different types of information which flows from the remote environment to the human operator. They are usually a combination of visual, auditory and haptic stimuli. In this paper, we consider the problem of efficiently providing haptic stimuli. Our motivation is their importance in enhancing the operator's performance in terms of completion time of a given task [14, 15, 19], accuracy [15, 23, 22], peak [7, 30] and mean applied force [30, 22]. In [30], the authors examined the effect of haptic force feedback on a blunt dissection task and showed that system performance improved up to 150% in comparison with providing no force feedback, while also decreasing the number of tissue damaging errors by over a factor of 3. Improved performance when providing force feedback was also demonstrated for telerobotic catheter insertion [9], suturing simulation [15], cardiothoracic procedures [10], cell injection systems [21], and fine microneedle positioning [26]. Other studies have linked the lack of significant haptic feedback to increased intraoperative injury in minimally invasive surgery operations [18] and endoscopic surgical operations [8].

*e-mail: adrian.ramos@iit.it
†e-mail: pacchierotti@dii.unisi.it
‡e-mail: prattichizzo@dii.unisi.it

IEEE World Haptics Conference 2013
14-18 April, Daejeon, Korea
978-1-4799-0088-6/13/$31.00 ©2013 IEEE

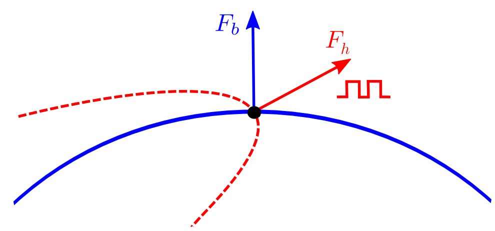


Figure 1: Proposed scenario, mixing kinesthetic and vibrotactile force feedback. The end-effector in shown in black, a remote object and resulting contact force (F_b) in blue, a virtual fixture and resulting vibrotactile force feedback (F_h) in red.

The information provided through the haptic channel is therefore an important tool during teleoperated surgery. It allows to detect the local mechanical properties of the remote tissue the surgical tool is interacting with, and distinguish between expected and abnormal resistance due, for example, to the unexpected presence of vessels [13]. Moreover, haptic feedback can also be employed to *augment* the surgical environment, providing additional valuable information to the operator. For instance, the surgeon could be provided with navigation cues, due to the action of *virtual fixtures*, i.e. software functions used in assistive robotic systems to regulate the motion of surgical implements. The motion is still controlled by the surgeon, but the system constantly monitors it and takes some action if the surgical tool fails to follow a predetermined procedure. Virtual fixtures play two main roles: they can either guide the motion of the surgical tool or strictly forbid the surgeon from reaching certain regions [1, 3]. A guiding virtual fixture attenuates the motion of the surgical implement in some predefined directions to encourage the surgeon to conform to the procedure plan. A forbidden-region virtual fixture is a software constraint which seeks preventing the tool from entering a specific region of the workspace. In this paper we will consider virtual fixtures protecting forbidden regions. This is a common scenario for biopsies, deep brain stimulation and functional neurosurgery [1, 17].

1.1 Mixing multiple sources of information

Haptic feedback can be employed to supply the surgeon with information about the remote tissue being manipulated, as well as other types of information, such as navigation cues. However, if the same perceptive channel is being used, there is a risk of confusing the source of the stimuli.

For this reason, we are interested in understanding how we can provide, through the haptic channel, multiple streams of information while making the surgeon aware of the source of the stimuli. Towards this objective, let us define *remote haptic feedback* as the force sensed by the surgical tool in the remote environment and *virtual haptic feedback* as the force fed back to the surgeon due to the action of virtual fixtures.

As already mentioned in the previous section, *remote haptic feedback* has been proved to significantly enhance surgeons' per-

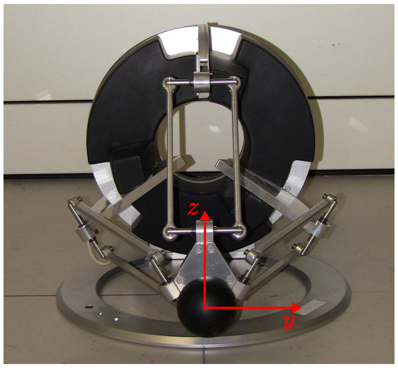


Figure 2: Experimental setup. The Omega 3 single-contact haptic device has been used in the experiments to provide vibrotactile and kinesthetic force feedback. The figure shows the y and z axes of the display.

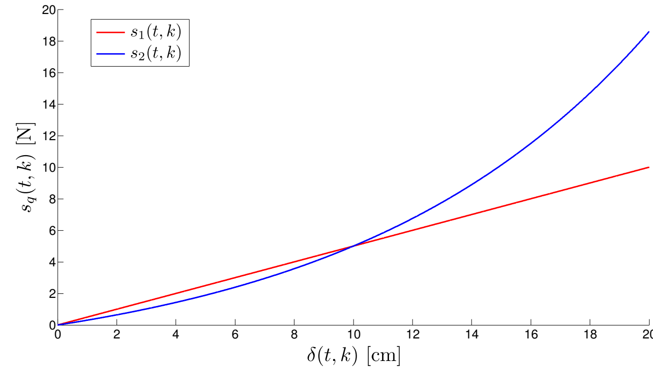


Figure 3: Experiment #1. Two different penalty functions have been considered, $s_1(t,k)$ showed a better accuracy, while $s_1(t,k)$ a faster completion time.

formance in teleoperated surgery. However, force feedback is not only important to make the surgeon aware of real properties of the tissue being penetrated, but also to provide additional information, through what we called *virtual haptic feedback*. One such kind are navigation hints, provided, for instance, by the aforementioned virtual fixtures. For example, Nakao *et al.* [16] presented a haptic navigation method which allows surgeons to avoid collision with forbidden regions by producing kinesthetic feedback through a 2D master manipulator. In [5] the authors studied how to enhance intracellular injection through haptic interaction with the operator. Two haptic virtual fixtures systems were considered. One was a parabolic force field designed to assist the operator in guiding the tool to a desired penetration point on the cell's surface, the second was a planar virtual fixture which attempted to assist the operator from moving the tool beyond the deposition target location inside the cell. Ren *et al.*, in [24], implemented dynamic 3-D virtual fixtures with haptic and visual feedback in minimally invasive beating-heart procedures. Virtual fixtures were generated from preoperative dynamic magnetic resonance or computed tomography images and then mapped to the patient during surgery. More recently, in [20], the authors developed a novel robotic catheter manipulation method implementing forbidden-region virtual fixtures. A virtual force generation algorithm was implemented, taking as input the signal coming from the catheter tip penetrating into the forbidden region, and rendering it back at the user interface.

Additionally to the aforementioned types of feedback, which are mostly kinesthetic, there is a growing interest in vibrotactile force feedback. It has been successfully employed to provide navigation information in those situations where kinesthetic and visual feedback is not suitable. In [4], for instance, the authors explored the possibility of presenting navigation information through a waist belt providing vibrotactile feedback. Results indicated the usefulness of vibrotactile cues for navigation purposes as well as for situational awareness in multi-tasks environments. A similar device was developed in [29], where a haptic belt was integrated with a directional sensor and a Global Positioning System (GPS), and employed as an intuitive navigation system. In [12], Lieberman *et al.* presented a robotic suit for improved human motor learning. It provided vibrotactile feedback proportional to the error between the effective and the learned motion. More recently, a vibrotactile orientation device for guiding the forearm posture was proposed in [6], and in [27] a vibrating haptic bracelet has been used for human-robot interaction in leader-follower formation tasks. Vibrotactile feedback has been also widely employed in robot-assisted surgery: Schoonmaker & Cao [28] demonstrated that vibrotactile stimulation is a viable substitute for force feedback in minimally invasive surgery, enhancing surgeons' ability to control the forces applied to tissue and differentiate its softness in a simulated tissue probing task. More recently, Kuchenbecker *et al.* presented the VerroTouch system [11], which measures the vibrations at the tip of the surgical tool and recreates them on the master handles for the surgeon to feel.

1.2 Contribution

In this work we analyse the problem of *combining* remote and virtual haptic feedback. That is, we want to present to the surgeon both a feedback stream coming from the tissue interaction with the surgical tool and a feedback input coming from the virtual cues, which have been superimposed to the environment to improve surgeons' performance. Moreover, the origin of such cues should be easy to recognize, in order to avoid confusion and consequent possible errors in the surgical procedure.

The approach proposed in this work consists of using a single-contact point haptic interface to provide force feedback to the operator, providing

(i) kinesthetic feedback to reproduce remote haptic feedback and

(ii) vibration cues to reproduce virtual haptic feedback,

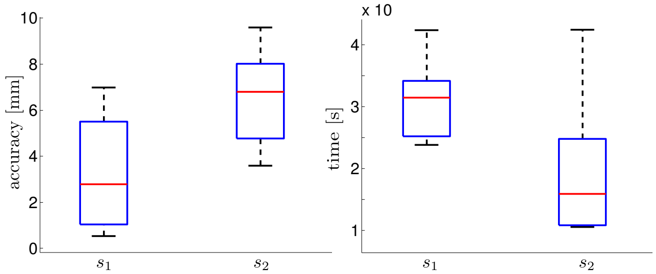
as depicted in Fig. 1. By means of two experiments, employing a single contact-point haptic device, we show that users are more efficient at recognizing unexpected obstacles when mixed vibrotactile-kinesthetic feedback is provided with respect to kinesthetic feedback only. Moreover, completion time and accuracy do not significantly deteriorate.

The paper is organized as follows: the effectiveness of vibrotactile feedback in providing navigation cues is discussed in Sec. 2, along with Experiment #1. A second experiments, carried out to analyse the performances of combining vibrotactile and kinesthetic feedback is presented and discussed in Sec. 3. Finally Sec. 4 addresses concluding remarks and perspectives of the work.

2 Experiment #1: Effectiveness of Vibrotactile Feedback in Providing Navigation Cues

Since we are going to employ vibrotactile cues in reproducing virtual haptic feedback, in this first experiment we analyse the efficiency in providing the surgeon with navigation cues through vibrotactile force feedback. The experimental setup consisted of an Omega 3 haptic interface (Force Dimension, CH), shown in Fig. 2.

The task consisted in moving the end-effector of the haptic device to a target position, being as precise as possible. Users relied on vibrotactile feedback only, which was controlled by a penalty



(a) Accuracy (b) Completion time

Figure 4: Experiment #1, boxplot analysis. On each box, the central mark represents the median, the edges of the box are the 25^{th} and 75^{th} percentiles, and the whiskers extend to the most extreme datapoints. Accuracy and completion time obtained employing s_1 and s_2 are shown, respectively, on the left and on the right side of each plot.

function based on the distance between the end-effector of the Omega device and the given target point. No visual feedback was provided. When the user felt he/she was as close as possible to the target point (i.e., no vibrations), he/she pressed a button on the computer keyboard and the task was considered completed. The system measured the error in reaching the target position and then set a new target point for the next trial.

In this preliminary experiment, the actuated handle vibrated along one direction only (the y-axis of the haptic device, as shown in Fig. 2), with a square-wave modulated amplitude. Let us define $p_k \in \Re^3$ as the position of the target at the k–th trial and $o(t) \in \Re^3$ as the position of the probe of the haptic device at time t.

The vibrotactile force feedback displayed along the y-axis can be expressed as

$$F_v = s_q(t,k)\ \mathrm{sgn}(\sin(\omega t)),$$

where the frequency of the signal ω was fixed at 250 Hz in order to maximally stimulate the Pacinian corpuscle receptors [2] and $s_q(t,k)$ is the amplitude of the wave, represented by a penalty function based on the distance $\delta(t,k) = \|p_k - o(t)\|$, i.e. the distance (in meters) between the position of the haptic probe and the target point.

Two different penalty functions have been considered, both of them rendering an amplitude of 5 N when the end-effector was at 10 cm of the target (see Fig. 3),

- $s_1(t,k) = 50\ \delta(t,k)$,
- $s_2(t,k) = 5\ \dfrac{e^{10\delta(t,k)} - 1}{e-1}$.

Eight participants (7 males, 1 females, age range 20 – 26) took part in the experiment, all of whom were right-handed. Six of them had previous experience with haptic interfaces. Each participant made eighteen repetitions of the vibrotactile navigation task, with nine randomized trials for each feedback modality

- vibrotactile force feedback with linear penalty function (i.e., employing $s_1(t,k)$ - task s_1)
- vibrotactile force feedback with exponential penalty function (i.e., employing $s_2(t,k)$ - task s_2)

Subjects were asked to be as precise and as fast as possible in completing the given task (i.e., in reaching the target point).

Completion time and accuracy (i.e., $\|p_k - o(t)\|$ at the end of each task) were recorded.

Fig. 4a shows the accuracy for each vibrotactile feedback modality (i.e., tasks s_1 and s_2). The mean final error was of 3.27 mm (std 2.59 mm) for task s_1 and 6.54 mm (std 2.09 mm) for task s_2. The collected data of each task passed the Shapiro-Wilk normality test. Then a parametric two-tailed unpaired t-test was performed, to evaluate the statistical significance of the differences between tasks (i.e. between the two vibrotactile feedback modalities). The p-values revealed a statistically significant difference between the groups ($p = 0.0149$).

Fig. 4b shows the completion time for each vibrotactile feedback modality. The mean completion time was of 30.97 s (std 6.30 s) with s_1 and 19.52 s (std 11.12 s) with s_2. The collected data of each task passed again the Shapiro-Wilk normality test. Then a parametric two-tailed unpaired t-test was performed. The p-values revealed a statistically significant difference between the groups ($p = 0.0239$).

From these tests we observed that with the linear feedback function (task s_1), users got closer to the target point, but with more difficulty to initially approach it. On the other hand, the exponential feedback function allowed a faster approach, but was more difficult to lock precisely on the target.

As expected, this experiment confirms that is possible to provide navigation hints employing vibrotactile feedback only. Moreover this results was obtained modulating only the amplitude of the vibration. This leaves room for improvement and additional feedback cues by modulating the frequency in future experiments.

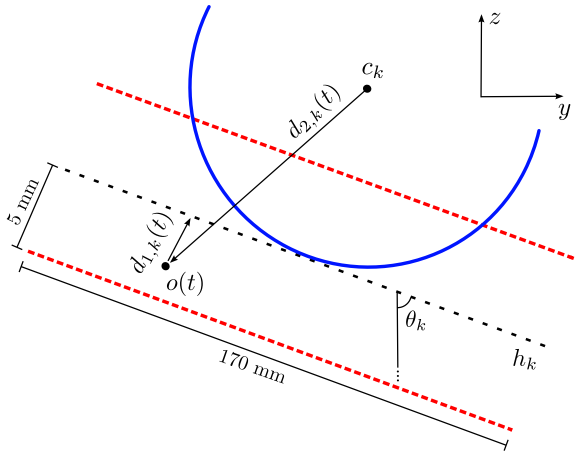
As already mentioned in Sec. 1.1, literature on navigation aids through vibrotactile force feedback is quite rich. However, even if many results already assess the efficiency of employing vibrotactile force feedback in providing navigation cues, we considered this additional experiment worth doing, in order to discuss the efficiency of the considered penalty functions and assess the efficiency of the Omega haptic device in providing vibrations.

3 Experiment #2: Combining Vibrotactile and Kinesthetic Cues

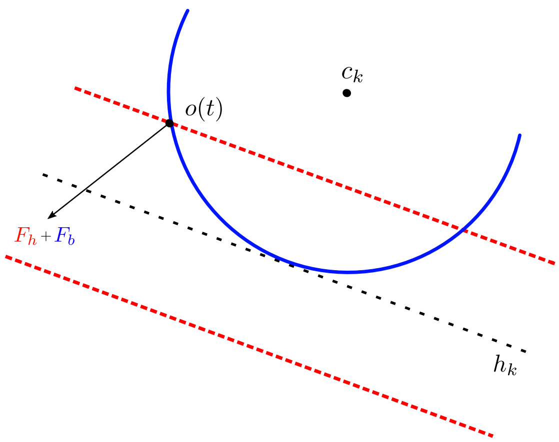
As mentioned in Sec. 1.2, we are interested in providing the surgeon with two different types of force feedback, one coming from the tissue he/she is manipulating (remote haptic feedback), and the other one from virtual fixtures (virtual haptic feedback). A traditional approach to make these pieces of information apparent is through the use of kinesthetic force feedback. However, as previously mentioned, this can make the operator not able to distinguish the source of the force feedback provided. In order to mitigate this issue, we chose to employ vibrotactile cues to represent virtual fixtures and kinesthetic feedback for remote tissue interaction.

To evaluate the effectiveness of our idea, we carried out an experiment in a virtual environment, modelling a virtual fixture and a stiff object (see Fig. 5). For the sake of simplicity we considered a planar environment. The virtual constraint consisted of a virtual two-dimensional tunnel, in charge of bounding the motion of the haptic probe within the tunnel, and the stiff object was modelled as a circle. The same haptic device employed in Sec. 2 and shown in Fig. 2 was used. The motion of the haptic device was constrained to two dimensions only, i.e. the y and z axes, as defined by the coordinate system of the device (see Fig. 2). The Omega exerted forces along its x axis to keep the handle on the given plane.

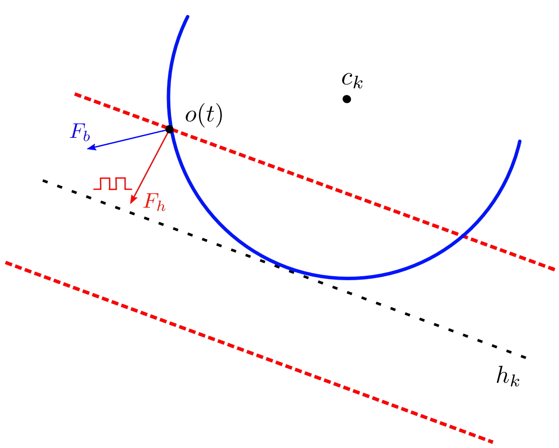
The task consisted in traversing the tunnel from one end to the other. Participants were told do their best to avoid the walls of the tunnel, and that they *might* feel a bulge (i.e., the stiff object) on their path. In such case, they were asked to report it and tell if they felt the bulge on the left or right side of the tunnel. As in Sec. 2, no visual feedback was provided to the subjects.



(a) Virtual environment



(b) Kinesthetic-only force feedback (task H)



(c) Mixed vibrotactile-kinesthetic force feedback (task V)

Figure 5: Experiment #2, visual representation of the virtual environment. The tunnel (virtual fixture) is shown in red, the end-effector $o(t)$ in black and the bulge in blue. The target path the users were asked to follow is h_k (dashed black). The inclination θ_k was randomly chosen at the start of each trial. The experiment consisted in presenting either vibrotactile (task V) or kinesthetic (task H) force feedback for the navigation aid (F_h) and kinesthetic force feedback for the stiff object (F_b).

The length of the tunnel (see Fig. 5) was 170 mm, with a width of 10 mm, and its orientation was randomly chosen. It was rotated (from vertical) by a random angle $\theta_k \in [-7\pi/16, 7\pi/16]$, where k indicates the trial number. Its center was defined by a line of equation $h_k : y = tan(\theta_k)\ z$. When users touched the edges of the tunnel, the force feedback could either be kinesthetic (task H) or vibrotactile (task V). Force feedback was controlled by a penalty function based on the distance between the position of the haptic probe $o(t) \in \Re^2$ and the current target path h_k. Let us define $K =$ 3000 N/m, $A = 500$ N/m. Hence, we can define the force fed back by the system to the operator as

$$F_h(t) = \begin{cases} V(\omega, t) & \text{if } \|d_1(t,k)\| \geq 5\text{mm}, \\ 0 & \text{if } \|d_1(t,k)\| < 5\text{mm}, \end{cases}$$

where $d_1(t,k)$ is the distance vector from the position of the haptic probe to the target path, and

$$V(\omega, t) = \begin{cases} A\ \text{sgn}(\sin(\omega t))\ \|d_1(t,k)\| & \text{for task V}, \\ K\ d_1(t,k) & \text{for task H}, \end{cases}$$

makes the system able to switch between tasks providing vibrotactile and haptic force feedback. As in the first experiment, ω was set to 250 Hz. For the haptic rendering the interaction is designed according to the god-object model [31]. To provide vibrotactile force feedback we chose a linear penalty function, similar to the one presented in Sec. 2, since it showed better performance, in terms of accuracy, with respect to the exponential one. However, we scaled up the amplitude of the vibrations in order to better render the nature of the forbidden-region virtual fixture.

The bulge was modelled as a circle whose center $c_k \in \Re^2$ was randomly placed in the plane, such that h_k was always tangent to its circumference (see Fig. 5). The force feedback F_b, generated by the interaction with the circle, was *always* displayed through the kinesthetic channel. The circle had a radius $r = 55$ mm and a stiffness $K = 3000$ N/m[1]. Let us consider $d_2(t,k) = o(t) - c_k \in \Re^2$ as the penetration vector inside the circle. We can therefore define the force F_b, fed back due to the contact with the bulge, as

$$F_b = \begin{cases} K\ d_2(t,k) & \text{if } \|d_2(t,k)\| < r, \\ 0 & \text{if } \|d_2(t,k)\| \geq r, \end{cases}$$

Therefore the total force fed back to the user while doing the experiment is

$$F = F_h + F_b.$$

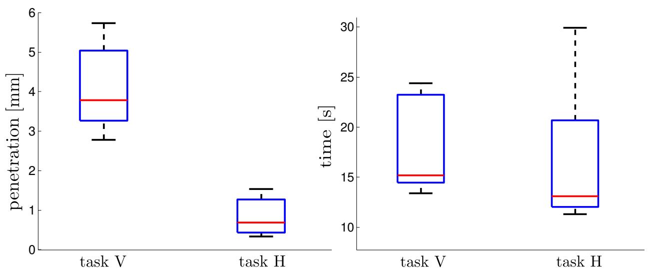
The force F was fully kinesthetic during task H and mixed vibrotactile-kinesthetic (i.e, F_h was vibrotactile and F_b kinesthetic) during task V.

Summarizing, the experiment consisted in presenting either vibrotactile (task V) or kinesthetic (task H) feedback for the navigation aid, i.e. the force due to the presence of the tunnel, and kinesthetic force feedback to render the stiff object, i.e. the bulge.

Nine participants (8 males, age range 20 – 26) took part in the experiment, all of whom were right-handed. All had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities. Each participant made thirty-two repetitions of the tunnel task, with sixteen randomized trials for each feedback modality:

- kinesthetic feedback only (task H),
- mixed vibrotactile-kinesthetic feedback (task V).

[1] This means that during task H, when both the stiff object and the virtual fixture were rendered through kinesthetic force feedback, the bulge and the tunnel had the same stiffness.



(a) Maximum penetration (b) Completion time

Figure 6: Experiment #2, boxplot analysis. On each box, the central mark represents the median, the edges of the box are the 25^{th} and 75^{th} percentiles, and the whiskers extend to the most extreme datapoints. Mean maximum penetrations and mean completion time, obtained employing vibrotactile (task V) and kinesthetic force feedback (task H), is shown, respectively, on the left and on the right side of the picture.

Trials were randomly presented to the subjects. Before the experiment, users were asked to perform 18 randomized trials as training. A small break was given between the training and the actual experiment. At the beginning of each trial, the haptic interface moved to the starting point. When the participant felt ready, he/she pressed the space bar and began moving towards the target. Once the opposite side of the tunnel was reached, the system played a beep sound and the handle moved to the next starting position. At the end of each trial, subjects were asked if they felt the bulge and, if so, on which side it was. Completion time and penetration inside the tunnel surface were recorded as well.

The collected data of each task passed the Shapiro-Wilk normality test. Then a parametric two-tailed unpaired t-test was performed (both for completion time and penetration inside the tunnel surface), in order to evaluate the statistical significance of the differences between tasks H and V.

Figure 6a shows the maximum penetration into the virtual fixture for each feedback modality. Its mean value was of 4.04 mm (std of 1.06 mm) when using mixed vibrotactile-kinesthetic feedback (task V) and 0.81 mm (std of 0.44 mm) employing kinesthetic feedback (task H). The p-value revealed a statistically significant difference between the two groups ($p < 0.0001$).

Figure 6b shows the completion time for each feedback modality. Mean completion time was of 17.60 s (std of 4.45 s) while using mixed vibrotactile-kinesthetic feedback (task V) and 16.49 mm (std of 6.14 s) when employing kinesthetic feedback only (task H). The p-value revealed no statistically significant difference between the two groups ($p = 0.3129$).

Finally, the percentages of recognition of the bulge were analyzed. The mean value of correct detection among users was 81.25% (std of 23.14%) while using mixed vibrotactile-kinesthetic feedback (task V) and 12.50% (std of 14.94%) employing kinesthetic feedback (task H). The p-value revealed a statistically significant difference between the two groups ($p = 0.0011$).

This experiment confirms that is possible to provide navigation hints employing vibrotactile feedback. Moreover this results was obtained modulating only the amplitude of vibrations, leaving room for large improvements. It is worth noting that no additional device had to be worn in order to provide vibrotactile feedback to the users. Vibrations were applied directly to the end-effector of the haptic device.

As expected, most of the subjects were not able to recognize the bulge while using kinesthetic feedback only. This means that the approach here proposed of employing mixed vibrotactile-kinesthetic feedback is a viable solution to make the operator aware of the source of the force being provided.

4 Conclusions and future work

A novel approach to haptic feedback in teleoperated surgery has been presented. Haptic feedback can be employed to make the surgeon perceive the local mechanical properties of the tissue being manipulated, as well as to provide him/her with additional information about the remote environment, such as navigation hints. However, when the same end-effector is used to present both types of information, there is the risk of confusing the source of the force feedback signals. For this very reason we proposed to employ a single-contact point haptic interface to display forces to the operator, providing kinesthetic force feedback to reproduce mechanical properties of the remote tissue and vibration stimuli to reproduce navigation cues.

We assessed the feasibility of providing navigation hints employing vibrotactile feedback and we showed that operators are more efficient at recognizing unexpected obstacles when mixed vibrotactile-kinesthetic feedback is provided with respect to kinesthetic feedback only. Moreover, completion time and accuracy did not significantly deteriorate.

Work is in progress to evaluate the effects of mixing kinesthetic and vibrotactile feedback in different ways, e.g. using kinesthetic feedback for the navigation aid and vibrotactile feedback to display tissue interactions. Work is also in progress to validate the approach with more subjects.

Acknowledgements

This work has been partially supported by the European Commission with the Collaborative Project no. FP7-ICT-2009-6270460, "ACTIVE: Active Constraints Technologies for Ill defined or Volatile Environments".

References

[1] J. Abbott, P. Marayong, and A. Okamura. Haptic virtual fixtures for robot-assisted manipulation. *Robotics research*, 28(1):49–64, 2007.

[2] R. Cholewiak and A. Collins. Sensory and physiological bases of touch. 1991.

[3] B. Davies, M. Jakopec, S. Harris, F. Rodriguez y Baena, A. Barrett, A. Evangelidis, et al. Active-constraint robotics for surgery. *Proceedings of the IEEE*, 94(9):1696 –1704, 2006.

[4] J. Erp, H. Veen, C. Jansen, and T. Dobbins. Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception*, 2(2):106–117, 2005.

[5] A. Ghanbari, X. Chen, W. Wang, B. Horan, H. Abdi, and S. Nahavandi. Haptic microrobotic intracellular injection assistance using virtual fixtures. In *Proc. of 11th International Conference on Control Automation Robotics & Vision*, pages 781–786, 2010.

[6] W. Guo, W. Ni, I. Chen, Z. Ding, and S. Yeo. Intuitive vibro-tactile feedback for human body movement guidance. In *Proc. of IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 135–140, 2009.

[7] B. Hannaford. Task-level testing of the jpl-omv smart end effector. In *Proceedings of the Workshop on Space Telerobotics*, volume 2, 1987.

[8] M. Hashizume, M. Shimada, M. Tomikawa, Y. Ikeda, I. Takahashi, R. Abe, F. Koga, N. Gotoh, K. Konishi, et al. Early experiences of endoscopic procedures in general surgery assisted by a computer-enhanced surgical system. *Surgical endoscopy*, 16(8):1187–1191, 2002.

[9] A. Kazi. Operator performance in surgical telemanipulation. *Presence: Teleoperators & Virtual Environments*, 10(5):495–510, 2001.

[10] C. Kennedy, T. Hu, J. Desai, A. Wechsler, and J. Kresh. A novel approach to robotic cardiac surgery using haptics and vision. *Cardiovascular Engineering*, 2(1):15–22, 2002.

[11] K. Kuchenbecker, J. Gewirtz, W. McMahan, D. Standish, P. Martin, J. Bohren, P. Mendoza, and D. Lee. Verrotouch: high-frequency acceleration feedback for telerobotic surgery. *Haptics: Generating and Perceiving Tangible Sensations*, pages 189–196, 2010.

[12] J. Lieberman and C. Breazeal. Tikl: Development of a wearable vibrotactile feedback suit for improved human motor learning. *IEEE Transactions on Robotics*, 23(5):919–926, 2007.

[13] D. Lorenzo, E. Momi, I. Dyagilev, R. Manganelli, A. Formaglio, D. Prattichizzo, et al. Force feedback in a piezoelectric linear actuator for neurosurgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 7(3):268–275, 2011.

[14] M. Massimino and T. Sheridan. Teleoperator performance with varying force and visual feedback. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 36(1):145–157, 1994.

[15] L. Moody, C. Baber, and T. Arvanitis. Objective surgical performance evaluation based on haptic feedback. *Medicine meets virtual reality 02/10: digital upgrades, applying Moore's law to health*, page 304, 2002.

[16] M. Nakao, K. Imanishi, T. Kuroda, and H. Oyama. Practical haptic navigation with clickable 3d region input interface for supporting master-slave type robotic surgery. *Studies in health technology and informatics*, pages 265–271, 2004.

[17] A. Okamura. Methods for haptic feedback in teleoperated robot-assisted surgery. *Industrial Robot: An International Journal*, 31(6):499–508, 2004.

[18] A. Okamura. Haptic feedback in robot-assisted minimally invasive surgery. *Current opinion in urology*, 19(1):102, 2009.

[19] C. Pacchierotti, F. Chinello, M. Malvezzi, L. Meli, and D. Prattichizzo. Two finger grasping simulation with cutaneous and kinesthetic force feedback. In *Haptics: Perception, Devices, Mobility, and Communication. Eurohaptics 2012*, Lecture Notes in Computer Science, pages 373–382, Tampere, Finland, 2012.

[20] J. Park, J. Choi, Y. Park, and K. Sun. Haptic virtual fixture for robotic cardiac catheter navigation. *Artificial Organs*, 2011.

[21] A. Pillarisetti, M. Pekarev, A. Brooks, and J. Desai. Evaluating the effect of force feedback in cell injection. *IEEE Transactions on Automation Science and Engineering*, 4(3):322–331, 2007.

[22] D. Prattichizzo, C. Pacchierotti, S. Cenci, K. Minamizawa, and G. Rosati. Using a fingertip tactile device to substitute kinesthetic feedback in haptic interaction. In *Haptics: Generating and Perceiving Tangible Sensations. Eurohaptics 2010*, Lecture Notes in Computer Science, pages 125–130, Amsterdam, The Netherlands, 2010. Springer Verlag.

[23] D. Prattichizzo, C. Pacchierotti, and G. Rosati. Cutaneous force feedback as a sensory subtraction technique in haptics. *IEEE Transactions on Haptics*, 5(4):289–300, 2012.

[24] J. Ren, R. Patel, K. McIsaac, G. Guiraudon, and T. Peters. Dynamic 3-d virtual fixtures for minimally invasive beating heart procedures. *IEEE Transactions on Medical Imaging*, 27(8):1061–1070, 2008.

[25] J. Rosen, B. Hannaford, and R. Satava. *Surgical Robotics: Systems Applications and Visions*. Springer Verlag, 2010.

[26] S. Salcudean, S. Ku, and G. Bell. Performance measurement in scaled teleoperation for microsurgery. In *Proc. of Conference on Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer-Assisted Surgery*, volume 1, pages 789–798, 1997.

[27] S. Scheggi, F. Chinello, and D. Prattichizzo. Vibrotactile haptic feedback for human-robot interaction in leader-follower tasks. In *Proc. of ACM PETRA 2012 Workshop on Robotics in Assistive Environments*, 2012.

[28] R. Schoonmaker and C. Cao. Vibrotactile feedback enhances force perception in minimally invasive surgery. In *Proc. of Human Factors and Ergonomics Society Annual Meeting*, volume 50, pages 1029–1033, 2006.

[29] K. Tsukada and M. Yasumura. Activebelt: Belt-type wearable tactile display for directional navigation. *UbiComp 2004: Ubiquitous Computing*, pages 384–399, 2004.

[30] C. Wagner, R. Howe, and N. Stylopoulos. The role of force feedback in surgery: Analysis of blunt dissection. *Haptics*, page 73, 2002.

[31] C. Zilles and J. Salisbury. A constraint-based god-object method for haptic display. In *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots*, volume 3, pages 146–151, 1995.