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Tool/tissue interaction feedback modalities in robot-assisted lump localization

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Abstract— **Providing a surgeon with information regarding contacts made between tools and tissue during robot-assisted interventions can improve task efficiency and reliability. It is hypothesized that various modalities of contact feedback have the potential to enhance performance in a robot-assisted minimally invasive environment. In this paper, (kinesthetic) haptic feedback is compared with visual feedback of haptic information in terms of several performance metrics. Using a haptics-capable master-slave test-bed for endoscopic surgery, experiments involving a lump localization task are conducted and the performance of human subjects is compared for these two modalities of contact feedback. It is shown that the two feedback modalities result in comparable localization accuracies – an advantage of visual haptic feedback due to the lower system complexity required – while the task completion times are significantly shorter with haptic feedback.**

I. Introduction

One of the important obstacles in endoscopic surgery is the significant degradation of kinesthetic/force feedback (haptic feedback) to the surgeon from the instrument and its contact with tissue. As a result, surgical tasks requiring accurate feeling of tissue characteristics such as palpation (probing tissue for determining its characteristics) are difficult to perform endoscopically. On the other hand, to tackle several other limitations of endoscopic surgery, robots have recently been introduced in surgical interventions [1]. Unfortunately, the currently available robotic systems have not yet been successful in terms of restoring feedback of instrument/tissue contacts to the surgeon.

The lack of haptic feedback to the surgeon can cause complications such as accidental puncturing of blood vessels or tissue damage. Indeed, lack of haptic feedback is regarded as a safety concern in endoscopic surgery because it could be potentially dangerous if instruments leave the limited field of view of the endoscopic camera. Furthermore, the endoscopic view can easily deteriorate due to the presence of fluids from the patient's body on the camera lens and can make it difficult for the surgeon to detect tissue damage in the absence of haptic feedback. As a solution to the problems caused by lack of haptic feedback, this paper hypothesizes that alternative modes of sensory feedback about instrument/tissue contacts have the potential to enhance performance during robot-assisted surgical tasks. In the following, we explain the modalities for contact feedback in a minimally invasive environment.

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II. Contact Feedback Modalities

A. Haptic feedback

In master-slave teleoperation with haptic feedback, the surgeon operates from and receives force feedback via a surgeon-robot interface (the master) while a surgical robot (the slave) mimics the surgeon's hand maneuvers inside the patient's body. For reflection of instrument/tissue interactions to the surgeon's hand, the following two devices are needed at the surgeon and patient sides: (a) A force-reflective surgeon-robot interface that transmits hand movements to the surgical robot and instrument/tissue interactions to the surgeon's hand. (b) An endoscopic instrument that acts as the end-effector of the surgical robot and is properly sensorized to measure the contact forces.

In surgical teleoperation, haptic feedback can provide the surgeon with the required perceptual information for optimal application of forces, thus reducing trauma to tissue. It can also shorten the task completion times by eliminating the need for prolonging the maneuvers and awaiting visual cues as to the strength of the grip, the softness of the tissue, etc. Lastly, for instruments with restricted maneuverability as in endoscopic surgery, haptic feedback is expected to improve the precision of manipulation. Research has been done to evaluate the impact of haptic perception on human sensory and motor capabilities for several surgical tasks. For instance, the ability to sense the puncturing of different tissue layers during the needle insertion task improves when users receive haptic feedback [2]. Moreover, study of the effect of force feedback on performing blunt dissection has shown that it reduces the number of errors, the task completion time, and the magnitude of contact forces [3].

B. Sensory substitution for haptic feedback

It has been established that, due to major difficulties in design and technology, incorporating full haptic interaction in a complex surgical system such as the da Vinci (from Intuitive Surgical) demands fundamental system re-designs and upgrades as well as long-term financial and R & D commitments from the manufacturer. However, in the short term and for some applications involving robotic surgery, it may be cost-effective and advantageous to provide alternative modes of sensory feedback to the surgeon, e.g., as visual display of haptic information. While there is more than one way of replacing haptic feedback, e.g., by auditory, visual, and vibro-tactile feedback, in this paper it is hypothesized that visual substitution for haptic feedback can provide sufficient feedback of an instrument's contact with tissue under certain conditions and can improve surgical outcomes. Visual display of haptic information, "visual force feedback", as overlaid on or beside the endoscope view can relay haptic information to the surgeon simply based on the size and/or color of the visual stimuli.

Visual sensory substitution has been found to improve a user's sensitivity for detecting small forces by allowing the use of high feedback gains without slowing down hand movements [4]. For manual and telerobotics operations of a surgical knot tying task, the forces applied in the robotic mode were closer to the forces applied in the manual mode when the users were provided with auditory/visual representation of haptic information [5]. It would be interesting to see the difference between force feedback (FF) and visual force feedback (VFF) in the robotic mode itself.

III. Experimental Setup

A force-reflective master-slave system appropriate for use as an endoscopic surgery test-bed has been developed (Figure 1). Through a user interface (master), the user controls the motion of a surgical tool (slave) and receives force/torque feedback of the slave/tissue interactions. This master-slave system is a useful test-bed for investigating the performance and effectiveness of different modalities for feedback of tool/tissue interaction in soft-tissue applications.

The developed master user interface is capable of providing the user with force feedback in all five degrees of freedom (DOFs) available in endoscopic surgery (pitch, yaw, roll, insertion, and handle open/close). The developed slave's endoscopic instrument is also capable of measuring interactions with tissue in all the five present DOFs. For details about this master-slave system, the reader is referred to another paper published in this proceedings [6].

IV. Experiments

Using the master-slave system, teleoperation experiments involving a tissue palpation task were conducted. Palpation is frequently used by surgeons to estimate tissue characteristics and its effectiveness greatly depends on haptic sensations. In the experiments, the master and slave subsystems were constrained for force-reflective teleoperation in the twist direction only (i.e., rotations about the instrument axis). The user twists the master causing the slave to probe the tissue using a small rigid beam attached to the slave's end-effector (Figure 1). The instrument interactions with tissue are in the form of torques about the instrument axis. This torque is measured and reflected to the user. In the haptic interface, the friction/gravity effects are determined and compensated for such that the user does not feel any weight on his/her hand when the slave is not in contact with an object.

In the following case study, two contact feedback modalities are compared in terms of their capability in transmitting critical task-related information to the user. For experiments involving visual substitution for haptic feedback, sixteen light-emitting diodes form a bar indicator for the magnitude of forces (Figure 1).

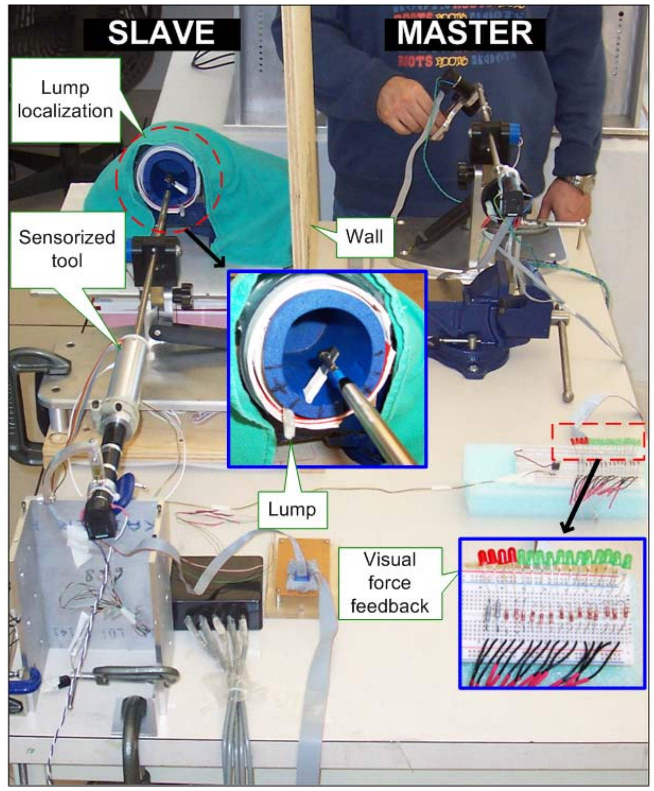

Fig. 1. Setup for telemanipulated lump localization.

A. Case study: VFF versus FF during lump localization

Experiments involving human subjects have been previously reported in the literature that compare the performance of users for a certain surgical task between the case of manual operation and the case of robotic operation with auditory/visual substitution for haptic feedback [5]. The question we would like to address is what the difference in terms of performance is between haptic feedback and visual substitution for haptic feedback during robotic operation. The task considered in this case study is to localize a lump embedded in a compliant environment.

1) Experiment design: Six subjects (2 males and 4 females) aged 24-34 participated in our experiments. The subjects were engineering students with little to average exposure to haptic feedback and visual substitution for haptic feedback. The task was to locate a rigid lump, which was embedded in an unknown location in a finite-stiffness homogeneous tissue model made from rubber. Lump localization was based on exploring the model and receiving haptic feedback using the master-slave setup (Figure 1). The lump was placed in one of five locations at approximately 34, 65, 92, 124 and 158 degrees with respect to the horizon. The size of the lump (5 mm) was chosen such that users could detect the lump in a reasonable amount of time. Each lump localization trial started from orienting the master handle (and the slave's end-effector) such that it was horizontal followed by twisting the handle to explore the tissue until the handle was again horizontal on the other side (equal to a wrist rotation of $+180^\circ$ for the user).

The subjects' primary goal was defined as pinpointing the lump by centering the slave end-effector on it. The subjects were told that the task completion time was a secondary performance metric that needed to be minimized, yet they could take their time if it helped to minimize the primary performance metric (i.e., localization error). This is different from most of the previous studies on sensory substitution, which have considered task completion time as the only metric for performance comparisons. A task was considered complete upon the subject's verbal signal that the lump was found.

Each subject performed two sets of tests with a short break between them. In each test, each of the five lump locations was presented twice to the subject: once in the presence of visual force feedback (VFF) about the levels of instrument/tissue interaction, and once in the presence of force feedback (FF). Therefore, in each test there were 10 trials (i.e., 10 combinations of lump location and feedback mode). The trials within a test were presented in a randomized order to the subjects. Before the experiments, each subject was given 3-4 practice trials until he or she felt comfortable with the operation of the master-slave system.

The subjects did not have camera vision from the slave side in order to keep tissue deformation cues from playing a role in lump localization – we do not consider nodules that can be visually detected through moving tissue. Also, to mask any audio feedback that can result from the friction between the tissue model and the slave's end-effector, the subjects wore headphones that played music loud enough to mask out any external sounds.

Prior to the experiments, each subject was briefed that our goal was to compare the user performance under visual force feedback and kinesthetic force feedback. In each trial of each test, the instrument/tissue contact forces, the end-effector position, and the task completion time were recorded. In addition to localization accuracy and task times, we also compared the energy supplied to tissue as lower energy corresponds to less trauma and probably less tissue damage.

2) Results: The bar graph of Figure 2a displays the statistics of the slave's final end-effector positions (radians) for the different lump locations. As is apparent from the error bars (standard deviations), there is consistency in terms of the detected position of each lump. Table I contains the means ($\mu_{\rm pe}$) and standard deviations ($\sigma_{\rm pe}$) of the position errors for the five lump locations. The values of mean position errors in this table suggest that VFF achieves higher levels of localization accuracy. In order to test this hypothesis and determine the nature of variations of the position errors, we used a two-tailed t-test and obtained the probability of the null hypothesis $\mu_1 = \mu_2$ for the five lump locations. The probability of the results assuming the null hypothesis for lump locations 1 to 5 were $p = 0.00019$, $p = 0.028$, $p = 0.515$, $p = 0.413$, and $p = 0.714$, respectively. These results indicate that for lump locations 3, 4, and 5, there is no significant difference in mean localization error between

TABLE I

LUMP LOCALIZATION ERROR STATISTICS

	Lump Location	1	2	3	4	5
VFF	$\mu_{\rm pe}$ (rad)	-0.009	0.003	0.026	0.009	0.005
	$\sigma_{\rm pe}$	0.091	0.079	0.084	0.069	0.072
FF	$\mu_{\rm pe}$ (rad)	0.123	0.078	0.049	-0.022	-0.010
	$\sigma_{\rm pe}$	0.108	0.103	0.150	0.167	0.150

VFF and FF. This might be partly due to the fact that the subjects experienced some difficulty in localizing the first two lump positions as they were too close to the starting point of the slave. In order to further investigate the accuracy of lump localization, we performed a one-way ANOVA test on the localization error statistics of the five lump locations for both VFF and FF ($F(4, 82) = 0.4589$, p-value$= 0.766$ for VFF; and $F(4, 82) = 3.31$, p-value$= 0.014$ for FF). These results indicate that the localization error means do not vary significantly across the five lump locations for VFF, but do vary significantly for FF.

Figure 2b depicts the statistics of the time (seconds) taken to localize a lump in each of the five locations. As a general observation, the mean localization time is significantly longer with VFF than with FF (267%, 192%, 201%, 151%, and 195% longer for lump locations 1 to 5, respectively). Right-tailed t-tests between VFF and FF for localization times of each lump location confirm this observation ($p = 4.515 \times 10^{-5}$, $p = 0.0013$, $p = 0.00017$, $p = 0.00036$, and $p = 0.00011$ for lump locations 1 to 5, respectively). The subjects were instructed to localize the lumps as accurately as possible regardless of the exploration time, which justifies the high levels of standard deviation in the time statistics. In order to investigate the effect of lump positions on the exploration time, a one-way ANOVA test was conducted on the exploration time statistics of the five lump locations for both VFF and FF ($F(4, 82) = 1.119$, p-value$= 0.353$ for VFF; and $F(4, 82) = 2.579$, p-value$= 0.043$ for FF). These results confirm the fact that the exploration time means do not vary significantly across the five lump locations for VFF but vary significantly for FF.

Figure 2c depicts the statistics of the energy (Joules; calculated as $\int_0^T f(t)v(t){\rm d}t$ where T, f, and v are the task completion time, the contact force, and the slave's velocity, respectively) supplied to the tissue during lump localization for each of the five lump locations with VFF and with FF. Excluding the first location, FF-based lump localization seems to supply more energy to tissue in comparison to VFF. Again, we tested this hypothesis by means of a right-tailed t-test ($p = 0.006$, $p = 0.141$, $p = 0.204$, $p = 0.001$, and $p = 0.003$ for lump locations 1 to 5, respectively). These results show that the mean of the energy supplied to tissue under VFF and FF varies significantly for lump locations 1, 4 and 5. A one-way ANOVA test for the energy over the five lump locations yielded $F(4, 82) = 2.96$, p-value$= 0.0244$ for VFF and $F(4, 82) = 2.812$, p-value$= 0.0306$ for FF, which indicate significant variations across the five lump locations for both modalities.

3) Discussion: The following trends were observed in lump localization performance with VFF and with FF:

1. The subjects were 100% successful in localizing the lumps under both VFF and FF with position errors significantly less than half the average distance between the lumps. No consistent trend was observed in favor of either approach with respect to the localization accuracy except for a weak tendency for better accuracy with VFF. Considering the lower system complexity required for implementing VFF, even an equivalent level of accuracy can be regarded as an advantage for VFF. However, it must be noted that with VFF, a user can perform well only if the sensitivity and resolution of the visual display is sufficiently high so that small variations in the reflected force become discernible.

2. The exploration time for VFF is considerably longer than for FF. This observation is justifiable given the fact that with VFF, the subjects have to constantly refer to the visual display in order to detect a significant variation in the contact force profile, which corresponds to a lump. Therefore, while providing visual feedback about instrument/tissue interaction is useful for the purpose of lump localization, the corresponding task times are longer due to the need for cognitive processing by the users. This conclusion is consistent with previous results for teleoperation of non-surgical tasks [4]. From the user's point of view, VFF's moderate need for human processing and interpretation, especially for dexterous tasks, in which the user has to keep track of several visual indicators and switch his/her attention between them without getting distracted from the main surgical task, may be a major drawback particularly for lengthy procedures (sensory overload).

3. With regard to the energy supplied to the tissue by the users, the results are not consistently in favor of either VFF or FF. The higher levels of supplied energy under FF for three locations (out of five) seem to be a result of the fact that the localization ability under FF is proportional to the slave's velocity. In contrast, the slower the slave moves, the higher the localization ability will be under VFF.

V. CONCLUDING REMARKS

A haptics-capable master-slave test-bed was used to study the effect of different modalities of tool/tissue contact feedback in the context of a soft tissue task. For localization of a lump embedded in a soft tissue, performance comparisons were made for situations in which haptic feedback is substituted by visual display of haptic information. It was observed that the localization accuracy is comparable for VFF and FF, meaning that in cases where a haptic user interface is not available, visual force feedback can adequately and cost-effectively substitute for force feedback. However, this comes at the expense of longer task completion times for VFF.

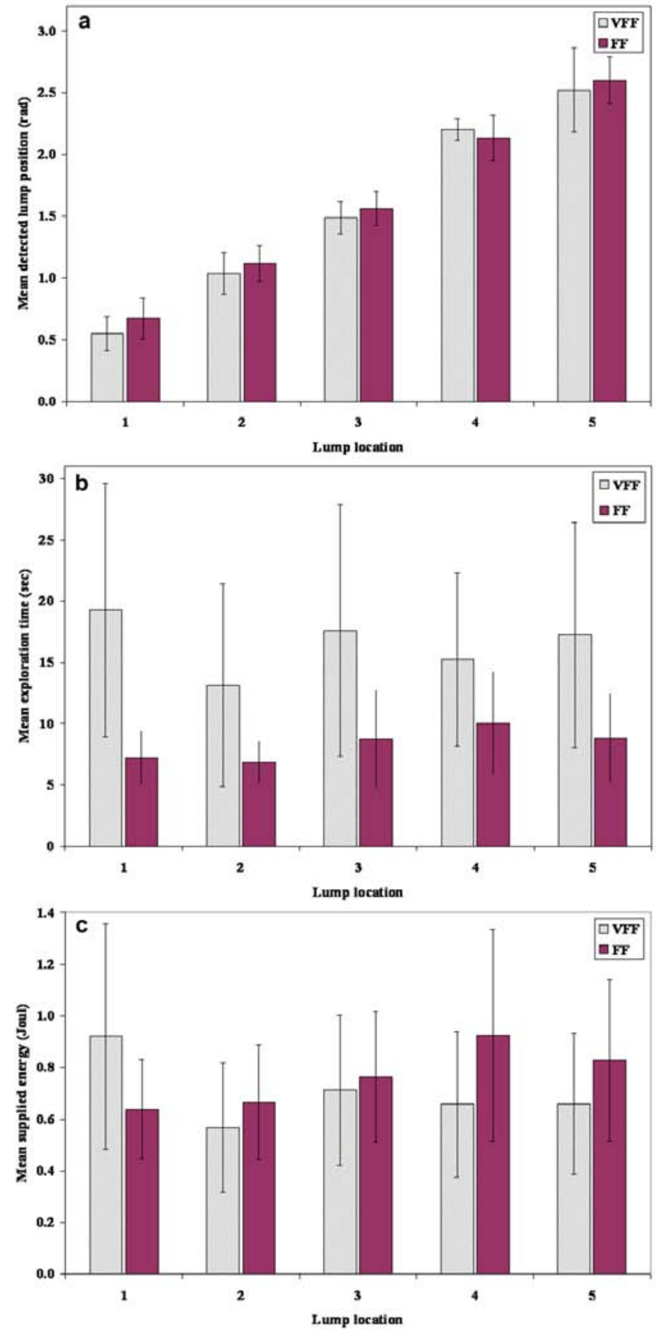

Fig. 2. (a) Mean detected lump position (rad); (b) mean exploration time (sec); (c) mean energy supplied to the tissue (Joul). Error bars show standard deviations.

REFERENCES

[1] R. H. Taylor and D. Stoianovici. Medical robotics in computer-integrated surgery. *IEEE Transactions on Robotics and Automation*, 19:765–781, 2003.

[2] O. Gerovichev, P. Marayong, and A. M. Okamura. The effect of visual and haptic feedback on manual and teleoperated needle insertion. In T. Dohi and R. Kikinis, editors, *5th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI)*, pages 147–154, 2002.

[3] C. R. Wagner, N. Stylopoulos, and R. Howe. The role of force feedback in surgery: analysis of a blunt dissection. In *10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 68–74, Orlando, FL, 2002.

[4] M. J. Massimino. *Sensory substitution for force feedback in teleoperation*. PhD thesis, MIT, Cambridge, MA, 1992.

[5] M. Kitagawa, D. Dokko, A. M. Okamura, and D. D. Yuh. Effect of sensory substitution on suture manipulation force for robotic surgical systems. *Thorac Cardiovasc Surg*, (129):151–158, 2005.

[6] M. Tavakoli, A. Aziminejad, R. V. Patel, and M. Moallem. Multi-sensory force/deformation cues for stiffness characterization in soft-tissue palpation. In *Proceedings of IEEE 2006 International Conference of the Engineering in Medicine and Biology Society*, New York, NY, 2006.