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Multi-sensory force/deformation cues for stiffness characterization in soft-tissue palpation

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Abstract— **In the commercially available robot-assisted surgical systems, camera vision constitutes the only flow of data from the patient side to the surgeon side. This paper studies how various modalities for feedback of interaction between a surgical tool and soft tissue can improve the efficiency of a typical surgical task. Utilizing a haptics-enabled master-slave test-bed for minimally invasive surgery, user performance during a telemanipulated soft tissue stiffness discrimination task is compared under visual, haptic, graphical, and graphical plus haptic feedback modes in terms of task success rate and completion time and the amount of energy transfer and consequently trauma to tissue. While no significant difference is found in terms of the task completion times, graphical cueing and visual cueing are found to lead to the highest success rate and the highest risk of tissue damage (proportional to energy), respectively.**

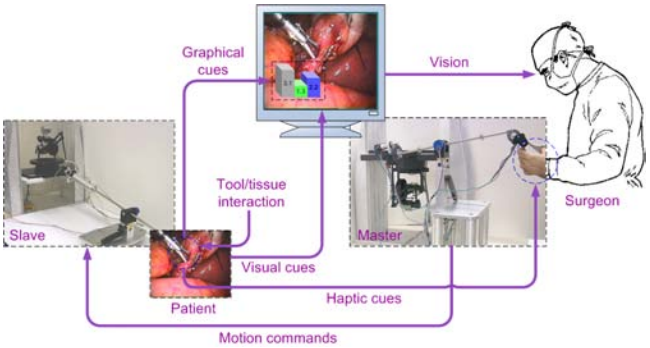

Fig. 1. Block diagram of master-slave teleoperation with several flows of sensory cues from the slave to the master.

I. INTRODUCTION

A master-slave system for robot-assisted minimally invasive surgery consists of three main parts: a robotic arm that holds and controls the endoscope, robotic arms that hold and actuate the surgical instruments, and a human-machine interface (HMI) for the robots. In such a system, as shown in Figure 1, the surgeon operates using the HMI (the master) while the surgical robot (the slave) follows the surgeon's hand maneuvers (transmitted from the HMI) inside the patient's body. For feedback of tool/tissue interactions to the surgeon's hand during master-slave teleoperation, it is imperative to have a force-reflective HMI that reflects tool/tissue interactions to the surgeon's hand in addition to a surgical robot that is properly sensorized to measure its interaction with tissue. This amounts to a need for a fundamental system re-design and upgrade in today's complex surgical systems (e.g., the da Vinci from Intuitive Surgical Inc.) before full haptic interaction can be incorporated in robot-assisted surgery. In the current surgical systems, there are only unilateral flows of surgeon's hand motions and camera vision data from the surgeon side to the patient side and vice versa [1], [2].

Haptic feedback in robot-assisted surgery can help to optimally apply forces on tissue, can shorten the task completion times, and can improve the precision of manipulation. On the other hand, the lack of haptic feedback to the surgeon is regarded as a safety concern in minimally invasive surgery because it would be potentially dangerous if instruments leave the limited field of view of the endoscopic camera. Furthermore, the endoscopic view can easily deteriorate due to fluids from the patient's body clouding the camera lens or due to network impairments in IP-based video streaming.

Video streaming over IP networks is increasingly becoming the technology of choice for a wide range of network multimedia applications including live video transmission in telerobotics-assisted surgery and therapy. Real-time IP applications that use TCP/IP, unlike best-effort applications that use UDP, must be transported through a network with minimal latency. In this method of transmission, the video quality can be easily affected by network congestion resulting in poor video quality at the surgeon side [3].

Degraded visual conditions caused by IP network impairments or other factors such as signal-to-noise degradation in wireless communication [4] or depth perception difficulties in 2-D vision can make it difficult to prevent tissue damage in the absence of haptic sensation for the surgeon. To tackle some of the shortcomings resulting from the absence of haptic feedback, in the short term and for some applications involving robotic surgery, it may be adequate and cost-effective to provide alternative modes of sensory feedback to the surgeon, e.g., through graphical representation of haptic information. In this paper, it is hypothesized that such cues can provide sufficient feedback of an instrument's

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contact with tissue under certain conditions and can improve surgical outcomes. Figure 1 shows how haptic feedback can be substituted by graphical cues overlaid on or beside the endoscope view to relay haptic information to the surgeon based on the size and/or color of the visual stimuli [5], [6]. In this paper, we study the effects of visual, haptic and graphical cues about tool/tissue interactions on user's performance for a typical surgical task.

II. EXPERIMENTAL SETUP

A force-reflective master-slave system appropriate for use as an endoscopic surgery test-bed has been developed (Figure 2). Through the master interface, a user controls the motion of the slave arm and receives force/torque feedback of the slave-environment interactions. The master is capable of providing the user with force sensation and kinesthetic sensation of the elasticity of an object in all five degrees of freedom (DOFs) available in endoscopic surgery (pitch, yaw, roll, insertion, and handle open/close). See [7] for a detailed description of the haptic master interface. The developed slave arm is an endoscopic instrument capable of actuating the open/close motions of a tip and rotations about its main axis. Due to the problems posed by the incision size constraint in minimally invasive surgery, strain gauge sensors are integrated into the end effector to provide a non-invasive way of measuring interactions with tissue in all the five present DOFs. For more information about the slave, see [8].

This master-slave system is a useful test-bed for investigating the performance and effectiveness of different tool/tissue interaction feedback modalities in soft-tissue applications. The Virtual Reality Peripheral Network (www.vrpn.org) has been used for network-based communication such that the slave can be telemanipulated from the master. Due to the proximity of the components of the master-slave system, the communication latency is negligible. To ensure that the user has accurate perception of a remote object's compliance, we implemented a "4-channel" haptic teleoperation control scheme that uses weighted summations of the master and slave forces as well as the difference in the positions of the master and the slave [9].

In the experiments in this paper, 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 2). The instrument interactions with tissue are measured and reflected in real-time to the user. In the haptic master 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 our experimental scenario, the visual link consisted of a 320 × 240 webcam-provided image, which is transmitted from the slave side to the master side via a H.323-based NetMeeting Internet video-conferencing application at a rate of 14 frames per second. The communication media was a 1000T-base Ethernet network. In order to present graphical cues about the levels of tool/tissue interaction forces, sixteen light-emitting diodes, which form a bar indicator for the magnitudes of forces, were located beside the screen that showed the tissue site to the user (see Figure 2).

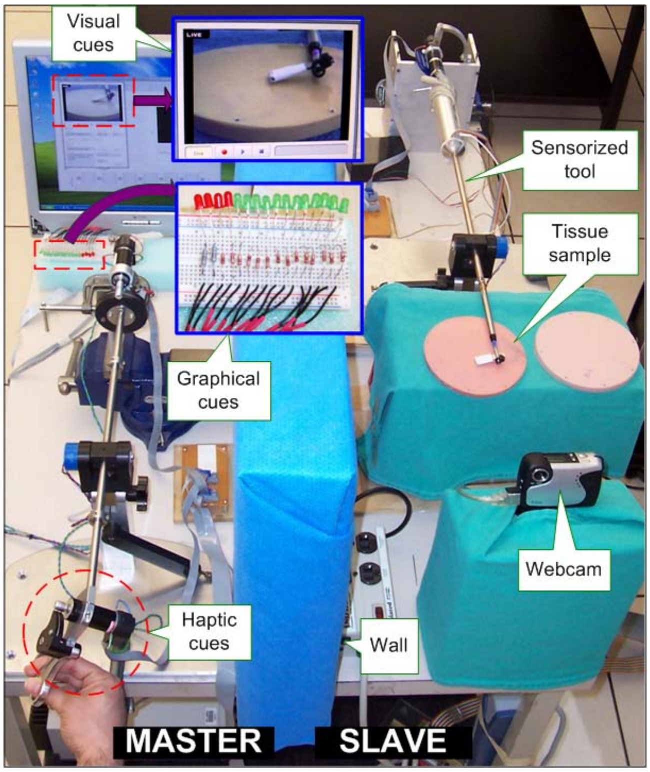

Fig. 2. Setup for telemanipulated tissue palpation.

III. EXPERIMENT DESIGN

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. The specific task considered here is to discriminate between any two soft tissues with different stiffnesses through telerobotic palpation. Several contact feedback modalities are compared in terms of their capability in transmitting critical task-related information to the user.

Six subjects (3 males and 3 females) aged 24-34 participated in our experiments. The subjects had average exposure to haptic and visual cues and average experience with the master-slave system. The subjects' primary goal was defined as distinguishing between different tissues in terms of their relative stiffness. After a tissue sample was presented to the subject and probed, it was replaced with a different or the same tissue sample upon the subject's verbal signal. The subjects would also verbally signify the completion of the task.

The subjects received visual, haptic, graphical, or graphical plus haptic cues about the level of tool/tissue interactions forces as the tool indented the soft tissue (see Figure 2). Since our intention was to study the utility of haptic and graphical feedback under degraded or suppressed visual conditions, camera vision from the slave side was switched off when the subjects received haptic and/or graphical cues so that visual cues did not play a role.

In each trial, one out of the above-mentioned four different feedback modalities and a combination of two out of three different tissue samples (two different tissues or the same tissue twice) were presented to the subject. In total, each subject made 16 trials (i.e., 16 combinations of feedback modality and tissue pair randomly selected out of the 24 possible combinations). The trials 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.

Each palpation trial started from orienting the master handle (the slave's end-effector) in vertical (horizontal) position followed by twisting the handle to explore the tissue (user's wrist rotation angle $\in$ $[0 \ 90°]$). Prior to the experiments, subjects were briefed that our goal was to compare the user performance under various cueing modes. In each trial, the tool/tissue interaction forces, the end-effector position, and the task completion time were recorded. In addition to task success rate and task times, we also compared the energy supplied to tissue since lower energy corresponds to less trauma and probably less tissue damage. The energy was calculated as $\int_0^T f(t)v(t)\mathrm{d}t$ where T, f, and v are the task completion time, contact force, and slave's velocity, respectively.

IV. RESULTS

The test results for the palpation task are shown in Figure 3 in the form of bar graphs of mean values. Figure 3a shows the trials' success rate for the four different feedback modes. As can be seen, graphical cueing is the most successful modality for tissue stiffness discrimination. To further investigate this, first a one-way ANOVA test was applied to the success rate statistics of the feedback modes ($F(3, 92) = 1.426$, p-value= 0.2401), which did not indicate significant difference among the success rate statistics. Due to the pass/fail nature of the tests (1: successful; 0: unsuccessful) and for a more accurate analysis, we used separate t-tests between different pairs of feedback modes. A two-tailed t-test between graphical and visual feedback modes ($t(24) = 1.163$, $p = 0.257$) shows no significant difference. However, a right-tailed t-test between the graphical and haptic feedback modes ($t(24) = 1.813$, $p = 0.0415$) indicates higher success rate for graphical feedback compared to haptic feedback. Another two-tailed t-test between haptic and haptic plus graphical feedback modes showed them to be almost identical ($p > 0.5$).

The bar graph of Figure 3b represents the mean values of task completion times (seconds) for different feedback modes. No clear trend can be deduced for task completion times. An ANOVA test for the four feedback modes ($F(3, 92) = 0.7627$, p-value= 0.5178) shows that there is no significant difference among the average task times.

Figure 3c shows the mean values of the energy supplied to tissue (Joules) under the four feedback modes. This graph indicates that the haptic plus graphical mode (very closely followed by haptic mode) and the visual mode supplied the lowest and the highest energy to tissues, respectively. An ANOVA test confirms significant difference between the haptic, graphical and visual modes from the energy point of view ($F(2, 69) = 6.3806$ corresponding to p-value= 0.000241, which based on 5% level of ruling for p-values implies significantly different mean energies). In order to further study the closeness of the mean supplied energy under the haptic and the haptic plus graphical modes, we used a right-tailed t-test, which confirmed that the null hypothesis $\mu_1 = \mu_2$ holds ($t(24) = 0.7355$ corresponding to $p = 0.2347$). Right-tailed t-test between the supplied energy statistics of graphical and haptic feedbacks ($t(24) = 2.069$, $p = 0.025$) shows that the mean supplied energy for the graphical mode is significantly higher than that for the haptic mode. Finally, a right-tailed t-test between visual and graphical feedback modes ($t(24) = 2.247$ corresponding to $p = 0.01725$) shows that visual cues supply significantly higher energy to tissue.

V. DISCUSSION

After analyzing the results of the palpation trials, the following trends were observed:

1. Since a subject had to decide whether the two tissue samples were "similar", "the first one softer compared to the second one", and "the first one harder compared to the second one", the chance level was 33%. Therefore, all of the success rates are well above this chance level. As for the relative success rate of different feedback modalities, the results show that for a task involving the comparison of force/deformation tissue characteristics, graphical cueing is advantageous over haptic cueing. One reason for the superior performance achieved with graphical cues compared to haptic cues is that the sensitivity of a graphical force indicator is only limited by the resolution of the force measurements, while the sensitivity of the human hand for force sensing is limited in nature (0.5 N or 7% is the just-noticeable difference [10]). The superiority of the graphical mode comes along with the benefit of simplicity of its implementation. On the downside, one should bear in mind that the domain of tasks that can benefit from graphical cues is not very extensive as with increased task complexity/dexterity (e.g., increase in a task's number of degrees of freedom), there can be a tremendous increase in the cognitive processing required by the user. An advantage of haptic cues is that they are intuitive and require the least amount of cognitive processing.

As for the success rate with visual cues, it was observed during the experiments that the depth of tissue indentation could not be precisely quantified by the subjects. While this may make one expect the success rate to be significantly lower for visual cueing compared to the graphical cueing, this was not corroborated by the two-tailed t-test – a fact that may be attributed to the relatively low number of trials (a total of 96 trials as a result of having 6 subjects and 16 trials per subject; an average of 24 trials per feedback modality). The success rate for visual cues strongly depends on the video's information content, which in turn can be attributed to various task-dependent and task-independent factors ranging from network conditions for IP-based video streaming to the camera's angle of view. For example, task performance might be seriously degraded if critical movements of the task are orthogonal to the camera view causing depth perception problems.

Although one might have expected that the graphical plus haptic mode resulted in a significantly higher success rate compared to haptic feedback, this was not corroborated by the two-tailed t-test that was done. In practice, it was observed that during the subjects' simultaneous exposure to the haptic and graphical cues in this particular task, they had strong tendencies toward the haptic portion, which made the statistics quite similar to those of the pure haptic mode.

2. With respect to task completion time, no concrete deduction can be made in favor of any of the utilized feedback modes. One's expectation would be that haptic cues result in the shortest task times, but in practice this was not the case due to the fact that the tissue stiffnesses were not significantly different and subjects needed to palpate each tissue usually more than once.

3. The worst performance in terms of supplying energy and consequently incurring damage/injury to tissue was provided by the visual cueing mode, in which the quality of images directly affects the sense of tissue indentation conveyed to the subject from the slave side. Moreover, a subject would have to supply a significant amount of energy before tissue deformations are quantifiable. As a result, the distance between the visual mode and the other modalities with respect to the supplied energy to tissue is quite noticeable.

VI. CONCLUDING REMARKS

In this paper, we compared users' performance under visual, haptic, graphical, and graphical plus haptic feedback modalities for a soft-tissue palpation task. Our goal was to study how effectively the graphical and/or haptic cues can replace a corrupted visual cue. It was found that graphical cueing leads to the highest rate of success in discriminating between two tissue samples with different stiffnesses, while visual cueing incurs the highest risk of tissue damage due to excessive tissue deformation. With respect to task completion times, no clear difference was observed between the different feedback modalities.

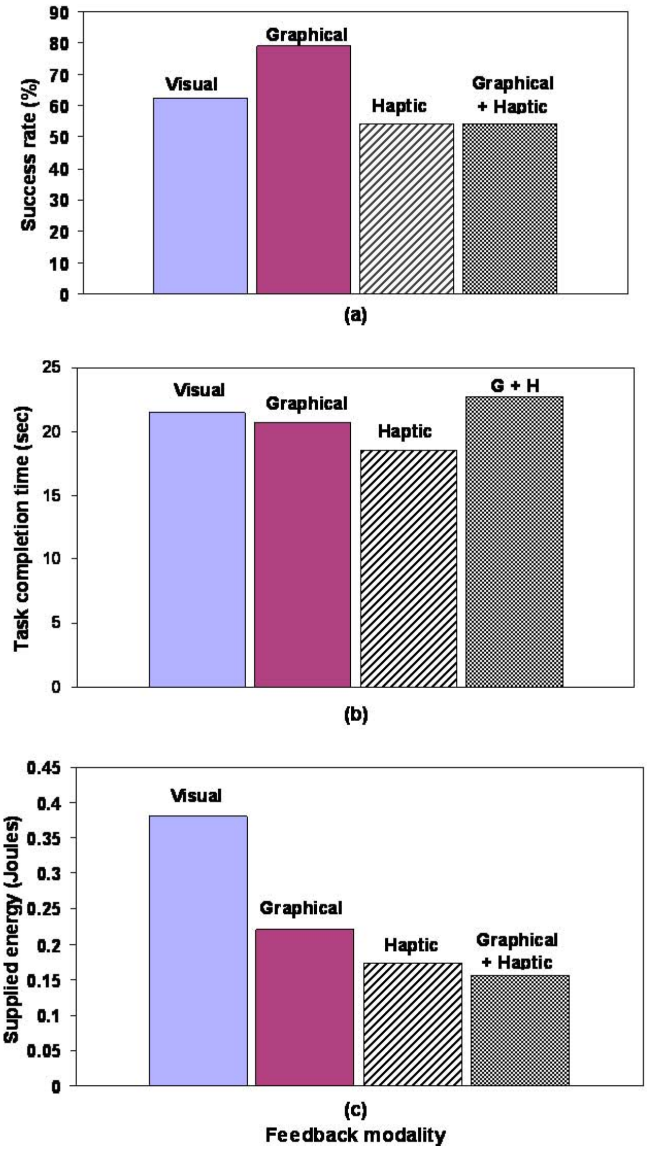

Fig. 3. (a) Mean success rate; (b) mean completion time (sec); (c) mean energy supplied to the tissue (Joul).

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