Potential Tissue Puncture Notification during Telesurgery

Rachael L'Orsa[1], Kourosh Zareinia[2], Liu Shi Gan[2,3],
Chris Macnab[1], and Garnette Sutherland[2]

[1] Department of Electrical and Computer Engineering,
[2] Project neuroArm, Faculty of Medicine,
University of Calgary, Canada
{ralorsa,cmacnab,kzareini,garnette}@ucalgary.ca
[3] IMRIS Inc., Winnipeg MB, Canada
lgan@imris.com

Abstract. This paper proposes the use of vibrotactile feedback during telesurgery to notify surgeons of potential tissue puncture. Puncture trials using an experimental telesurgical apparatus were performed on an artificial membrane to characterize general force ranges at which punctures occur. The average force threshold during puncture was established, and human operators then attempted to apply a maximum force to the membrane without causing a puncture via the telesurgical apparatus. As the surgical tool-tip approached the pre-established force threshold, a wrist-mounted haptuator worn by the operators vibrated a warning. Warnings via different sensory modalities (auditory and tactile) were compared both with and without force feedback. Results show that the use of a warning via either sensory modality decreases the maximum force applied by the operator, thereby decreasing the occurrence of unintentional punctures. The inclusion of force feedback achieved similar results, though task completion times were significantly increased.

Keywords: haptics, haptuator, keyhole surgery, teleoperation, telesurgery, tissue puncture.

1 Introduction

The 'minimally invasive' or 'keyhole' paradigm for surgery or microneurosurgery offers many advantages to patients over traditional surgical approaches, such as decreased postoperative hospitalization times, improved cosmesis, and reduced surgical site infections [1], [2]. However, it decouples surgeons from their sense of touch, reduces their dexterity within the patient's body, and has a steep learning curve [3]. The use of telesurgical robots can alleviate many of these drawbacks [4], [5], [6], [7], but currently no commercially-available systems restore the sense of touch to surgeons, i.e. incorporate haptics. This lack of sensation can lead to difficulties ascertaining tissue condition and/or properties [8], which can in turn lead to the unintentional perforation of blood vessels and other critical

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structures. These unintentional punctures constitute one of the major sources of complications for minimally invasive surgical procedures, particularly during initial entry into the patient's body [9]. A telesurgical system that could assist surgeons in identifying tissue condition and properties using alternative sensory channels and also provide notifications of high applied forces could potentially ease surgeon workload during surgery while reducing surgical complications.

This paper seeks to introduce a new method for avoiding unintentional tissue puncture by providing surgeons with additional sensory (particularly haptic) feedback during telesurgical procedures. To our knowledge, this is the first application of haptic feedback for force threshold notifications in the surgical field. Some research has been done comparing the use of visual, auditory, and tactile feedback for notifying drivers of impending collision events, where it was found that haptic feedback was less invasive [10] and more alerting [11] than the other two modes alone. Some studies have found that multisensory notifications rendered synchronously can have an additive effect, such as when auditory notifications paired with their tactile counterparts appeared to be louder [12].

While these studies report mixed findings for the efficacy of single channel versus multisensory feedback for vehicle operators, there are no comparable results in the literature for telesurgery and no indications that findings from these studies would generalize to activities such as tele-microneurosurgery. Most experimental haptics research to date for telesurgery has focused on the accurate reproduction of force feedback for surgeons (and to a much lesser extent, vibrotactile feedback [13]), haptic displays [14] and sensors [15] to allow for tissue property determination via telepalpation or surgical simulation [16], and haptic fixtures [17] to provide fixed position-based safety controls during surgery. While haptic fixtures are the most commonly applied haptic safety control for telesurgical systems, such so-called forbidden regions generally neither allow for modulation of applied forces nor permit surgeons the autonomy to decide to proceed if it is safe or necessary to do so, with very few exceptions [18]. Thus this study represents a first foray into vibrotactile notifications to reduce unintended tissue puncture during telesurgery.

Furthermore, the importance of haptic (particularly force) feedback to surgical tasks remains a controversial topic, with very little data available in the literature to either support or contradict its inclusion in telesurgical systems. We seek to add to this body of knowledge by investigating the impact of force feedback on our puncture notification trials.

The remainder of this paper is divided as follows: Section 2 introduces the experimental design and apparatus, Section 3 describes the results, and Section 4 provides conclusions and future directions.

2 Experimental Design

Experiments utilize a custom prototype 7 degree of freedom (DOF) telesurgical system, though it remains in Z-lock with movement restricted solely to the Z-axis. A square metal tube (1.5" x 1.5" x 3") forms a simulated membrane enclosing an air-filled cavity, achieved by mounting it on a wooden base for stability and fitting it with an adhesive strip of translucent plastic. This flat and taut artificial membrane, while dissimilar from real tissue, allows for a relatively static contact geometry during tool-tip interactions. An automated, increasing orthogonal force repeatedly disturbs the artificial membrane until the system's end-effector tool-tip punctures through it. These trials establish an average puncture force, which in turn establishes a range of threshold forces at which warnings should occur during teleoperation.

2.1 Apparatus

Figure 1 depicts a basic schematic diagram of the system setup. A SensAble Phantom Premium 3.0L/6DOF haptic interface is used as he master, controlling a Kuka KR-6 slave robot for all experiments. A custom 7th DOF in the form of an actuated fine gripper microsurgical tool coupled with an ATI Gamma 6DOF force/torque sensor attaches to the robot's end-effector. The tool allows for precision gripping and rolling, and while neither function is utilized for these experiments, the tool's actuators remain powered throughout to maintain its grip and roll at constant values. The Premium 3.0 reproduces forces from the Gamma with some scaling (a force gain of 0.8) but without smoothing when its amplifiers are activated.

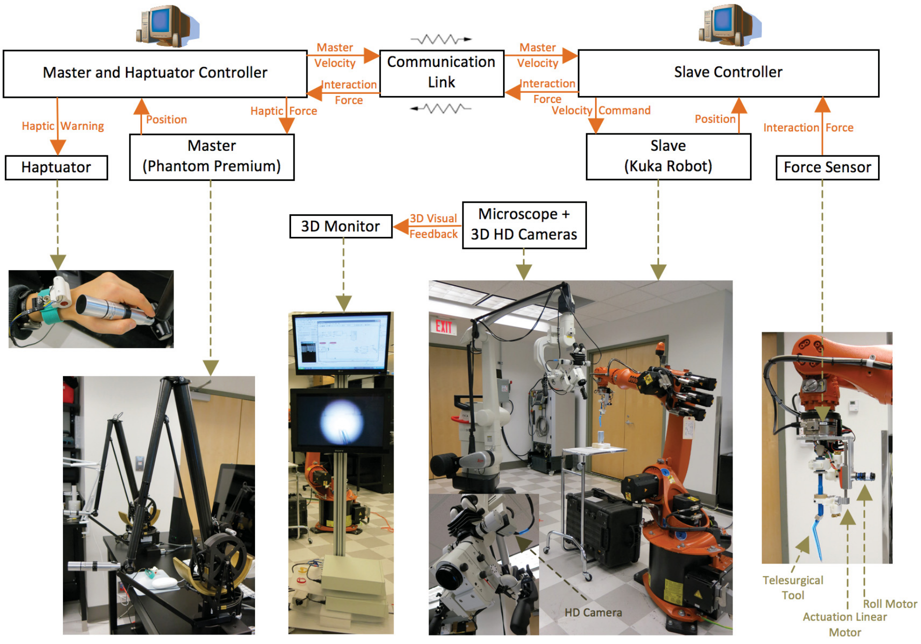

Fig. 1. System diagram

A Dell Dimension 4700 with a 3.0GHz Pentium 4 processor running 32-bit Windows XP Professional SP3 with 4GB of RAM processes information for the master system, connecting the Premium 3.0, an external speaker, and a haptuator. The haptuator provides high-bandwidth, iron-free, recoil-based electromagnetic vibrotactile actuation at different frequencies and amplitudes [19]. Microsoft Visual C++ 2010 interfaces between the haptuator, the external speaker, and the master PC via the UDP protocol.

The slave system uses a custom PC with a 3.3GHz Intel CORE i5 processor running 32-bit Windows 7 Professional SP1 with 4GB of RAM. The slave PC connects to the Kuka workstation and a Quanser Q2-USB data acquisition board (DAQ). The Quanser DAQ interfaces with the precision grip/roll motor, the force sensor and its accompanying hardware (a National Instruments DAQ and signal conditioning box provided by ATI), and a linear Faulhaber minimotor with accompanying controller for actuating the custom microsurgical tool. Matlab/Simulink R2011a with Quanser QUARC 2.2 blocks provides a real-time interface between hardware and the master and slave PCs respectively. Master and slave PCs communicate over a LAN via the TCP/IP protocol.

Also, a Leica M525 OH4 surgical microscope coupled with two Ikegami HDL 20D microscope camera systems, a Sony LMD2451MD LCD monitor, and RealD 3D glasses provides a magnified real-time 3D video feed of the tool-tip's interaction with the artificial membrane.

2.2 Characterization of Average Puncture Force

The slave robot starts at a home position where the angles for joints 1 through 6 are [0 -90 76 0 103 0] degrees respectively. As previously mentioned, the linear actuator for the custom microsurgical tool maintains a ‘closed’ position. The artificial membrane sits on a free-standing tray centered approximately one inch below the slave robot end-effector's tool-tip. A Matlab/Simulink program controls the end-effector's tool-tip as it advances in the negative direction along the Z-axis (i.e. down, into the membrane) with a constant velocity of 0.01 m/s, until stopped by an experimenter when membrane puncture is visually and audibly confirmed. The slave robot then reinitializes to its home position, and a new artificial membrane is fitted for the next experiment.

Twenty such individual trials are performed using the automated program to help maintain experimental conditions between trials. The maximum force for each trial defines the puncture force. As the variance in puncture force is low, the average puncture force from all twenty trials defines the force threshold (hereafter referred to as the ‘puncture-force threshold’) for the real-time potential puncture notification trials that follow.

2.3 Real-Time Potential Puncture Notification

Defining a force margin allows operators time to react to a potential puncture notification before they apply forces that exceed the predefined puncture-force threshold. All notification trials use a roughly 50% force margin, though future experiments should investigate the impact of this factor on operator response. Depending on the trial, notifications are generated by either the haptuator (for a vibrotactile warning), the external speaker (for an auditory warning), or both. As identified through preliminary trials, the two major sources of variance between experiments are the operator and the type of feedback (or lack thereof) applied. Each of the eight sets of trials has its own code, as shown in Table 1, where a given set either serves as a control (visual feedback only, no warnings) or defines the type of feedback applied.

Table 1. Set codes

FF	V	V + H	V + A	V + H + A
no	S1	S2	S3	S4
yes	F1	F2	F3	F4

The top four sets (S1 through S4) are visual feedback only (V), visual and haptic (vibrotactile) feedback together (V + H), visual and auditory feedback together (V + A), and all three types of feedback together (V + H + A). The bottom four sets (F1 through F4) are the same, but include force feedback (FF).

For the first sets (S1 and F1), a real-time 3D video feed provides visual feedback of the tool-tip's interaction with the artificial membrane, and operators must gauge their applied force based on the minimal (∼2mm) membrane deformation alone. The second sets (S2 and F2) provide vibrotactile haptic feedback via the wrist-mounted haptuator. The haptuator is mounted on the operator's non-dominant wrist, i.e. not on the arm with which they operate the haptic interface. The characteristics of the haptic and auditory feedback (a 60 dB, 0.02 second 'beep' repeated at a frequency of 50 Hz) is kept constant throughout all trials for all operators, as is the position of the external speaker.

Five successful trials are performed by each operator for each of the eight sets of experiments, where a successful trial is one in which no puncture occurs. Thus any given data set may contain more than five trials if punctures do occur, but the data for each operator will contain exactly five trials for which the operator caused no punctures. For each consecutive trial, a pseudo-random integer generator in Matlab chooses which set to apply. Operators are unaware of this choice and cannot anticipate either notifications or force feedback. The forty successful trials constitute one block, which is then repeated by different operators. Two operators, one with no previous teleoperation experience and one with a multi-case history of neuroArm [20] operation, perform the full experiment. Both are neurosurgeons, but neither is trained on the experimental apparatus.

The operators familiarize themselves with the system via 3-5 initial trials. They then apply as much force as possible to the artificial membrane using the telesurgical setup, without causing a puncture and without decreasing the applied force, until they are satisfied that they have achieved a maximum.

3 Results

Since the variance in puncture force during characterization trials was 0.14 N, the 13.4 N average for all twenty force characterization trials became the puncture-force threshold for the real-time potential puncture notification trials. Given the roughly 50% force margin (rounded down to the nearest integer), this means that notifications occurred when operators applied a force in excess of 6.0 N to the membrane.

Figure 2 compares the force data for all five successful trials of one operator's S4 and F4 sets. Force feedback trials show lower forces yet higher task completion times. The force fluctuations in the F4 sets is typical of operators unaccustomed to force feedback, and highlights the need for further investigation into ideal amounts of training.

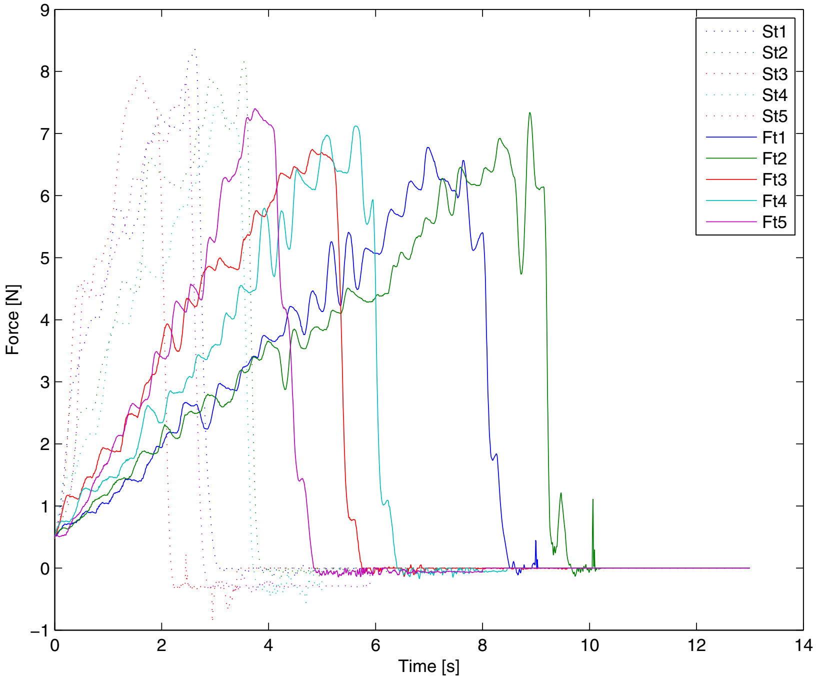

Fig. 2. Representative comparison of data with and without force feedback

The maximum force, the time to achieve maximum force, and a Boolean denoting puncture occurrence are stored as metrics for each trial. Within each of the eight sets, maximums, minimums, and means are calculated that reveal several general insights:

1. On average, the use of notifications decreased the amount of applied force and the task completion time regardless of sensory modality.
2. There were no discernible trends between modalities.
3. On average, the use of force feedback decreased the amount of applied force yet increased the task completion time regardless of sensory modality.

Multiple ANOVAs performed in Excel on the experimental data using a value of $\alpha = 0.05$ support these findings. Table 2 shows the number of punctures caused by each operator over all sets of trials. By inspection, the number of punctures differs between operators, though neither caused any punctures when audio or the combination of haptic and audio notifications were applied.

Table 2. Puncture results

Operator	$S1$	$S2$	$S3$	$S4$	$F1$	$F2$	$F3$	$F4$
1	4	0	0	0	2	0	0	0
2	2	1	0	0	0	0	0	0

Table 3 shows a summary of the total punctures caused by both operators. In general, fewer punctures occurred when any type of notification was applied. Furthermore, the inclusion of force feedback decreased the number of punctures that occurred both with and without notifications.

Table 3. Summary of warning impact on total punctures

Set	No Warnings	Warnings
S	6	1
F	2	0
Both	8	1

Applied forces and task completion times for all successful trials for both operators were compared with respect to the use of force feedback. Table 4 shows that on average, 8.16% less force was applied by the operators when force feedback was used, though it took them 95.62% longer to complete the task. These effects were confirmed as being significant via ANOVAs, by an $F = 4.71 > F_{\text{critical}} = 3.97$ with $p = 0.03$ for the applied forces and an $F = 29.17 >> F_{\text{critical}} = 3.97$ with $p < 0.001$ for the task completion times. No significant variation was attributed to the differences between operators. That the use of force feedback produces fewer punctures is likely due to this decrease in applied force.

Table 4. Comparison of results with and without force feedback

FF	Ave. Force [N]	Ave. Time [s]
no	8.91	2.82
yes	8.18	5.52
% change	-8.16	95.62

Applied forces and task completion times for all successful trials for both operators were also compared with respect to the use of notifications. Table 5 highlights the percent increase or decrease in the average applied force and task completion times when no notification was used (set codes S1 and F1), versus when only haptic notifications (S2 and F2), only audio notifications (S3 and F3), both haptic and audio notifications (S4 and F4), or any kind of notifications (S2 through S4 and F2 through F4) were used. In general, decreases of 22.57% in average applied force ($F = 97.11 >> F_{\text{critical}} = 3.92$ with $p < 0.001$) and 34.61% in average task completion time ($F = 17.55 >> F_{\text{critical}} = 3.92$ with $p < 0.001$) were achieved with the use of any type of notification. Again, no significant variation was attributed to the differences between operators.

Table 5. Comparison of results with and without notifications

Type of warning	Ave. Force [N]	% Change	Ave. Time [s]	% Change
none	10.29	N/A	5.64	N/A
haptic	8.25	-19.78	3.16	-43.98
audio	7.72	-24.91	3.38	-39.97
both	7.92	-23.03	4.52	-19.88
any	7.96	-22.57	3.69	-34.61

Though it appears from Table 5 that purely audio feedback and purely haptic feedback most successfully decreased the applied force and task completion times respectively, the ANOVAs indicated no significant variation could be attributed to the effect of the type of notification on either metric. However, the differing reactions of the two operators to the various types of notifications were significant for applied force ($F = 5.49 > F_{\text{critical}} = 4.02$ with $p = 0.02$).

4 Conclusion

Based on this preliminary investigation, it appears that giving operators a scale (i.e. warnings) with which to gauge their proximity to a given force threshold allows them to moderate forces applied during telesurgery and thus to avoid unintentional tissue punctures. Of the sensory channels tested for this paper, it was not possible to identify whether auditory, haptic, or a combination of the two improved operator performance the most. However, it was found that both the inclusion of force feedback and the provision of notifications through either modality decreased applied forces, though at the cost of increased task completion times for force feedback. Follow-up experiments should be performed in a clinical setting and expanded to a group of operators with a larger sample size. A characterization of operator preferences regarding feedback modalities for notifications during surgery should be performed, and the impact of varied force margins for notifications should be explored. An investigation of reaction times based on notification modality would be appropriate, and a comparison of operator performance between fully random trials (as reported in this paper) and set-random trials (where the sets are performed in random order, but all five trials within a set are performed consecutively) could give insight into learning curves for the operation of such systems. Furthermore, a comparison of operator performance with and without feedback anticipation (when the operators are expecting to receive a notification and thus rely less on visual information) could help determine a more clear relationship between sensory feedback channels and surgical performance.

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