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Visual and tactile feedback for a direct-manipulating tactile sensor in laparoscopic palpation

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Abstract

Background

Laparoscopic surgery limits surgeons' tactile sense that can contribute to intraoperative tumor detection.

Methods

We have developed a simple and biocompatible tactile sensor. This study aimed to design and evaluate visual and tactile feedback from the sensor for laparoscopic tumor detection. A line graph was offered through a monitor as the visual feedback. A normal force was presented to the user's foot as the tactile feedback. Twelve novices conducted a detection task of a phantom tumor for 4 conditions (no feedback, visual feedback, tactile feedback and a combination of both types of feedback).

Results

The visual feedback was significantly more effective in detection than no feedback. Moreover, both visual and tactile feedback led to safer manipulation with significantly smaller load and lower scanning speed, respectively.

Conclusions

The results suggest that visual and tactile feedback can be useful for laparoscopic palpation; however, their effects depend on the ways of presentation.

Keywords

laparoscopy; palpation system; tumor detection; sensory feedback

1. Introduction

Laparoscopic surgery provides many benefits to patients compared to conventional open surgery. On the other hand, surgeons have faced some limitations; in particular, input from their tactile sense is hardly available. Laparoscopic resection of an early-stage gastric tumor, which is located on the inner surface of the stomach and invisible from outside the stomach, is conducted on the basis of the information obtained by preoperative marking under per-oral endoscopy. However, intraoperative detection of the tumor is quite difficult because the tumor cannot be visually detected through a laparoscopic image and the stomach mostly deforms during the surgery. If the surgeons' tactile sense were compensated, they could detect the tumor through palpation because tumors are generally stiffer than normal tissue [1-3]. Intraoperative tumor detections might reduce unnecessary resection of normal tissue, and thereby, enhance the quality of laparoscopic surgery.

Many research groups have tried to achieve intraoperative tumor detection in minimally invasive surgery such as laparoscopic surgery. For instance, automated palpation systems with a Gaussian process adaptive sampling [4], a force modulation strategy abstracted from human manual palpation [5], machine learning algorithms [6], and

simultaneous estimation of stiffness distribution and registration [7] were developed. Although automated palpation can achieve high accuracy and repeatability, the control scheme might be extremely difficult in a surgical situation. Thus, these studies investigated system performances only at a preliminary level such as using fixed tissue phantoms.

Moreover, master-slave surgical systems with force estimation [8, 9], a BioTac tactile sensor [10], strain gauges [11], and a tactile sensing array [12, 13] were developed. In these systems, surgeons can adjust slave movements according to the target tissue and conduct tumor detection on the basis of feedback from master consoles. Although surgeons can get benefits such as motion scaling and tremor reduction, the systems tend to be expensive and complex, which impedes widespread application. Moreover, intuitive manipulation of the master console is important, but hardly any knowledge on how to design such a system exists.

For laparoscopic palpation, a tactile sensor using an optical sensing scheme [14], a grasper with multiple force-sensing elements [15], palpation probes with a pressure sensing array [16, 17], a wireless sensing capsule [18] and a tactile sensor using a piezoelectric vibrator [19] were developed. These devices have a long and thin shape like a forceps or a small shape like a capsule, which can be grasped by a forceps. Thus, surgeons can directly manipulate these devices in the same way as for laparoscopic instruments. However, these devices have some complexity and they are less cost-effective because of the use of multiple sensing elements for the devices. Regarding surgical applications, a simple and low-cost tactile sensor is preferred for using the sensor in a disposable manner. It also should have electrical safety for body tissue and applicability to sterilization. In palpation systems with direct manipulation, visual feedback such as using a color map is popular whereas the use of tactile feedback is less often considered.

We have developed a forceps-type tactile sensor for laparoscopic tumor detection [20]. The sensor has high surgical applicabilities such as having suitable dimensions, electrical safety for body tissue, simple structure, low-cost and sterilization adaptability. Our scenario is that a surgeon directly manipulates the sensor and performs tumor detection based on realtime feedback from the sensor. The sensory feedback for tumor detection also affects on manipulation movement. In manual palpation, humans use complex modulation strategies of contact force and scanning speed [5, 21]. These studies imply that humans appropriately change their motor control according to the sensory information and the current sensing environment. We attempted to utilize human sensory-motor ability and bring adaptable and robust sensing by giving sensory feedback to the surgeon.

It is an important research question how the information measured by a tactile sensor should be fed back to the surgeon in such a way that performance and effectiveness improve [22]. In master-slave surgical systems, there are studies to investigate the effectiveness of various ways of feedback. For instance, Gwilliam *et al.* investigated the effects of haptic and visual force feedback on identification performance of an embedded rigid object and exploratory movements [9]. Tavakoli *et al.* compared visual and force feedback in terms of lump localization performance, exploration time and supplied energy to the tissue [11]. On the other hand, in palpation systems with a directly manipulated tactile sensor, there are few studies considering the use of tactile feedback whereas visual feedback is popular as mentioned above. To the best of our knowledge, there is no study comparing the effects of various ways of feedback on system performance and exploratory movements for palpation systems with direct sensor manipulation.

In this study, we aim to design and evaluate ways of feedback from the tactile sensor for laparoscopic tumor

detection. We considered two ways of feedback that could be of use in surgical applications. One is visual feedback through an extra monitor placed next to the laparoscope monitor. Another is tactile feedback; we developed a tactile display using a voice coil motor for presentation of a normal force to the surgeon's foot, which is a so-called unclean area. Thus, the tactile display does not need to be sterilized for clinical use. A psychophysical experiment with a detection task using phantoms of the stomach wall with/without a tumor was conducted in a simulated laparoscopic setup for 4 conditions regarding feedback from the tactile sensor; no feedback, only the visual feedback, only the tactile feedback and a combination of the visual and the tactile feedback. During the experiment, pressing force and sensor position were measured to analyze the behavior of participants. Moreover, we conducted a few informal trials with four expert surgeons to assess the practical effectiveness of the sensory feedback. The findings in this study offered good suggestions for the design of the feedback methods for laparoscopic tumor detection.

2. Materials and methods

2.1. Tactile sensor

We have developed a tactile sensor using acoustic reflection for laparoscopic tumor detection [20]. The sensor uses a long and thin acoustic cavity with a deformable part as a sensing area, a speaker and a microphone. A sinusoidal acoustic wave with a single frequency is continuously inserted into the acoustic cavity. The sensor can detect the deformation magnitude due to the force applied to the sensing area by measuring the amplitude of the acoustic wave in the cavity. The sensor does not have any electrical elements within the part that is inserted into a patient's body. It has high applicability to laparoscopic surgery because it has suitable dimensions and electrical safety for body tissue. It can also be used in a disposable manner because of its low fabrication costs.

Figure 1 shows the tactile sensor for the laparoscopic palpation system. The sensor is composed of a sensor tip having the sensing area, an aluminum tube and a handle in which the speaker and the microphone were embedded. We used a sinusoidal acoustic wave with a frequency of 3065 Hz, which was determined according to results of theoretical analyses [20] and the experimental resonance characteristics of the sensor used. The sampling frequency of the sensor is 1 kHz. The sensor detects a uniaxial force applied to the sensing area, which is located on the side of the tip. Thus, if the surface of the target tissue is continuously scanned by the tactile sensor, tumor detection can be conducted on the basis of the temporal change of the sensor output.

2.2. Feedback ways of the sensor output

2.2.1. Visual feedback

A line graph on a monitor is offered to the user. The height of the line graph on the monitor $h(x,t)$ at a time t is given by the following equations;

$$\begin{aligned} & \text{if } t \leq T \\ & h(x, t) = \begin{cases} C_v e_v \left(\frac{T}{L} x \right) & \left(x \leq \frac{L}{T} t \right) \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (1)$$

$$\begin{aligned} & \text{if } t > T \\ & h(x, t) = C_v e_v \left(t - T \left(1 - \frac{x}{L} \right) \right) \end{aligned} \quad (2)$$

where, $x \in [0, L]$ shows the horizontal axis on the monitor, $L = 238$ mm is the width of a presenting area, and $C_v = 159$ mm/V is the gain of the visual feedback. The line graph offers the time history for $T = 5$ s. $e_v(t)$ is the sensor output smoothed by a low-pass filter with a cut-off frequency of 10 Hz to reduce noise. Figure 2 shows the typical visual feedback when the user scans phantoms of the stomach wall with/without a tumor. The user can see two peaks if they appropriately scan the outside surface of a phantom with the tumor in a lateral direction. The tumor has a toroidal shape (details are provided in “Stimuli” section), and the sensor responds with two small peaks in this case. The typical sensor output was about 0.03 V peak to peak; thus, the height of the peaks was about 4.8 mm on the monitor. The typical distance between the monitor and participants' eye-position was about 1 m.

2.2.2. Tactile feedback

The body part to which the tactile feedback will be applied is an important factor to consider in the design of a clinical device. Although the finger has better tactile sensitivity compared with other areas of the body, the necessary sterilization of a tactile display on the finger imposes serious design issues. The foot is a better choice because it is an unclean area of surgeons, and a tactile display for the foot does not need to be sterilized. Schoonmaker *et al.* attempted vibrotactile feedback to the bottom of the foot according to forces measured at a surgical tool tip for minimally invasive surgery [23]. They showed that the addition of vibrotactile feedback provided better control of force application.

In this study, we developed a tactile display using a voice coil motor for the user's foot. The tactile display was designed to present a normal force to the upper side of the foot (instep) since this area has higher tactile sensitivity to static pressure than other areas of the foot [24]. Figure 3 shows the tactile display for the instep. It is composed of a voice coil motor (AVM30-15, Akribis Systems Japan Co., Ltd.), a linear guide, a rubber hemisphere, a flexible stand and a base. The display can be fixed by placing the user's foot on the base. The rubber hemisphere guarantees stable contact with the instep.

The tactile display presents a force on the basis of the sensor output as shown by the following equation,

$$f(t) = C_t e_t(t) \quad (3)$$

where, $C_t = 196.9$ N/V is the gain of the tactile feedback. If the typical sensor output is obtained as shown in Figure 2(a) (0.03 V peak to peak), the tactile display presents a force of 5.9 N peak to peak. The gain was determined on the basis of a preliminary experiment so that participants clearly felt the force change due to the tumor but did not feel pain. If the user appropriately scans the phantom with the tumor, they can feel two sequential peaks in the same way as the

visual feedback. The refresh rate of the force presentation is 250 Hz. $e_t(t)$ is the sensor output filtered by a band-pass filter with a band-width of 0.5–10 Hz. According to Weber's law [25], a just noticeable difference in a stimulus is proportional to the intensity of the standard stimulus. If the tactile feedback is linear for the sensor output, the offset force during contact with a phantom brings less sensitivity for small force changes due to the tumor. Thus, the high-pass portion of the filter acts to reduce the offset of the sensor output.

3. Psychophysical experiment

We investigated the effects of the ways of feedback on user performance and exploratory movements through a psychophysical experiment. Our scenario in this study is that surgeons preoperatively know the position of the tumor by per-oral endoscopy. Then, the surgeons intraoperatively determine a region of interest based on pre-known information, and they inspect the region with the tactile sensor to discriminate whether the region includes the tumor or not. Thus, we employed a detection task to assess the fundamental effect of the sensory feedback on discrimination of two types of stimuli with different subsurface features (with/without the tumor).

3.1. Participants

Twelve persons (6 male and 6 female, age range 18–24, mean 21) were paid to participate in this experiment. All participants were strongly right-handed according to Coren's test [26]. They did not have any medical background. They gave their written informed consent before participation. The experimental procedure was conducted in accordance with the ethical standards of the Helsinki Declaration and approved by the Ethical Committee of Nagoya Institute of Technology.

3.2. Stimuli

The detection target is a 0-IIc (superficial ulcerative) type tumor, which is the most common type of an early stage gastric cancer. The tumor is located on the mucosal side of the stomach wall and cannot be detected visually from the serosal side in laparoscopic surgery. We designed phantoms of the stomach wall with/without the tumor on the basis of the typical dimensions and softness of the actual stomach wall and the 0-IIc type tumor. Figures 4(a) and (b) show the phantoms used in the experiment. The phantoms had a length of 180 mm, a width of 120 mm and a thickness of 9 mm. They have two layers made of two different polyurethane gels. One layer is a harder sheet made of a gel with the hardness of Asker C 2 (Hapla Pudding Gel, PL-5, POLYSIS Co., Ltd.) imitating the serosa of the stomach wall. The other layer is a softer sheet having folds made of a gel with the hardness of Asker C 0 (Hapla Pudding Gel, PL-00, POLYSIS Co., Ltd.) imitating the mucosa. The tumor is made of the same gel as the harder layer. The thicknesses are 2 mm and 7 mm for the harder and the softer layer, respectively. The tumor has a toroidal shape, and the cross section of the phantom with the tumor is shown in Figure 4(c). The outer diameter of the tumor is 20 mm, the inner one is 13 mm, and the height is 8 mm. We compared the stiffness of surgically resected stomachs and the phantom through the measurement with a durometer (ASKER Durometer Type FP, Kobunshi Keiki Co., Ltd.). The stomachs and phantom

were placed on a rigid plate, and the durometer was pressed against them from the mucosal side. For the actual stomachs, the mean stiffness was Asker FP 34 (value range 0–68) for the normal area and Asker FP 44 (value range 20–100) for the tumor area. The mean stiffness of the phantom was Asker FP 63 for the normal area and Asker FP 81 for the tumor area. Although the phantom has higher stiffness than the actual stomach and tumor, these values are not largely different because they lay in the stiffness range of the actual stomach and tumor. Each phantom was placed on a base, where a urethane sponge with a thickness of 20 mm was stuck on the surface of a semicylindrical acrylic base with a radius of 30 mm, as shown in Figure 4(d) to imitate that the stomach does not have flat surfaces. Moreover, the stomach is located on the ventral side of the pancreas, which is a harder organ than the stomach and fixed to the retroperitoneum with minimal deformation. Thus, we assumed that the phantom on a sponge created a condition similar to that of the actual one.

3.3. Setup

Figure 5 shows the experimental setup. It was composed of a laparoscopic training box (Endowork-Pro II, Kyoto Kagaku Co., Ltd.), a 12 mm-trocar (ENDOPATH XCEL CB12LT, Ethicon Inc.), a camera, a monitor for displaying the camera image, the tactile sensor, a laptop PC for the visual feedback and the tactile display. The participants stood in front of the training box during the experiment. They were asked to wear headphones playing white noise to avoid hearing sound from the acoustic tactile sensor although the sound was hardly audible. All participants wore the same socks prepared for the tactile display. The participants used their right hand for manipulation of the sensor and always placed their right foot on the base of the tactile display. They could always see the monitor that presented the camera image regardless of the experimental condition. To avoid visual detection of the tumor, the training box was covered with a black cloth and the camera image was a little blurred by adjusting the focus. A marker (black circle) was attached above the sensing area for easy observation of the sensor position.

The stimuli were placed on a 3-axis force sensor (Gamma SI-32-2.5, ATI Industrial Automation, Inc.), and they were fixed to the inside of the training box to keep their position constant regardless of random stimulus presentation. The position and posture of the sensor were measured by a motion capture system (OptiTrack, NaturalPoint, Inc.) with 6 cameras, which were located over the experimental setup and the participant. A custom-made marker set (4 spherical markers) was fixed to the sensor for rigid body registration of the sensor. Exerted force and sensor movements were measured at sampling frequencies of 1 kHz and 120 Hz, respectively.

3.4. Experimental design

The experiment consisted of the following 4 conditions regarding the feedback from the tactile sensor; no feedback condition (N), the visual feedback condition (V), the tactile feedback condition (T) and combined the visual and tactile feedback condition (VT). In condition N, the participants did not receive any feedback from the system. In condition V, the laptop PC presented the line graph according to Equations (1) and (2) but the tactile display did not work during the experiment. In condition T, the tactile display presented the normal force according to Equation (3). The laptop PC did not present any meaningful information and only showed a constant line graph at zero regardless of the sensor output. In condition VT, the participants received both visual and tactile feedback. In all conditions, direct haptic information

was always available because participants physically interacted with the stimuli through the rigid sensor probe.

To reduce learning effects, each condition was conducted on a different day. Figure 6 shows an example of the experimental procedure for one participant. The interval of each condition was more than 24 hours, and all participants completed the 4 conditions within 3 weeks. The order of the conditions was counterbalanced across the participants. Each experimental day consisted of a practice session and an experiment session.

3.4.1. Practice session

The participants practiced the sensor manipulation under the corresponding condition. They were asked to memorize the difference of the corresponding feedback when they palpated the stimulus with/without the tumor by the sensor. They were informed that the tumor was always located at the horizontal center of the phantom, and they were allowed to switch the stimulus with/without the tumor if they wanted. The practice session consisted of the following two parts.

First practice was conducted outside the training box. The main purpose of the first practice was to become familiar with the characteristics of the tactile sensor. The participants were instructed to laterally and continuously scan the surface of the phantom by the sensor. They were informed that the sensing area is located at the side of the sensor tip, and they were instructed to adjust the longitudinal sensor position if they could not perceive the feedback from the sensor. The time limit of the first practice was 5 minutes. The time limits in the practice session were determined on the basis of a preliminary experiment so that the participants had sufficient time for their practices.

In the second practice, the participants practiced the sensor manipulation inside the training box. The main purpose was to practice the sensor manipulation in the actual experimental situation. The participants could not directly see the stimulus and the sensor movement and could only see through the camera image. The time limit of the second practice was 10 minutes.

3.4.2. Experiment session

In the experiment session, a two-alternative-forced-choice procedure was employed. The participants were asked to answer “yes” (tumor was present) or “no” (tumor was absent) on the basis of the corresponding feedback. Each trial had a 30 seconds limit. They were asked to discriminate the stimulus as quickly as possible and also to grade the confidence in their answer on a scale between 1 (not confident at all) to 100 (very confident). The response time was measured with a stopwatch. If the participants ran out of the time limit, they were forced to stop the sensor manipulation, and then, to report a binary answer and a confidence rating. This session contained 50 trials in total. The first 10 trials were treated as practices, and the participants received the correct answer after each trial. Five of each stimulus type (with/without tumor) were randomly presented in these 10 trials. If the percent correct was less than chance level (50%), the participants were allowed to practice again inside the training box with a 5 minutes limit except for the no feedback condition. After the extra 5 minutes practice, no further practice trials with feedback were given. Five of the participants needed these extra 5 minutes. The remaining 40 trials were actual trials, and the results were used for analyses. Twenty of each stimulus type were randomly presented. In the actual trials, the participants were allowed to have about 5 minute breaks after each 10 trials.

3.5. Data analysis

3.5.1. Detection sensitivity

In this study, we aimed to reveal the sensitivity of the participants to distinguish the stimuli with/without tumor. In a yes-no experiment, a hit rate $H \in [0, 1]$ (the proportion of “yes” responses when the tumor is present) and a false alarm rate $F \in [0, 1]$ (the proportion of “yes” responses when the tumor is absent) can be calculated. If participants achieve better sensitivity, the hit rate and the false alarm rate approach to 1 and 0, respectively. Here, using either the hit rate or the false alarm rate as detection sensitivity is inappropriate because they are contaminated by participant's criterion (willingness to say “yes”). Thus, applying signal detection theory [27] is one of the solutions to remove the influence of the criterion, where both the hit rate and the false alarm rate are considered for calculation of a sensitivity index.

In addition, the detection strategy of participants can be analyzed through receiver operating characteristic (ROC) curves, which show pairs of (F, H) for different criterions. When the criterion increases and decreases, a point on a ROC curve approaches to $(0, 0)$ and $(1, 1)$, respectively. Here, the basic detection theory assumes normal distributions of internal response against repeated stimulus presentations, and an entire ROC curve can be estimated from a single pair of (F, H) (an example is shown in Figure 7 as a black dashed line). However, preliminary analyses revealed that underlying distributions were no longer normal; thus, we tried to plot empirical ROC curves from binary responses and confidence ratings of the participants. There were $2N$ ($= 200$) possible responses (binary answers $\times$ the total number of levels on the rating scale) from a participant for each trial. Since confidence ratings indicate participants' criterion [27], we can derive multiple pairs of (F_i, H_i) , ($i = 1, \dots, 2N - 1$). By plotting and connecting all pairs of (F_i, H_i) on the ROC space, the empirical ROC curve can be drawn (an example is shown in Figure 7 as a black solid line). Then, the area under the empirical ROC curve can be used as a sensitivity index without any model assumption. To calculate the area under the ROC curve, each area under a series of trapezoids were summed up as the sensitivity index A_g as follows [28];

$$A_g = \frac{1}{2} \sum_{i=0}^{2N-1} (F_{i+1} - F_i) (H_{i+1} - H_i) \quad (4)$$

where (F_0, H_0) equals $(0, 0)$, and (F_{2N}, H_{2N}) equals $(1, 1)$. A_g ranges from 0 to 1, and chance level is 0.5.

3.5.2. Data extraction

We calculated the average normal force and scanning speed during each trial in the experiment sessions. Here, the left-right, the front-back and the vertical directions of the force sensor were defined as y -, x - and z -axis, respectively, as shown in Figure 5. The y -axis force was defined as tangential force. The resultant of the x - and z -axis forces was defined as normal force. All forces were smoothed by low-pass filters with a cut-off frequency of 10 Hz. We used the tangential force to extract each lateral scanning, and the threshold was set to 10% of the maximum tangential force during each trial because the range of the tangential force varied widely between participants. The motion capture

system provided the position and posture of the marker set, which was fixed near the handle of the sensor. The three-dimensional position of the center of the sensing area was calculated from the positional relationship between the sensing area and the marker set. The scanning speed at the center of the sensing area was calculated by using the sampling period (1/120 s). The calculated scanning speed was filtered with a low-pass filter with a cut-off frequency of 5 Hz to reduce numerical noise.

3.5.3. Statistical test

Effects of the experimental condition on detection performance and the exploratory movements were investigated through statistical tests. The significance level was set to 0.05. Before analyses, a Shapiro-Wilk test was conducted to check whether the all dependent parameters were distributed normally. If the Shapiro-Wilk test was violated, a non-parametric Friedman test was conducted to compare obtained parameters between the 4 conditions. In case a significant result was obtained, post-hoc 6 Wilcoxon signed rank tests for all possible combinations were conducted with Holm-Bonferroni correction. If the assumption of the normal distribution was confirmed, Mauchly's sphericity test was conducted to confirm the assumption of homogeneity of variance. Then, a one-way repeated ANOVA with experimental condition as a factor was conducted. If the assumption of homogeneity of variance was violated, Greenhouse-Geisser correction was applied. In case a significant result was obtained, post-hoc 6 paired *t*-tests were conducted with Holm-Bonferroni correction.

4. Results

4.1. Detection performance

Figure 8 shows empirical ROC curves for each experimental condition. The area under the ROC curve A_g was calculated as detection sensitivity for each participant. Figure 9 shows the detection sensitivity, the confidence of answer and the response time for all participants. White, light gray, dark gray and black bars indicate the results for conditions N, V, T and VT, respectively. Statistical tests were conducted to investigate the effect of the condition (and the experimental order) on the detection sensitivity, the confidence rating and the response time.

4.1.1. Detection sensitivity

Figure 10(a) shows the detection sensitivity for the experimental conditions. The horizontal line inside the box shows the median. The top and bottom of the box show the upper quartile Q_3 and lower quartile Q_1 , respectively. The upper and lower whiskers show the maximum and minimum values within $[Q_1 - 1.5 \text{ IQR}, Q_3 + 1.5 \text{ IQR}]$, where $\text{IQR} = Q_3 - Q_1$. Open circles show outliers. A non-parametric Friedman test on the detection sensitivity for experimental condition showed a significant influence of condition ($\chi^2(3) = 11, p = 0.011$). Wilcoxon signed rank tests showed a significant difference between conditions N and V ($W(12) = 5, p = 0.029$). This result shows that the detection sensitivity in condition V is significantly higher than that in condition N.

Figure 10(b) shows the detection sensitivity for the experimental order. A Friedman test on the detection

sensitivity for experimental order showed no significant influence of the order ($\chi^2(3) = 3.8, p = 0.28$). The result indicates that the order of the condition did not significantly affect the sensitivity.

4.1.2. Confidence of answer

Figure 10(c) shows the confidence rating for condition. An ANOVA showed a significant influence of condition ($F(1.8, 20) = 6.6, p = 0.0078$). Paired t -tests showed a significant difference between conditions N and V ($t(11) = 3.3, p = 0.042$). This result is similar to that of the detection sensitivity for condition.

4.1.3. Response time

Figure 10(d) shows the response time for condition. An ANOVA showed no significant influence of condition ($F(3, 33) = 1.2, p = 0.32$). This result shows that the condition did not significantly affect response time.

4.2. Exploratory movements

Figure 11 shows the normal force and the scanning speed for all participants. Statistical tests were conducted to investigate the effect of condition on the exploratory movements.

4.2.1. Normal force

Figure 12(a) shows the normal force for each condition. A Friedman test showed a significant influence of condition ($\chi^2(3) = 11, p = 0.014$). Wilcoxon signed rank tests showed significant differences between conditions N and V ($W(12) = 71, p = 0.046$), and between conditions N and VT ($W(12) = 76, p = 0.0014$). The result shows that the normal forces in the conditions V and VT are smaller than those in condition N.

4.2.2. Scanning speed

Figure 12(b) shows the scanning speed for each condition. A Friedman test showed a significant influence of condition ($\chi^2(3) = 13, p = 0.0053$). Wilcoxon signed rank tests showed significant differences between conditions N and T ($W(12) = 73, p = 0.024$), and between conditions N and VT ($W(12) = 77, p = 0.0059$). The result shows that the scanning velocities in the conditions T and VT are smaller than those in condition N.

5. Informal trials with expert surgeons

To assess the practical effectiveness of the feedback of the sensor output in laparoscopic tumor detection, we conducted a few trials with expert surgeons.

Four well-experienced surgeons of laparoscopic surgery voluntarily participated. The experimental setup was almost the same as that described in Section 3.3., but no visual feedback was offered because surgeons always see the endoscopic monitor during laparoscopic surgery, and it is not practical to see an extra monitor during the operation.

Three stimuli with different tumor positions were prepared by shifting the position of the phantom of the stomach wall on the semicylindrical sponge. One of the stimuli was randomly put inside the training box, without fixing it; thus, stimulus position and posture could freely be changed by the participant. Two surgeons—an operator and an assistant—stood on the left and right sides of the laparoscopic training box. The operator manipulated the tactile sensor with his/her dominant hand to scan the surface of the stimulus; with a forceps in the other hand adjusting the position and posture of the stimulus. The assistant surgeon cooperated with the operator manipulating the sensor. Before the actual scanning of the tumor in the training box, the operator surgeon felt the tactile feedback outside the training box for several seconds to familiarize with the feedback as a rehearsal. Then, the surgeon tried to identify the position of the tumor in the phantom inside the training box.

Three out of four expert surgeons could correctly localize the phantom tumor in the first trial. The fourth surgeon firstly pointed out an incorrect position, but could correctly localize the tumor in the second trial. This surgeon commented that s/he mistook the fold of the phantom stomach for the tumor in the first trial. Other surgeons commented that they could find the position of the tumor through the tactile feedback from the sensor. They also commented that for optimal performance, they should become more familiar with the tactile feedback as some specific skills for the sensor manipulation should be acquired.

6. Discussion

First, we will discuss the procedure and setup for the psychophysical experiment with novice participants. Figure 10(b) shows that the detection sensitivity did not significantly depend on the experimental order. This validates the experimental design, in which the order was counterbalanced across participants, and time intervals were inserted among the experimental conditions to reduce learning effects. Regarding the detection sensitivity, the median for the condition N was 0.75 and exceeded chance level (0.5). This indicates that the participants could utilize the direct haptic information to distinguish the stimuli. Some participants commented that the camera image could also be used as the cue for detection because a little change in the sensor movement or the deformation due to the tumor could be observed. In addition, participants tended to use larger normal force in condition N as shown in Figure 12(a), which brings higher stress on the tissue. This might indicate that participants tried to increase the intensity of direct haptic information. The stimuli used in the experiment were fixed in the training box whereas the actual stomach wall often shifts according to applied tangential force. Thus, direct haptic information might be less informative, and the feedback of the sensor output might be more efficient in a real surgical situation. Regarding the response time, it did not significantly depend on condition. Possibly, an effect of condition did not show up because of the short time limit (30 s).

In the following sections, we will discuss the effects of each type of feedback on the detection sensitivity and the exploratory movements, and characteristics of them in the point of view of clinical applications. Moreover, we will finally discuss the practical effectiveness of the sensory feedback from the tactile sensor according to the results of

the informal trials with expert surgeons.

6.1. Visual feedback

The experimental results show that visual feedback is sufficient for tumor detection. Visual feedback was the line graph, which offered time history of the sensor output for 5 seconds. Thus, participants could discriminate the tumor on the basis of the shape of the line graph as shown in Figure 2. We have hypothesized that the visual channel might be overloaded in condition V because the camera image and the line graph were simultaneously presented on two different monitors. However, the participants did not frequently need to pay attention to the camera image once they learned the appropriate manipulation of the sensor.

Regarding the exploratory movements, the visual feedback has the effect to decrease the normal force for tumor detection. This is probably because of the visual feedback provided by the quantitative sensor output through the line graph; thus, the participants could adjust the normal force on the basis of the height of the line graph. In addition, if the normal force was too large, the line graph was out of range on the PC monitor. This might have worked as an implicit indication of the overload of normal force. Thus, the gain of the visual feedback might affect the range of the normal force used.

From the point of view of clinical applications, decreasing the normal force has a positive effect because it brings less mechanical stress on the tissue. Moreover, the advantage of visual feedback is that surgeons can share the sensing information and this might bring transparency of the decision. On the other hand, the visual feedback needs extra space for the additional monitor to the laparoscopic monitor. A possible solution to this issue is to superimpose the sensor output information on the camera image, as shown in [8]. However, this brings less visibility of the surgical field. In addition, a possibility of the overload of the visual channel [29] remains because the surgeons should pay attention to the laparoscopic image in actual surgery. In future work, we will improve the visual feedback to address these issues.

6.2. Tactile feedback

The detection sensitivity showed no significant difference between conditions T and N. There were some possible sources providing confusive tactile feedback to the participants. For instance, the participant could feel a force fluctuation due to the fold of the inside of the stimuli when they used a large normal force. It has also been reported that benefit of force feedback in a teleoperation system depends on experience in robot-assisted minimally invasive surgery [30]. All participants were novices in laparoscopic surgery, and they could not interpret the tactile feedback accurately. Moreover, some participants who achieved better performance in condition N commented that the tactile feedback somewhat interfered the direct haptic information from the sensor probe. Thus, a way of tactile feedback should carefully be considered in laparoscopic palpation system, where users can receive direct haptic information. A possible solution is optimizing the gain for each participant so that the tactile feedback appropriately augments the direct haptic information.

The tactile feedback has the effect to decrease the scanning speed. A possible reason of low speed is that the participants tried to recognize the tumor shape through tactile feedback. The tumor used in the experiment has a toroidal

shape, and the typical sensor output during the scanning has two peaks, as shown in Figure 2(a). Regarding human tactile performance of temporal discrimination, humans can definitely perceive two sequential stimuli when the inter-stimulus interval exceeds 100 ms for electrical stimulation [31]. Thus, a low scanning speed might help to perceive two sequential force stimulations due to the tumor. On the other hand, the tactile feedback has no effect on the normal force. This might be because the tactile feedback presented the high-passed sensor output; thus, the participant could not know quantitative sensor output through the tactile display. In future work, we will continue to improve the way of tactile feedback toward more efficient tumor detection.

The effect to decrease the scanning speed might bring less risk of accidents such as an undesired collision between the sensor and the tissue. In addition, the tactile display developed in this study has high applicability to surgical situations because the display was designed for the foot, where sterilization is not necessary. When the surgeons conduct palpation, they only have to insert their foot into the display; thus, the display does not disturb the surgeon during other surgical tasks. However, the surgeon should take off their footwear for the usage, and the inconvenience remains when they need to move their foot for the operation of other surgical instruments through foot pedals. When designing an improved version of our tactile display, we will take this aspect of inconvenience into account.

6.3. Combination of visual and tactile feedback

The detection sensitivity showed no significant difference between conditions VT and N. We have hypothesized that the combination of both types of feedback could achieve the highest detection sensitivity due to maximum likelihood integration [32]. Figure 9(a) shows that some participants increased their sensitivity at condition VT. However, the overall tendency shows that condition V achieved the highest performance, and the integration of visual and tactile feedback brought lower performance than that of condition V as shown in Figure 10(a). A possible explanation is a cross-modal masking effect. Ide *et al.* experimentally demonstrated that tactile stimulation can suppress visual perception [33]. If the participant could not interpret the tactile feedback appropriately as mentioned in the previous section, the tactile feedback might degrade the visual feedback and bring uncertainty of the tumor detection.

The combination of the visual and tactile feedback has the effect to decrease both the normal force and scanning speed. This means that the effects of each type of feedback did not interfere in terms of the exploratory movement. Decreasing both normal force and scanning speed brings less energy supplied to the tissue, which might relate to less damage to the tissue [11]. Thus, if the tactile feedback were improved, better detection with decreasing effect of normal force and scanning speed could be achieved by utilizing both visual and tactile feedback.

In this study, we revealed that the type of signal processing of feedback (such as clipping and filtering) as well as modality affects the exploratory movements in our laparoscopic palpation system. This indicates that the participants reasonably changed their behavior according to the characteristics of the feedback information and modality.

6.4. Practical effectiveness

The results of the informal trials with expert surgeons indicate that the feedback from the tactile sensor might be effective for practical use in laparoscopic surgery. Whereas the surgeons could find the position of the tumor through the tactile feedback from the sensor, they commented that they should become more familiar with the tactile feedback as some specific skills for the sensor manipulation should be acquired. In future work, we will try to seek more effective and even more intuitive ways to provide the feedback.

7. Conclusion

In this study, we designed and evaluated ways of feedback from a tactile sensor for laparoscopic tumor detection. We used a previously developed simple and biocompatible tactile sensor using acoustic reflection. As one type of feedback, a monitor presenting a line graph of the low-pass filtered sensor output (< 10 Hz) was prepared as visual feedback. As another type of feedback, we developed a tactile display for the upper side of the user's foot. It presents normal force that relates to the high-pass filtered sensor output (0.5–10 Hz). The tactile display has advantages for surgical applications because the foot is in the unclean area of a surgeon and does not need to be sterilized. Thus, the whole system has a high applicability to clinical situations.

A psychophysical experiment was conducted in a setup simulating laparoscopic surgery for twelve novices. Four feedback conditions (no feedback, only the visual feedback, only the tactile feedback and a combination of the visual and tactile feedback) were compared in terms of detection sensitivity and exploratory movement. We employed signal detection theory to analyze participants' sensitivity and measured normal force and scanning speed during the experiment. The experimental results showed that the visual feedback can achieve significantly higher sensitivity and participants' confidence in their answer compared to no feedback. The tactile feedback has no significant effect on the sensitivity. In addition, visual feedback has an effect to decrease normal force and tactile feedback has an effect to decrease scanning speed. Interestingly, the combination of both types of feedback has both effects. Moreover, a few informal trials with four expert surgeons were conducted. The surgeons could localize the correct position of a phantom tumor according to the provided tactile feedback.

We will improve the ways of the visual and tactile feedback toward better and even more intuitive tumor detection with small normal force and low scanning velocity. Moreover, the end goal of our research is intraoperative tumor localization; thus, we will also investigate how feedback ways affect on tumor localization performance.

Conflict of interest

The authors have no conflict of interest to declare.

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References

1. Krouskop TA, Wheeler TM, Kallel F, *et al.* Elastic moduli of breast and prostate tissues under compression. *Ultrason Imaging* 1998; 20(4): 260–274.
2. Phipps S, Yang THJ, Habib FK, *et al.* Measurement of tissue mechanical characteristics to distinguish between benign and malignant prostatic disease. *Urology* 2005; 66(2): 447–450.
3. Hoyt K, Castaneda B, Zhang M, *et al.* Tissue elasticity properties as biomarkers for prostate cancer. *Cancer Biomark* 2008; 4(4-5): 213–225.
4. Garg A, Sen S, Kapadia R, *et al.* Tumor localization using automated palpation with Gaussian Process Adaptive Sampling. In *Proceedings of IEEE International Conference on Automation Science and Engineering*, 2016; 194–200.
5. Konstantinova J, Cotugno G, Dasgupta P, *et al.* Palpation force modulation strategies to identify hard regions in soft tissue organs. *PLOS ONE* 2017; 12(2): 1–24.
6. Nichols KA, Okamura AM. Methods to segment hard inclusions in soft tissue during autonomous robotic palpation. *IEEE Trans Robot* 2015; 31(2): 344–354.
7. Srivatsan RA, Ayvali E, Wang L, *et al.* Complementary model update: A method for simultaneous registration and stiffness mapping in flexible environments. In *Proceedings of IEEE International Conference on Robotics and Automation*, 2016; 924–930.
8. Yamamoto T, Vagvolgyi B, Balaji K, *et al.* Tissue property estimation and graphical display for teleoperated robot-assisted surgery. In *Proceedings of IEEE International Conference on Robotics and Automation*, 2009; 4239–4245.
9. Gwilliam JC, Mahvash M, Vagvolgyi B, *et al.* Effects of haptic and graphical force feedback on teleoperated palpation. In *Proceedings of IEEE International Conference on Robotics and Automation*, 2009; 677–682.
10. Pacchierotti C, Prattichizzo D, Kuchenbecker KJ. Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery. *IEEE Trans Biomed Eng* 2016; 63(2): 278–287.
11. Tavakoli M, Aziminejad A, Patel RV, *et al.* Methods and mechanisms for contact feedback in a robot-assisted minimally invasive environment. *Surg Endosc* 2006; 20(10): 1570–1579.
12. Talasaz A, Patel RV. Integration of force reflection with tactile sensing for minimally invasive robotics-assisted tumor localization. *IEEE Trans Haptics* 2013; 6(2): 217–228.
13. Li M, Luo S, Xu G. A tactile sensing and feedback system for tumor localization. In *Proceedings of International Conference on Ubiquitous Robots and Ambient Intelligence*, 2016; 259–262.
14. Xie H, Liu H, Seneviratne LD, *et al.* An optical tactile array probe head for tissue palpation during minimally

invasive surgery. *IEEE Sens J* 2014; 14(9): 3283–3291.

15. Schostek S, Binser MJ, Rieber F, *et al.* Artificial tactile feedback can significantly improve tissue examination through remote palpation. *Surg Endosc* 2010; 24(9): 2299–2307.
16. Naidu AS, Patel RV, Naish MD. Low-cost disposable tactile sensors for palpation in minimally invasive surgery. *IEEE ASME Trans Mechatron* 2017; 22(1): 127–137.
17. Miller AP, Peine WJ, Son JS, *et al.* Tactile imaging system for localizing lung nodules during video assisted thoracoscopic surgery. In *Proceedings of IEEE International Conference on Robotics and Automation*, 2007: 2996–3001.
18. Beccani M, Natali CD, Sliker LJ, *et al.* Wireless tissue palpation for intraoperative detection of lumps in the soft tissue. *IEEE Trans Biomed Eng* 2014; 61(2): 353–361.
19. Omata S, Murayama Y, Constantinou CE. Real time robotic tactile sensor system for the determination of the physical properties of biomaterials. *Sens Actuators A Phys* 2004; 112(2–3): 278–285.
20. Tanaka Y, Fukuda T, Fujiwara M, *et al.* Tactile sensor using acoustic reflection for lump detection in laparoscopic surgery. *Int J Comput Assist Radiol Surg* 2015; 10(2): 183–193.
21. Konstantinova J, Li M, Mehra G, *et al.* Behavioral characteristics of manual palpation to localize hard nodules in soft tissues. *IEEE Trans Biomed Eng* 2014; 61(6): 1651–1659.
22. Culmer P, Barrie J, Hewson R, *et al.* Reviewing the technological challenges associated with the development of a laparoscopic palpation device. *Int J Med Robot* 2012; 8(2): 146–159.
23. Schoonmaker RE, Cao CGL. Vibrotactile force feedback system for minimally invasive surgical procedures. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, 2006: 2464–2469.
24. Dohi M, Mochimaru M, Kouchi M. Distribution of tactile sensitivity and elasticity in Japanese foot sole. *KANSEI Engineering International* 2004; 5(2): 9–14.
25. Kandel ER, Schwartz JH, Jessell TM. *Principles of neural science*. 4th ed. New York: McGraw-Hill; 2000.
26. Coren S. *The left-hander syndrome: The causes and consequences of left-handedness*. New York: McGraw-Hill; 2000.
27. Macmillan NA, Creelman CD. *Detection theory: A user's guide*. 2nd ed. New York: Lawrence Erlbaum Associates; 2005.
28. Irwin P, Robert H. Sampling variability of the area under the ROC-curve and of d'e. *Psychol Bull* 1969; 71(3): 161–173.
29. Richard P, Coiffet P. Human perceptual issues in virtual environments: sensory substitution and information redundancy. In *Proceedings of IEEE International Workshop on Robot and Human Communication*, 1995: 301–306.
30. Wagner CR, Howe RD. Force feedback benefit depends on experience in multiple degree of freedom robotic surgery task. *IEEE Trans Robot* 2007; 23(6): 1235–1240.
31. Pastor MA, Day BL, Macaluso E, *et al.* The functional neuroanatomy of temporal discrimination. *J Neurosci* 2004; 24(10): 2585–2591.

32. Ernst MO, Banks MS. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 2002; 415(6870): 429–433.
33. Ide M, Hidaka S. Tactile stimulation can suppress visual perception. *Sci Rep* 2013; 3: 3453.

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Figures

Figure 1. Forceps-type tactile sensor using acoustic reflection.

Figure 2. Typical visual feedback when a user scans a phantom of the stomach wall. (a) Visual feedback for a phantom with tumor. (b) Visual feedback for a phantom without tumor. Horizontal axis shows time. Vertical axis shows the sensor output. Black arrows indicate the peaks that mark the tumor.

Figure 3. Tactile display presenting a normal force to the user's instep. (a) Composition of the tactile display. (b) Usage of the display.

Figure 4. Stimuli for the psychophysical experiment. (a) Phantom of the stomach wall with tumor. (b) Phantom without tumor. (c) Cross-sectional drawing of phantom with the tumor. (d) Phantom was placed on a semicylindrical sponge in the experiment.

Figure 5. Experimental setup. Dashed rectangle shows the inside of the training box.

Figure 6. Example of the experimental order. To reduce learning effects, each condition was conducted on a different day, and the order was counterbalanced across all participants.

Figure 7. ROC curves on a (F, H) space. Dashed line shows ROC curve with assumption of normal distributions. Solid line shows an example of empirical ROC curve. Area under the empirical ROC curve A_g was used as sensitivity index in this study.

Figure 8. Empirical ROC curves for experimental conditions. Black solid lines show ROC curves for twelve participants. Red solid lines show the average ROC curves of the participants. Black dashed lines show chance level.

Figure 9. Detection performance in individual participants. White, light gray, dark gray and black bars indicate the results for conditions N, V, T and VT, respectively. (a) Detection sensitivity. (b) Confidence ratings. (c) Response time.

Figure 10. Summary of detection performance. (a) Detection sensitivity for the condition. (b) Detection sensitivity for the experimental day. (c) Confidence ratings for the condition. (d) Response time for the condition. *indicates $p < 0.05$ with post-hoc Wilcoxon signed rank tests or t -tests with Holm-Bonferroni correction.

Figure 11. Exploratory movements in individual participants. White, light gray, dark gray and black bars indicate the results for conditions N, V, T and VT, respectively. (a) Normal force. (b) Scanning speed.

Figure 12. Summary of exploratory movements. (a) Normal force for the condition. (b) Scanning speed for the condition. *indicates $p < 0.05$ and $**p < 0.01$ with post-hoc Wilcoxon signed rank tests with Holm-Bonferroni correction.