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学位論文題目	Design of Sensory Display Technologies for a Laparoscopic Palpation System in Harmony with a Surgeon （術者と調和した腹腔鏡下触診システムに向けた感覚情報提示技術の構築）
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論文内容の要旨

Palpation is an important technique in the clinical field to obtain mechanical information about body tissue and to localize a hard mass such as a tumor within soft tissue. It relies on input from a surgeon's tactile sense; however, tactile input is rarely available in minimally invasive surgeries such as a laparoscopy. If the surgeon's tactile sense were compensated for by computer technologies, surgeons could perform intraoperative localization of the tumor immediately before a resection, which might reduce any unnecessary resection of normal tissue. In this thesis, it is aimed to achieve intraoperative localization of an early-stage gastric tumor that cannot be visually detected during laparoscopic surgery. The focus of this study is temporal information-based palpation, in which a single output is acquired from a direct-manipulating tactile sensor and fed back to the surgeon in real-time. This is advantageous because the use of a single output results in the overall simplicity of the palpation system, and the direct manipulation can be considered as a natural extension of current laparoscopic surgery techniques. Moreover, the real-time feedback is aimed at assisting with effective decision-making on the part of the surgeon. In this study, display methods for the sensor output to the surgeon were designed and evaluated to facilitate effective laparoscopic palpation. The ultimate goal was harmonization with the surgeon, i.e.,

maximizing both the performance of the surgeon (who possesses flexible sensory-motor control and decision-making capabilities based on his/her broad knowledge) and that of the system (which possesses superior computational capabilities over those of the surgeon). In addition, the goal includes the enhancement of the surgeon's confidence in his/her decision making over and above the enhancement of functional performance such as the reduction of localization errors.

Firstly, the visual and tactile feedback of the single sensor output were evaluated and discussed. As visual feedback, a line graph of the time-series output was prepared on an additional monitor to the laparoscopic monitor. As tactile feedback, a device that presents a normal force to the surgeon's foot was assembled. In addition, a psychophysical experiment that used four conditions (no feedback, visual feedback, tactile feedback, and a combination of both types of feedback) was conducted to investigate the effects of the means of feedback on the users' detection performance of a phantom gastric tumor as well as their behavior during the detection. The results showed that the visual feedback was significantly more effective in detection than no feedback, whereas the tactile feedback did not significantly enhance detection. Moreover, both visual and tactile feedback led to safer manipulation with a significantly smaller load and lower scanning speed, respectively. The findings indicated the usefulness of visual feedback in laparoscopic palpation and the necessity for the redesign of the tactile feedback whereas both types of feedback contributed to the positive effect on the manipulation.

The previous findings suggest that visual feedback of the time-series sensor output is effective in detection. However, visual feedback can be problematic, as it requires an extra monitor which would occupy valuable space in the operating room. Furthermore, a major concern is the possibility of visual sensory overload since the surgeon should concentrate primarily on the laparoscopic image. An assistance algorithm was, therefore, proposed as the replacement for the surgeon's decision based on visual information. The algorithm was designed to analyze the time series of the sensor output and provide independent detection results from the surgeon. This approach is advantageous because the reliability and safety of the manipulation are ensured by a human operator, but a more effective detection might be expected from the collaboration between a human and the algorithm. The algorithm used a deep neural network to analyze the time-series of the sensor output. The algorithm was validated using the data acquired in the previous psychophysical experiment. The validation result supports the feasibility of the proposed algorithm for detection assistance during laparoscopic palpation.

Tactile feedback of the sensor output is advantageous in laparoscopic surgery because it avoids any possible sensory overload in comparison with visual feedback.

However, the previous experiment showed no significant effect of the tactile feedback (provided by the device to the foot) on detection. To assess this issue, the spatial coincidence between the manipulating hand of the sensor and the feedback site was reconsidered. The contribution of the final part of this thesis is the development and evaluation of a pneumatic tactile ring, which is a clinically applicable tactile display presenting pressure to one of the fingers on the manipulating hand. Since the tactile ring is driven by pneumatic power, it is lightweight, cost-effective, disposable, and sterilizable. The fundamental performance of the tactile ring was investigated, and a psychophysical experiment including a localization test of a phantom tumor was performed. The results of the experiment showed that the provided tactile feedback significantly reduced the absolute error of the tumor localization and increased participants' confidence in their answers. It was shown that the feedback through the tactile ring was effective in laparoscopic tumor localization. In addition, clinical tests with surgeons were conducted on actual patients with early-stage gastric cancer. The results of the tests suggested that the tactile ring is applicable to laparoscopic surgery and effective for the localization of an actual gastric tumor.

The results and findings in this thesis characterized our approach and showed its effectiveness. Moreover, they also may expand existing knowledge in the related research field. The characterization of the visual and tactile feedback of the time series of the sensor output provides suggestions for the design of sensory feedback in not only laparoscopic palpation but also other computer-aided surgery such as robot-assisted minimally invasive surgery. Moreover, the deep neural network-based assistance algorithm as the replacement for the surgeon's visually based decision exhibited a novel approach for the collaborative decision making between human and computer. Finally, the development and evaluation of the pneumatic tactile ring showed a valuable example of effective devices validated with clinical tests on actual patients.

論文審査結果の要旨

触診は手術において重要な手技の一つであり、特に、早期胃癌のように視覚で検出できない病変部の位置同定に有効である。しかし腹腔鏡下手術では、術者の触覚が大きく制限され、触診が困難である。そこで、触診を支援するシステムが実現されれば、病変部を術中に位置同定でき、過不足ない切除に繋がる。本論文では、システム実現のアプローチとして以下の3点に着目している。1) 直接操作型のセンサプローブを利用し、従来の手術機器の延長として、術者のスキルに基づいた安全かつ柔軟な操作を可能とする。2) 単一センサ出力のみを利用し、支援システムをシンプルに構成する。3) 術者へ計測情報をリアルタイムに提示し、術者の経験や知識を活かした診断を実現する。特に本論文では、情報提示に着目した技術開発および評価を行っているが、システムの術者との調和、すなわち、人と機械の特性を考慮し両者の性能を最大限生かすことを軸としている。加えて、単なる性能の向上のみならず、触診における術者の確信度、さらにはやりがいの向上も指向している。

まず、直接操作型センサプローブからの出力の視覚および触覚提示として、モニタによる波形表示と術者の足背部へ力を提示する装置を準備し、心理物理実験を行い、各提示手法が腫瘍検出およびプローブ操作へ与える影響を調査した。その結果、検出感度と確信度については、視覚提示により有意に向上するが、触覚提示は効果が見られなかった。またプローブ操作については、視覚提示が押付力低下、触覚提示がなぞり速度低下に有意に寄与することが示された。本結果は、コンピュータ支援手術における情報提示手法の設計において、重要な示唆を与えるものである。

視覚提示は、その検出における有効性が示されたものの、術者は常に腹腔鏡映像を注視していることから、追加の視覚情報は感覚過負荷を引き起こし、術者の疲労や性能低下をもたらす可能性が残っていた。そこで、視覚提示の有効性を活かしつつ、その置換となるアルゴリズムを提案した。本アルゴリズムは、時系列センサ出力をリアルタイムに深層ニューラルネットワークで解析し、術者と独立した検出結果を音声等を通じて提示するものである。評価を行い、プローブ操作者のデータを事前学習に用いれば、人の視覚に基づく判断と同等の検出が行えることが確認され、その実現可能性が示された。提案手法は、人による適切なプローブ操作があって初めて、アルゴリズムによる検出も可能となることから、人とコンピュータの協働において新たな提案を与えるものである。

触覚提示は、検出における有効性が示されなかったが、その原因として、提示位置である足背部とセンサ操作を行う手が離れており、空間的一致性が低かった。そこで、一致性向上のため提示位置を足背部から指へと変更し、空気圧を用いた装着性の高いリング型提示装置を開発した。工学的視点で提示装置を評価し、触診に必要な性能を有していることを確認し、さらに心理物理実験も行い、装置からの触覚提示が腫瘍の位置同定に有効であるかを調べた。その結果、リング型装置からの触覚提示によって、位置同定誤差が有意に低減し、かつ確信度が有意に向上することが示された。加えて、早期胃癌を有する患者を対象にした臨床試験も行い、本触覚提示が腹腔鏡下手術における触診において有効であることが示された。このように、実験室で準備された環境のみならず臨床環境での有効性を示した装置は多くなく、本結果は重要な一例となる。

以上の成果は、学術雑誌（審査有）論文3編に公表されており、これらの学術的価値から博士論文として十分な内容だと判断される。よって、博士（工学）の学位論文として適格であると認める。