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学位論文題目	Development of Multicomponent Force Sensory Systems and Palpation Methods for Enhancing Tumor Localization in Laparoscopic Surgery （腹腔鏡下手術における腫瘍の位置同定を強化するための多成分力覚システムと触診法の開発）
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論文内容の要旨

For most types of cancer, surgery to remove the cancerous tumor is the most effective treatment. The effectiveness of this treatment depends mainly on the assessment of the primary tumor characteristics, such as its location, size, and depth. This information allows surgeons to remove the entire tumor with minimum margins while preserving the function of the remaining organ, thereby enhancing cancer's curability and the patient's postoperative quality of life. In open surgery, surgeons can determine the tumor by palpating the target tissue with their fingers. In minimally invasive surgery (MIS), such as laparoscopic surgery (LS), surgeons could rely on sensory feedback from laparoscopic feedback devices, such as ultrasonic or haptic devices, to examine abnormal tissues. This thesis aims to develop tissue palpation systems using haptic devices for surgeons to determine tumors intraoperatively, especially in LS. The systems should consist of biocompatible elements that could ensure the safety requirements in a clinical environment. Moreover, the simplicity of the devices' structure is required in the development of the palpation systems. Too many sensing (or display) elements might cause the complex structure and bulk size of the haptic devices. Thus, this thesis focuses on the

balance between the devices' functions and the simplicity in their structure. We developed devices capable of two force sensing (or display) components, including normal and shear force components, to achieve the balancing purpose in this thesis. Moreover, if the obtained information is stable and largely unaffected by the tissue deformation, the surgeon's motions, or the method of the target tissue information transmission to the surgeons, it will be helpful for the surgeon's decision-making in their tumor detection. Furthermore, the system proposed in this thesis also aims to enable surgeons to identify the characteristics of tumors, such as depth and size.

Firstly, a forceps-type tactile sensor was developed for intraoperative tumor detection in LS for early-stage gastric tumor resection surgery. The tactile sensor based on the acoustic reflection principle provides real-time visual information of the two contact force components, including normal and shear force information. Since the tactile sensor has no electrical components inserted into the patient's body, it offers great advantages in MIS, such as disposable, sterilizable, and electrical safety. Surgeons can use the tactile sensor to palpate the stomach's surface to detect the tumor. However, the bending of the gastric tissue due to the force applied by surgeons often reduces the sensitivity of tumor detection. The results of a tissue palpation experiment with a phantom of the stomach wall showed that the normal force information fluctuated significantly during the palpation procedures, leading to difficulty in tumor localization. On the other hand, the shear force information obtained from the tactile sensor was relatively stable. It changed significantly at the tumor location, regardless of the bending of the tissue and the sensor's movements by the user. This could potentially improve the performance and confidence of the surgeon in localizing tumors intraoperatively.

Visual feedback used in the first part of this thesis is a common feedback modality to represent the contact force component information to surgeons. However, since surgeons need to focus on laparoscopic images during surgery, this feedback modality may cause overloads of the visual channel. Tactile feedback that is a promising alternative to provide contact force information to surgeons can prevent sensory overload in MIS. The second part of this thesis aims to develop a ring-type tactile display (SuP-Ring), that can provide normal and shear force feedback to assist surgeons in laparoscopic tumor localization. Normal indentation, a substitutional feedback modality, was employed to represent the force feedback (intensity). Tactile display using this tactile feedback modality could provide reliable contact force information because the shear force feedback is regardless of friction between the human skin and tactile display's moving element, compared to the other tactile feedback modalities such as lateral skin stretch. In addition, the SuP-Ring using pneumatic power is simple, low-cost, sterilizable and disposable. The fundamental investigations of the tactile display showed that users could perceive the change of the shear force feedback regardless of the differences in the normal force feedback. The effectiveness of the SuP-Ring for tumor localization was also determined through a simulated tissue palpation with an artificial phantom tissue having an embedded tumor. The experimental results showed that the shear force feedback of the tactile display could improve the performance and confidence of users in localizing the tumor, and the normal force feedback could contribute to ensuring the safety requirements in MIS.

Detecting the tumor location is only the first step of the tumor localization procedure in MIS. Surgeons should determine the tumor characteristics, such as tumor depth and size, to perform a maximum tumor resection procedure. In the final part of the thesis, we proposed a palpation strategy using tactile feedback to assist the surgeon in determining the tumor feature information. In this palpation strategy, the depth of the tumor can be determined by recognizing the presence of the tumor at the given depth position (indentation depth) of the sensor, while the tumor size may be obtained by localizing the edges of the tumor. Fundamental experiments were conducted to investigate the use of contact force component information in determining tumor features using the proposed strategy. The results indicated that the normal force is more useful in estimating the indentation depth, and the shear force is highly effective in detecting the regions and edges of the tumor. Through tissue palpation tasks with artificial tissue phantom, participants who received both normal force and shear force feedback from the SuP-Ring could identify the depth and size of the embedded tumor with 66 % and 65 % accuracy, respectively.

In summary, the results and findings in this thesis demonstrate the essence of using tactile devices having multicomponent force feedback function in intraoperative tumor localization. The tactile sensor with shear force measurement function could provide stable and effective visual information of contact force response in tumor area for surgeons. The tactile display with normal and shear force feedback displays could prevent the surgeons' visual channel from overloading, enhance the surgeons' performance and confidence in detecting the tumor, and enable surgeons to determine the depth and size of the tumor. These proposed devices and palpation methods could contribute to improving the surgeons' decision-making in intraoperative tumor localization to minimize the tissue resection margin, preserving the patient's organ function after surgery.

論文審査結果の要旨

本論文では、腹腔鏡下手術における腫瘍の位置同定のための触覚センサシステムの開発を目的としている。腫瘍の位置は術前にMRIなどで事前に把握されているが、術中に臓器が動くことから腫瘍の位置の正確な把握は難しく、触診による検出が有効である。先行研究では、圧力分布を計測できる触覚センサシステムや、押付け力を触覚フィードバックするシステムが提案されているが、構造の複雑さや装置の大きさ、生体への安全性、センサ使用時の操作力の影響を受けやすいなどの問題があった。これに対し、シンプルさと機能性のバランスを図り、押付け力と剪断力を計測できる音響式の触覚センサおよび空気圧式の触覚フィードバックシステムを提案し、位置同定のための触診方法を提案しその有効性を示した。

まず、反射音を用いた触覚センシング原理を応用して、鉗子形状のセンサプローブ内部に2つの音響経路を設計し、プローブ先端の押付け力と剪断力の計測が可能な触覚センサを開発した。本センサは、生体内に挿入される部分に電気素子を含まず、パイプ状であることから生体安全性が高く臨床適用性に優れる。特に、剪断力計測するために設計した音響経路と接触子の構造は、プローブの細さを保つようデザインされ独創的である。胃がんを模擬したサンプルに対するしこり検出の実験では、なぞり動作に対して押付け力が変動するのに対して、剪断力は安定し、腫瘍として配置したしこりに対して十分なセンサ応答が見られ、検出に有効であることを示した。

続いて、剪断力を触覚提示する手法を検討し、ベルトなどを用いて直接的に剪断力を指先に提示するのではなく、指輪型のデバイスを用いて、空気圧による圧力提示で剪断力を代行提示するフィードバックシステムを開発した。3つの圧力提示部位を設けて、押付け力と剪断力の大きさと方向を提示できるコンパクトかつ軽量な装置を提案した。触覚の再現ではなく、触覚の即時性や運動との統合性に着目して使用者の認知を利用する手法であり、アプローチとして新規性が高く、心理物理実験を通して、押付け力と剪断力の両方の情報が提示されることで、検出能力向上と押付け力の増大を防ぐ効果があることを示した。提案システムの性能を検出能力だけでなく操作性の観点から示した点は、応用研究として高く評価できる。提案装置は、軽量、小型、複数の力情報の提示の観点から、腹腔鏡下手術だけでなく、ソフトロボティクスやバーチャルリアリティ分野に対しても有用であり、更なる展開も期待される。

さらに、腫瘍の位置同定に向けて、提案した触覚提示システムの活用を検討した。押し込み力と剪断力について、9種類の大きさと深さが異なるしこりに対するセンサ応答を調査し、信号検出理論を用いて、位置同定のためのセンサ操作方法および解析手法を提案した。押付け力の計測はセンサプローブの押し込み量の推定に有効であり、剪断力の計測を加えることで、しこりの深さと大きさの識別が行える可能性を示した。さらに提案手法を用いた心理物理実験を行い、深さと大きさをそれぞれ66%および65%の精度で識別できることを示した。性能分析と人を用いた実験を通して、提案システムを用いた腫瘍の位置同定への有効性を示し、信頼性の高い評価を行っている。また、剪断力提示に関する自由度の向上など、臨床応用に向けた課題およびその解決方法を考察し、提案システムの限界や有効範囲を明らかにした。

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。