Suction-Fixing and Stiffness-Tunable Liver Retractor for Laparoscopic Surgeries

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博士論文（要約）

Suction-Fixing and Stiffness-Tunable Liver Retractor for Laparoscopic Surgeries

(腹腔鏡下手術のための吸着固定ならびに可変剛性を特徴とする

肝臓リトラクタに関する研究)

金　埈煥

Non-invasiveness and stability are important issues for liver manipulation in laparoscopic liver resection because inappropriate manipulations can harm liver tissues or vessels. Owing to the large number of blood vessels contained in the liver, damage on the liver can result in serious bleeding. In present clinical procedures, a surgeon grasps the liver with graspers at a single contact point and retracts the liver for liver parenchymal transection. Excessive grasping force may tears the tissue due to high-pressure contact with the liver surface. To avoid such contact, some surgeons use retractors to form a broader contact surface. This, however, sometimes leads to the instability of liver holding, such as liver slipping off during retraction. A broader contact area and holding stability in grasping are key concepts in achieving non-invasive and stable organ manipulation. One promising way is suction fixation. Multiple suction pads adhere to the liver surface and can achieve stable grasping without slippery. Their adequate spatial distribution can also reduce the contact pressure at each pad. Such suction fixation devices have been attempted in previous research. The devices used were either rigid bodies which prevent sufficient contact with the curved organ surfaces, or soft bodies which could have a good contact, but, could not provide stable organ position holding during the manipulation. It requires having both shape followability and position holding ability, which may be a trade-off in terms of device stiffness. The goal of this thesis is realization of non- or less-invasive and stable liver manipulation for laparoscopic liver resection. This thesis presents a novel concept on liver retractor. The proposed retractor was featured on suction fixation, stiffness tuning, and pneumatic actuation for achieving both shape followability and position holding ability.

Requirements for liver retractor in liver parenchymal transection can be summarized as follows: (1) The diameter must be smaller than 12 mm; (2) It must grasp the curved liver surface whose minimum curvature radius is 56 mm; (3) Grasping force must be up to 5 N against horizontal pulling and 2 N for vertical pulling; (4) Severe tissue damage such as capsular tear and external bleeding must be prevented. The proposed liver retractor consists of a shaft and a finger. The finger performs suction fixation, stiffness tuning, and pneumatic actuation as its functions in the procedure. It begins in a low-stiffness state with a straight shape and bends to follow the curved liver surface. It is then turned to a high-stiffness state to tenaciously hold the liver in position as all suction pads are adhered to the liver surface. The finger consists of suction pads, a stiffness-tuning mechanism, and a pneumatic actuator. Suction fixation is performed by the suction pads. By vacuuming the air through the suction pads, the pads are adhered onto the liver surface. The suction pad consists of a shaft, a suction cup, and a joint. A soft and elastic joint causes the suction cup to passively tilt to reduce the amount of moment working on the contact surface. Stiffness tuning of the finger is performed by stiffness-tuning mechanism. The stiffness-tuning mechanism consists of two continuous beams that are flexibly bendable and non-stretchable. The outside of the beams is sealed with an elastomer tube. Stiffness tuning is achieved by restraining the motion of the beams using vacuum control. There is an air clearance between the beams at first and the beams can slide due to no or weak motion constraint. Interior of the stiffness-tuning mechanism is vacuumed when all suction pads are attached to the liver surface. The beams are then pressed by the atmospheric pressure and their motion is restrained. When the beam motion is restrained, the two individual beams act as one single beam and its stiffness against the bending force increases compared to when the beams can slide without motion constraint. One-Degree-of-Freedom (1-DoF) actuation of the finger is performed by the pneumatic actuator. The pneumatic actuator consists of a fiber-reinforced stretchable chamber and a non-stretchable sheet. By inflating the stretchable chamber, the finger bends downward because of the elongation difference between the stretchable chamber and the non-stretchable layer. The thickness and width of the finger was 10 mm and 6 mm, respectively. The finger was attached to the 12 mm diameter shaft having a 1-DoF rotation joint. The vacuum pressure applied to the retractor was set to -50 kPa, and theoretical suction force was 5.3 N.

Bending rigidity of the stiffness-tuning mechanism was evaluated through the bending test. The bending rigidity was 267.4±15.0 $\times10^{-6}$Nm^2 in the low-stiffness state. The bending rigidity for each initial curvature radius of 50, 100, 150, 200, and ∞ mm were 1311.6±12.0, 1290.0±6.7, 1249.8±3.0, 1207.8±16.0, and 1130.6±12.0 $\times10^{-6}$Nm^2 in the high-stiffness state, respectively. The bending rigidity increased about 4.2 times in the high-stiffness state when the curvature radius was ∞ mm. Shape followability of the proposed retractor was evaluated using a phantom. The finger was bent to the various curved surface and adsorption success rate was evaluated. The adsorption success rate for each curvature radius of 50, 100, 150, 200, and ∞ mm were 76, 88, 94, 100, and 100%, respectively. Grasping force was evaluated using silicon rubber phantoms. The proposed retractor grasped the phantoms, and pulled them in each vertical and horizontal direction until the finger was detached. The grasping force in each direction was measured by the force-moment sensor and compared with the conventional rigid and flexible suction-fixing retractors. The grasping force of the proposed retractor against liver phantoms, whose surficial curvature radius ranged 50-200 mm, was 3.1±0.2 N against the vertical pulling and 4.3±0.1 N against the horizontal pulling. It showed about 1.6 times larger grasping force than conventional retractors in case of horizontal pulling. Retraction success rate was evaluated using in-vitro bovine livers. The proposed retractor grasped a spot near the cutting line and opened the transection surface until the liver tissue at the cutting line was tensioned. The retraction success rate was 100% for all cutting depth of 10, 30, and 60 mm. It was 100, 100, 80, and 40% for the retracted liver weight of 343, 590, 783, and 922 g, respectively. Spatial tissue tension distribution at the cutting line during the retraction was evaluated using an in-vitro porcine liver. 40 (8×5) measurement points were made on the liver surface. The grasper and proposed retractor grasped and pulled the liver and the displacement of the measurement points during the pulling was evaluated. The tissue stretch was concentrated on the vicinity of the grasping spot in case of the grasper whereas it was distributed along 50 mm of grasping area in case of the retractor. Displacement of the measurement points along the 50 mm cutting line was -0.2±0.6 mm in the grasper and 1.1±0.3 mm in the retractor. Tissue damage was evaluated in an in-vivo swine test. The liver was grasped and horizontally pulled with 3 N pulling force for 1, 5, 10, and 20 minutes. After the experiment, the liver surface and inner of the grasping spot were observed by naked-eye and pathological examination with HE staining. No capsular tear and external bleeding was observed in all cases. Subcapsular hematoma was observed right after the retraction. It was observed within 5 mm diameter and 2 mm depth from the liver surface. It started alleviation in few minutes and recovered to normal level in 4 hours. Required cutting time was evaluated in in-vitro swine liver parenchymal transection. The proposed retractor could perform the transection with 36% reduced cutting time compared to the grasper. Operability was evaluated in an in-vivo swine liver parenchymal transection. No significant trouble was found in retractor insertion/withdrawal, grasping, and lateral retraction. The retractor, however, showed weak grasping against anterior retraction.

Experimental results showed that the proposed retractor could achieve less-invasive and stable liver manipulation. The proposed stiffness-tuning mechanism worked well in the practical condition for the laparoscopic liver resection. The retractor could deform and grasp well the curved target surface having practical curvature radii. Its grasping force for horizontal pulling was smaller than the requirement, however, it could open transection surface and apply tissue tension to the cutting area in practical condition. It could apply even tissue tension to the broader area on the cutting line during the retraction. In addition, it could perform liver manipulation without accompanying serious tissue damages such as capsular tear and external bleeding. It only caused the negligible level of subcapsular hematoma. These results demonstrated that the proposed retractor could improve liver manipulation in terms of increasing grasping and retraction stability and reducing invasiveness. The proposed retractor also showed effectiveness and acceptable operability in liver parenchymal transection, and its feasibility for the practical use was suggested.