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Friction behavior at minimally invasive grasper/liver tissue interface

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ABSTRACT

Preliminary simulations of tissue clamping and dragging operations in MIS were made by using compression and friction testing under different clamping forces and dragging speeds. Results showed that the injury degree of the liver gradually increased with increasing clamping force. The maximum static friction force increased with increasing clamping force and dragging speed, and dragging displacement before sliding increased with increasing clamping force and decreasing dragging speed, which indicated that low clamping force and high dragging speed may be more likely to cause slipping at the jaw-liver interface. There exists a safe operation zone, in which there was neither liver damage nor slipping at the jaw-liver interface. The results can provide safe thresholds for doctors during grasping task in MIS.

1. Introduction

The introduction of minimally invasive surgery (MIS) into the operating room has led to significant advantages for the surgical patient. MIS can minimize the invasiveness of a surgical procedure, thus reducing the trauma, recovery time, and overall healthcare cost to the patient. However, these minimally invasive procedures have also incorporated the disadvantages of limited dexterity, lack of 3D visualization, poor ergonomic design and lack of haptic feedback, which reduce the accuracy of force feedback to the surgeon from the tool-tissue interaction [1–3]. As the surgeon is no longer in direct contact with the patient or surgical tools and must use only their visual sense to approximate the tool-tissue interaction forces, the surgeon's perception of the tool–tissue interaction forces may be higher or lower than the actual force at the tool tip. Higher force usually induces tissue trauma, while lower force can cause grasper and tissue slipping when dragging tissue, reducing operation efficiency [4,5]. The function of laparoscopic graspers is to realize clamping, gripping and dragging organ or tissue. Modern laparoscopic graspers usually have a tooth structure at the end effector to improve the efficiency of clamping. However, this structure may cause non-uniform pressure distribution. Excessive pressure during organ and tissue retraction with laparoscopic graspers is one of the causes of intraoperative injury in laparoscopic interventions [6,7]. It is reported that grasper-related trauma during laparoscopic procedures has a 2–4% risk of injury to the bile duct, bowel, vascular structures, significantly higher than in open abdominal surgery [7–10]. An observational study by Tang et al. found that 66% of human errors identified during laparoscopic cholecystectomy were related to graspers, 13% of which, in turn, were related to excessive force exertion [11].

On the investigation of the pressure distribution of grasper-tissue interaction, Payandeh et al. have shown that the average magnitude of the grasping force in a typical palpation task is approximately 12.5 N [12]. Similar research studies have found the maximum grasping force was 16 N [12,13]. Cartmill et al. found that the pinch force required to prevent tissue slipping out of the grasper, while hanging from the tissue a 250 g load at a direction perpendicular to the plane of the end effector, generated localized peak tissue stresses as high as 800 kPa [14], which was beyond the safety threshold of 200 kPa estimated by De et al. for cell apoptosis in abdominal organs [15,16]. Some researchers designed a laparoscopic grasper equipped with strain gages or sensors and then conducted in vivo and in situ experiments with different tissues to measure forces during grasping [2–4,13,17]. In most of the studies above, the compressive stress was measured and computed by finite element analysis, however, the tractive force or friction force during dragging tissue was rarely studied. The combination of critical pressure values and friction force which neither induced tissue injury nor cause tissue slipping out of the grasper are not clear. Little current data is available to suggest stress magnitudes that are safe for tissue manipulation.

A few studies referred to the friction between surgical devices and soft tissue interfaces have been reported. Frank et al. preliminarily tested the friction behavior between the clamp and the small intestine in laparoscopic operation, the result showed that the friction coefficient was 0.6–0.9 and 7 N of sealing force was recommended to prevent leakage [18]. Kim et al. reported that the friction

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between endoscopic capsule and the small intestine of pig was 10–50 mN. With the load increasing, the friction coefficient reduced from 0.2 to 0.08. The friction resistance increased with the movement speed of endoscopic capsule rising [19]. Takashima et al. characterized frictional interactions between the catheter and the blood vessel wall by using experimental and numerical analysis [20]. Oldfield et al. examined tool–tissue interactions, strain energy release rate and deformation by using blade insertions into a gelatin soft tissue phantom experiments and accompanying finite element simulations [21]. However, research work on the frictional behavior between the grasper-tissue interfaces is still very limited.

Therefore, the goals of the present study are to characterize the frictional behavior on the grasper–tissue interface under different clamping load and dragging speed, to determine the relationships between slipping and clamping force and dragging speed for tissue manipulation, and to ultimately identify safe thresholds during grasping the studied tissues. The results can provide a safe force for doctors during grasping and palpation tasks in MIS.

2. Materials and methods

2.1. Specimen preparation

Porcine liver was chosen as a target tissue for this study due to its similarity in structure and function to the human liver. The liver is a solid organ located in the abdominal cavity and is composed of a mass of lobules held together by fine areolar tissue. Porcine liver was selected because it is a relatively homogeneous tissue and generally robust as a surgical model. Five fresh porcine livers were collected from a local abattoir. They were preserved in an icebox and delivered to the laboratory within 2 h postmortem, and tested within 4 h after extraction so as to avoid dehydration. All livers were trimmed into similar shape with 10 ± 1 mm thickness in the same position. All tests were performed at a room temperature of 20 ± 3 °C and relative humidity of $60 \pm 5\%$ to simulate the operation room temperature and humidity. The tests began when the temperature of the liver samples reached the room temperature after about 1 h from the icebox. During the tests, the liver surface was sprayed with physiological saline every half an hour to simulate its surface moisture in the body.

Laparoscopic grasper specimen (Shanghai Yida Medical Instrument Co., Ltd., China) was atraumatic grasping forceps with serration, which was supplied by Xiangya Hospital Central, South University, China. The structure of the grasper is shown in Fig. 1. It is widely used in clinical laparoscopic surgery, such as: cholecystectomy, hysterectomy, liver, gastric and intestinal resection. The serrated structure on the jaw surface of the grasper is to increase the friction force between the grasper and tissue interface and prevent slippage during traction operation. The contact area of the jaw with the tissue is 24.0 mm^2.

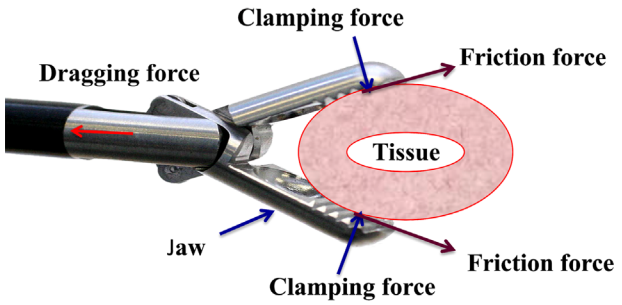

Fig. 1. Schematic diagram of grasper-tissue interaction mechanics analysis.

2.2. Experimental setup

In minimally invasive manipulation, tissue clamping and traction operations accounts for the largest proportion of procedure duration [22]. Thus, the operating security by using a grasper is essential to complete the operations. There are two main forces: clamping force and friction force at the grasper-tissue interaction during dragging tissue manipulation, as shown in Fig. 1.

The clamping force was tested by using a microcomputer control electronic universal material testing machine (HY0580, Shanghai Hengyi Testing Machine Co., Ltd., China), as shown in Fig. 2. The HY0580 is composed of a force transducer (Transcell Technology Inc., America), a full digital AC servo motor (Panasonic MINAS A4 SERIES Corp., Japan), a high precision synchronous speed reducer and four differently shaped clamps. The force transducer's resolution is 0.01% and its measurement range is from 1 mN to 100 N. The displacement accuracy is $\leq 0.2\%$ and the displacement range is up to 800 mm. The test speed range is 0.001 to 500 mm/min. The HY0580 is fully computer-controlled and a sampling rate is at 50 samples per seconds to data files. The testing repeatable accuracy is $\leq 0.5\%$. In the present work, the indenter was one of the jaws of the laparoscopic grasper. It was removed from the grasper and bonded to a stainless steel column. The stainless steel column was connected to the copper cylindrical friction probe by a threaded connection and then was fixed on the clamp of the HY0580, as shown in Fig. 2. Previous studies have found the maximum grasping force was 16 N [12,13]. These results are used as a general guideline for the necessary force output that is required of laparoscopic tools for grasping and palpation tasks. According to this, the clamping force was 1 to 16 N in this study in order to research the relationship between tissue trauma and force magnitude. The jaw was pressed onto the liver sample at a speed of 2 mm/s to achieve the preset clamping force, and then the press speed was close to zero. Since then, the clamping force remained the preset force and duration was 60 s to simulate grasping operation and study the creep properties of the liver sample. Compression stress and strain can be calculated as

$$\text{Stress}: \sigma = \frac{F}{A_0}$$

where F is the compression force, and A_0 is the area of the jaw.

$$\text{Strain}: \varepsilon = \frac{H_0 - H_s}{H_0}$$

where H_0 is the initial thickness of the liver sample, and H_s is the compressed thickness of the liver sample.

The compression stress and creep deformation of the liver sample with time under different clamping force can be measured. The liver sample was placed on the test bench of the bottom of the HY0580. Three repeated tests were performed on the different sites for each sample under the same testing parameters.

The friction tests were conducted by using a UMT-II series multi-specimen Biomedical Micro-Tribometer (UMT-II, CETR Corporation, America), as shown in Fig. 3. The unidirectional sliding wear mode from left to right was selected to simulate the dragging tissue operation. The liver sample was placed on the specially designed workbench with one end fixed on the clamper of the workbench to simulate in situ experiments during grasping. The counterpart of the jaw used in compression testing was used for the friction tests. After the compression testing, the counterpart was attached to a suspension system of the UMT-II. It pressed onto the liver sample at a programmed speed of 2 mm/s which was the same as the compression test speed. When the force was loaded to the preset normal force (clamping force), the jaw moved linearly at a constant sliding speed. As obvious trauma appeared in the liver when the clamping force was more than 5 N (see Section