Quantifying Surgeon Grasping Mechanics in Laparoscopy Using the Blue DRAGON System

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ABSTRACT. Mechanical testing of abdominal organs has a profound impact on surgical simulation and surgical robotics development. Due to the nonlinear and viscoelastic nature of soft tissue it is crucial to test them in surgically relevant ranges of applied force, deformation, and duration for incorporating haptic realism into surgical simulators and for safe operation of surgical robots. In order to determine these ranges, a system known as the Blue DRAGON was used to track the motions and the forces applied to surgical tools during live procedures for quantifying how surgeons typically perform a minimally invasive surgical procedure. Thirty-one surgeons of varying skill were recorded performing three different surgical tasks. Grasping force (as applied to the tool handles) and handle angle for each tool were the signals of interest among 26 channels total acquired by the system in real time. These data were analyzed for their magnitudes and frequency content. Using the tool contact state, an algorithm selected tissue grasps to analyze measures during grasps only, as well as obtain grasp durations. The mean force applied to the tool handles during tissue grasps was 8.52 N ± 2.77 N; maximum force was 68.17 N. Ninety-five percent of the handle angle frequency content was below 1.98 Hz ± 0.98 Hz. Average grasp time was 2.29 s ± 1.65 s, and 95% of all grasps were held for 8.86 s ± 7.06 s or less. The average maximum grasp time during these tasks was 13.37 s ± 11.42 s. These results form the basis for determining how abdominal tissues are to be mechanically tested in ranges and durations of force and deformation that are surgically realistic. Additionally, this information may serve as design specifications for new surgical robots or haptic simulators.

1. Introduction & Background

Grasping is one of the most frequently used tool/tissue interactaion in minimally invasive surgery. Previous studies focused on measuring and analyzing the forces and torques being applied by the surgeons during two common laparoscopic procedures.[1, 2] The Blue DRAGON was used to track the forces/torques applied to surgical tools, as well as their kinematics, during live procedures.[3, 4] Prior studies on the mechanical behavior of tissues during compression *in-vivo* have applied forces 5 N or less[5-7] and/or at higher frequencies[5] than those observed in actual surgery. As part of the current research, the magnitude, rate, and duration of compressive loads applied to tissues by grasper jaws when manipulated by surgeons during normal procedures was studied as a subset of the database collected by the Blue DRAGON. Results from this study provide more appropriate ranges for mechanical testing of abdominal organs.

2. Methods & Tools

Thirty-one surgeons of varying skill were recorded using the Blue DRAGON systems (Figure 1) while performing 3 different surgical tasks on an *in-vivo* animal model (pig): running the bowel in two directions and passing the stomach behind the esophagus (stomach wrap). These tasks were chosen as simple, repeatable tasks in which the tool directly interacts with soft tissues and represent tasks performed in many procedures. These three tasks only involved tissue manipulation. Twenty-six surgeons were categorical residents at different levels of their residency training (6 subjects in their first year, 5 subjects in years 2-5) and 5 were surgeons expert in videoendoscopic procedures. Of the 31 surgeons, 26 were right-handed (RH), and 5 were left-handed (LH) (1 R1, 2 R2, 1 R5, 1 X). Data collection consisted of 13 channels for each hand, including tool orientation and position, as well as the forces and torques being applied, but the main signals of interest for this study were grasping force (as applied to the tool handle; F_g), handle angle (Q_g), and tool/tissue contact state. All animal procedures were performed in an AALAC-accredited surgical research facility (Center for Videoendoscopic Surgery) under an approved protocol from the institutional animal care committee of the University of Washington. Subjects were allowed a maximum of 15 minutes per task and were not prompted in any way. An expert surgeon manipulated the video endoscopic camera.

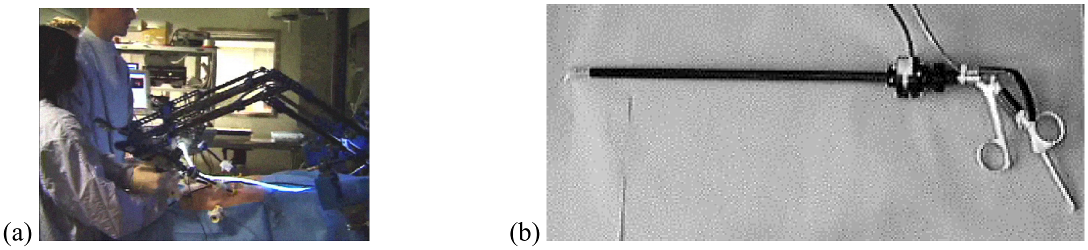
(a) (b)

Figure 1: The experimental system: (a) Blue DRAGONs in use during a live animal surgical procedure. (b) Instrumented grasper that is part of the Blue DRAGON system used for measuring applied forces/torques as well as grasping force

Tool usage varied depending on the surgical task, but it was fixed regardless of the handedness of the subjects. During the surgical task involving examining of the bowels, a Babcock grasper was used for the right hand and a bowel clamp for the left hand tool. For creating a wrap around the stomach, a Babcock grasper was used again for the right hand tool, while an atraumatic grasper was used for the left hand tool.

Tissue grasping was defined as any time the endoscopic tool's jaws were in contact with the tissue, a force (F_g) of greater than 1.0 N was being applied to the handle, the handle was open (Q_g) more than 0.008 rad, and handle velocity was ≤ 0 (closing or steady). These criteria were used by a computerized algorithm to automatically parse the data into periods of *tissue grasps* from the entire database. Upon visual inspection of the data, this algorithm was found to successfully pick out grasps as well as grasp-and-hold periods. Using this algorithm, grasp time (G_t) was also analyzed. G_t theoretically represents the length of time from when a tissue is first grasped to when it is released. Each measure was taken for each subject-task-hand dataset, meaning the data from one hand of one subject performing one task. For the 31 subjects, 3 tasks, and 2 hands, this would produce a theoretical 186 data points but was reduced to 150 data points for practical reasons.

3. Results

A typical recording of F_g while running the bowel is shown in Figure 2a. Note the relatively clear demarcation of individual grasps (approximately 10 of them). A typical power spectrum of Q_g is shown in Figure 2b, during the same task as shown in Figure 2a. It can be seen that the majority of the frequency content is below 5 Hz.

The overall statistics of the data were examined and key findings are summarized below. These form the basis for an understanding of how surgeons — in general — grasp tissues, at least for these particular tasks. All measures were taken across all subjects and tasks and hands.

- Mean F_g applied to the handles, across all data: 7.35 N ± 2.45 N
- Mean F_g applied, *during tissue grasps*: 8.52 N ± 2.77 N
- Maximum F_g observed over all data: 73.73 N
- Maximum F_g observed *during tissue grasps*: 68.17 N
- Mean of maximum F_g from each subject-task-hand, across all data: 28.55 N ± 9.20 N
- Mean of maximum F_g from each subject-task-hand, *during tissue grasps*: 24.98 N ± 8.14 N
- Maximum spreading force, across all data: 24.35 N
- Mean of maximum spreading force from each subject-task-hand, across all data: 10.21 N ± 3.94 N
- Mean frequency that contains 95% of F_g, *during tissue grasps*: 0.92 Hz ± 1.09 Hz
- Mean percentage of F_g that lies below 5 Hz, *during tissue grasps*: 99.35% ± 1.35%
- Mean frequency that contains 95% of Q_g, *during tissue grasps*: 1.98 Hz ± 0.98 Hz
- Mean percentage of Q_g that lies below 5 Hz, *during tissue grasps*: 98.37% ± 1.03
- Mean handle velocity *during tissue grasps*: 0.047 rad/s ± 0.056 rad/s
- Mean tissue grasp time (G_t): 2.29 s ± 1.65 s
- Maximum G_t: 66.27 s
- Mean of maximum subject-task-hand G_t: 13.37 s ± 11.42 s
- 95% of grasps from each subject-task-hand were held for less than (average): 8.86 s ± 7.06 s

Additional analyses were carried out on the Blue DRAGON data to examine the differences in measures across the various factors (handedness, skill level, surgical task, and hand used). The results indicate no significant differences (α=0.05) in the measures when performed by left- or right-handed surgeons. There were differences in applied force and frequency content across the different skill levels. The stomach wrap task had significantly higher forces applied compared to the bowel running tasks. Hand used had little effect, despite the different tool types in each hand.

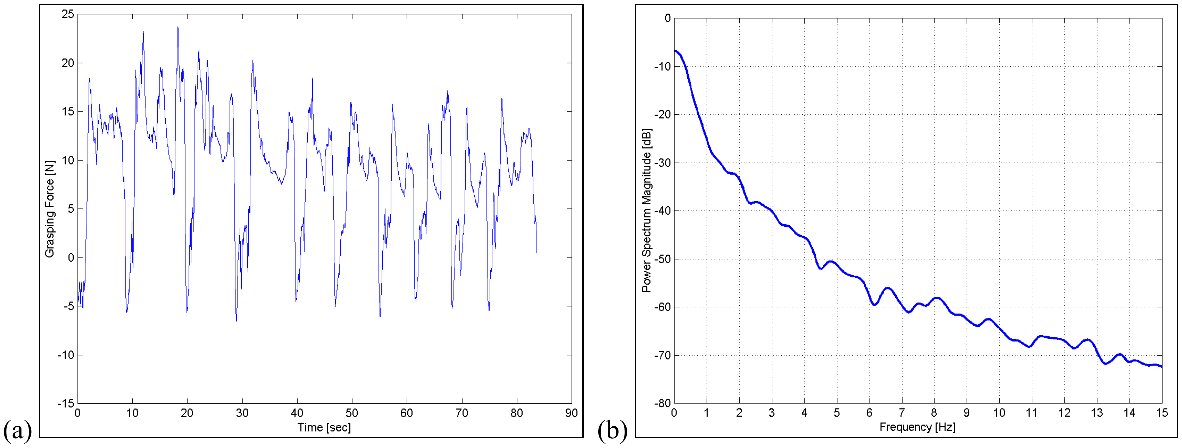

Figure 3: Grasping mechanisms in laparoscopic surgery: (a) Typical grasping force-time plot recorded during a running-the-bowel task performed by an expert surgeon (left hand), (b) Handle angle power spectrum recorded during a running-the-bowel task performed by an expert surgeon (left hand)

4. Conclusions and Discussion

The grasping mechanics of 31 different surgeons performing 3 surgical tasks involving tool tissue interaction have been measured. The results indicate that surgeons, for the tasks and tools under study, grasp tissue with less than 10 N of force, for durations 10 s or less, and at frequencies less than 2 Hz. These loading characteristics determine the preferred experimental loading profiles in order to measure soft tissue mechanical properties in ranges relevant to minimally invasive surgery for providing realism in surgical simulators.[8, 9] Additionally, this information may serve as design specifications for new surgical robots or haptic simulators.

No significant differences were observed between left- and right-handed surgeons. There were differences in handle frequency content and the forces applied by different skill levels. More expert surgeons tended to apply greater average grasping force and moved the handle with higher frequencies. Significantly greater forces were applied during the stomach wrap task compared to bowel running. Operating hand had no significant effect. For the given tasks, the recorded signals do not appear to be good differentiators of skill, which indicates the need for more complicated analysis techniques, such as Markov modeling.[4]

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