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Analysis of the tractive force pattern on a knot by force measurement during laparoscopic knot tying

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ABSTRACT

Background: Quantifying surgical skills assists novice surgeons when learning operative techniques. We measured the interaction force at a ligation point and clarified the features of the force pattern among surgeons with different skill levels during laparoscopic knot tying.
Methods: Forty-four surgeons were divided into three groups based on experience: 13 novice (0–5 years), 16 intermediate (6–15 years), and 15 expert (16–30 years). To assess the tractive force direction and volume during knot tying, we used a sensor that measures six force-torque values (x-axis: Fx, y-axis: Fy, z-axis: Fz, and xy-axis: Fxy) attached to a slit Penrose drain. All participants completed one double knot and five single knot sequences. We recorded completion time, force volume (FV), maximum force (MF), time over 1.5 N, duration of non-zero force, and percentage time when vertical force exceeded horizontal force (PTz).
Results: There was a significant difference between groups for completion time ($p = 0.007$); FV (total: $p = 0.002$; Fx: $p = 0.004$, Fy: $p = 0.007$, Fxy: $p = 0.004$, Fz: $p < 0.001$, Fxy/Fz: $p = 0.003$), MF (total: $p = 0.004$; Fx: $p = 0.015$, Fy: $p = 0.035$, Fxy: $p = 0.009$, Fz: $p = 0.001$, Fxy/Fz: $p = 0.041$); time over 1.5 N ($p = 0.002$); duration of non-zero force ($p = 0.029$); and PTz ($p < 0.001$). PTz showed the only significant difference comparing intermediates with experts (intermediates: 13.7 ± 9.0, experts: 4.9 ± 3.2; $p < 0.001$).
Conclusions: We clarified the characteristics of the force pattern at the ligation point during suturing by surgeons with three levels of experience using a force measurement system. We revealed that both force volume and force direction differed depending on surgeons' skill level during knot tying.

1. Introduction

In contrast with open surgery, laparoscopic surgery requires specific expertise in areas such as stereoscopic visual ability, hand-eye coordination, and instrument manipulation in a limited space. With recent progress in engineering technology, quantifying operative maneuvers now plays an important role in assisting surgical skills learning. Previous studies have evaluated the accuracy of suture technique, range of forceps motion track, task completion time, and force pattern of dissection maneuvers.[1–5]

Becoming proficient in laparoscopic surgery requires significant time and effort for novice surgeons. Analyzing the technical differences between novices and experts to obtain an objective index clarifies these differences, and quantifying the measurements helps beginners efficiently and accurately learn expert-level operation skills. A basic and essential technique that must be mastered in laparoscopic surgery is suturing. Previous reports have evaluated the force magnitude at the ligation point during suturing.[6–9] These reports showed that beginners apply a large force magnitude, have increased task time, and use long path lengths with forceps. Although visual force feedback has the potential to improve tissue handling skills and help novices acquire surgical skills,[10,11] high-frequency or continuous presentation of visual feedback does not consistently contribute to the learning process, and in some cases may even hinder skill acquisition.[12] Simply measuring the force magnitude cannot convey the maneuvers used by experts; detailed

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analysis of the characteristics of experts' skilled movements is needed to understand the differences between surgeons of varying levels of experience.

We hypothesized that the force magnitude at the ligation point decreases and the force direction changes with increasing skill during knot tying. In this study, we measured the force direction at the ligation point. Although several reports have measured the force magnitude on the suturing platform during knot tying,[6,7,10] we focused on analysis of the force direction to determine the differences in the force pattern during knot tying among surgeons of three skill levels.

2. Methods

2.1. Force measurement system

To assess the tractive force direction during knot tying, we constructed a force platform by attaching a sensor that measures six force-torque values (USL06-H5-50N, Tec Gihan Co., Ltd., Kyoto, Japan). This force sensor measures approximately 2 cm^2 and records horizontal forces (the sensor plane vector) within ±25 N and vertical forces (the vector perpendicular to the sensor plane) within 50 N at the center screw hole on the sensor plane. A slit Penrose drain recommended by the Society of American Gastrointestinal and Endoscopic Surgeons (Part 50302, Limbs & Things Inc., Savannah, GA) was screwed to the sensor and placed with the force platform inside a box trainer (11363-100 MCM-1, Kyoto Kagaku Co., Ltd., Kyoto, Japan) (Fig. 1).

2.2. Calibration

The loaded force at the center screw hole (F-screw) was measured when force was applied at a ligation point on the Penrose drain (F-penrose). The F-screw value was then used to estimate F-penrose (eF-penrose), and the coefficient of the matrix (CM) was calculated. After calculating CM, we performed a verification experiment to confirm that there was little or no discrepancy between the eF-penrose estimated using the F-screw value and the actual loaded F-penrose value measured during loading of any given value.

2.3. Experimental procedure

All 44 gastrointestinal surgeons were recruited for this study at a domestic conference (Japan Society for Endoscopic Surgery) and divided into three groups: 13 novice, 16 intermediate, and 15 expert surgeons (Table 1). The study protocol was approved by the Ethics Committee of the Graduate School of Medicine, Kansai Medical University, Osaka, Japan (protocol number 922).

Generally, suturing involves needle driving and knot tying. In this study, we excluded needle driving from the evaluation task, because needle driving consists primarily of a rotary movement moving the needle along its curve, and involves different skills than for knot tying. The force pattern of needle driving is expected to differ from knot tying at the ligation point. Therefore, although participants performed both needle driving and knot tying in this study, we focused only on the knot-tying maneuvers to evaluate the tractive force at the ligation point. All participants completed one double knot and five single knot sequences using a standard laparoscopic needle driver (k26173, Ethicon Endo-surgery, Cincinnati, OH) with Vicryl 3-0 SH (J527H, Johnson & Johnson, Somerville, NJ) cut to precisely 15 cm in length. Before beginning the task, surgeons were instructed to tie a knot accurately within 500 s. They were not informed which parameters were evaluated.

2.4. Evaluating the force pattern

The force pattern consists of the following elements: the force magnitude (measured by a force sensor in Newtons (N)), the force volume (the parameter calculated by multiplying the force magnitude and time (N*time)), and the force direction (the force magnitude in the direction of each axis (x-axis (Fx), y-axis (Fy), z-axis (Fz), and xy-axis (Fxy)). We measured the completion time for the six sequences of knot tying, force volume, maximum force, time exceeding 1.5 N, duration of non-zero force (eliminating force data points that were under 0.1 N), and force direction. The rate of vertical force with horizontal force (v/h) and the percentage of time when the vertical force exceeded the horizontal force (PTv) were also evaluated, because the tractive force direction on a knot can differ with varying levels of surgical experience.

2.5. Statistical analysis

All data are expressed as mean ± standard deviation. Statistical analysis involved creating a bell curve in Excel 2015 (Social Survey Research Information Co., Ltd., Tokyo, Japan). All parameters were compared between the three groups using the Kruskal–Wallis test, and the Steel–Dwass test was used as a post hoc test to analyze differences between groups. A p-value < 0.05 was considered statistically significant.

3. Results

3.1. Calibration

Calibration was performed at loading values of 0.98 N, 1.96 N, and 2.94 N in the x and y directions, and values of 1.37 N, 2.35 N, 3.33 N, 4.31 N, and 5.00 N in the z direction using a pulley with a

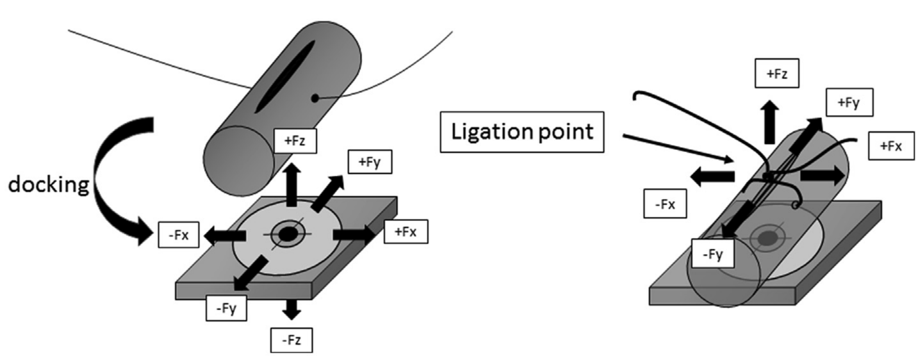

Fig. 1. Penrose drain attached to the force sensor by screws. Following calibration, it was possible to measure the force magnitude at the ligation point.