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Surgical technique analysis using dynamic measurement of surgical instruments for practical laparoscopic surgery training*

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***Abstract*—To improve the efficiency of surgical skill transfer and proficiency in laparoscopic surgery, an objective method of quantifying surgical skills was developed. Surgical trainings for laparoscopic nephrectomy were conducted using cadavers, and the movements of surgical instruments were measured using Mocap system in 46 trainings. Because the surgical techniques required are different depending on the surgical process, the entire nephrectomy was divided into three surgical processes (Part 1: colon mobilization, Part 2: renal vascularization, and Part 3: dissection of the remaining tissue), and skill analysis was performed for each process. Surgeons were categorized into three groups according to the number of surgical experiences (novice: 0-9 surgeries, intermediate: 10-49 surgeries, and experts: 50 or more). Three-group tests were conducted on 111 features extracted from the surgical instrument movement data. The three-group tests showed that there were significant differences among the three groups in the surgical processes: part 1, part 2, and part 3. Principal component analysis (PCA) was conducted using the features that showed significant differences in the efficiency of the operation.**

I. Introduction

Laparoscopic surgery requires fewer incisions and is less burdensome on the patient. However, the degrees of freedom of manipulation of surgical instruments are limited, it is difficult for a surgeon to feel the reaction forces from the surgical instruments, and the field of view is limited because the surgical site can only be viewed through an endoscope, and it is difficult to understand the three-dimensional structure of the surgical site because endoscopic images are two-dimensional. Therefore, laparoscopic surgeries require advanced surgical skills. Currently, education in laparoscopic surgery is provided through simulated operations using organ models and animal organs, as well as through practical training in the clinical doctors. However, surgical education has often been inefficient and time-consuming due to the lack of objective and numerical methods to evaluate surgical skills. Therefore, an objective method of quantifying surgical skills has been eagerly expected to improve the efficiency of surgical education.

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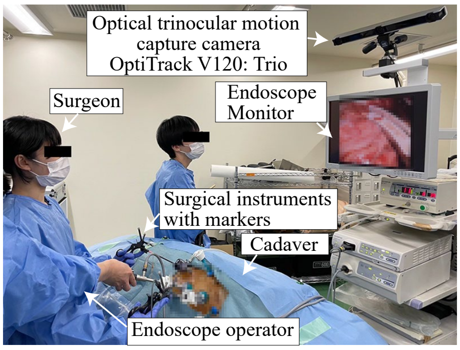


Fig.1 Laparoscopic surgery training in CST

Studies on quantifying surgical skills have been conducted so far [1-4]. However, these studies evaluated only a single task in simulated surgery using organ models, etc., and therefore are far from the actual surgical situation. Although some studies on skill evaluation in simulated surgery using animal organs have been reported [5, 6], they are limited to simple analysis of the operating speed and trajectory of surgical instruments. The authors have developed a practical laparoscopic surgical training model [7] using porcine organs for (1) tissue dissection and vascularization around large blood vessels and (2) renal parenchymal sutures.

Furthermore, actual laparoscopic surgery involves many surgical processes [8], and it is necessary not only to evaluate the entire surgical process simultaneously but also to analyze each separately. Therefore, in this study, laparoscopic surgery training on nephrectomy using a cadaver, which is similar to the actual surgery, is divided into three major surgical processes (part 1: colon mobilization, part 2: renal vascularization, and part 3: dissection of the remaining tissue) based on the advice of experienced urologic surgeons. The differences in movements of forceps among novices, intermediates, and experts are analyzed (Fig. 1). To clearly understand the differences in motion features among the novices, intermediates, and experts, principal component analysis (PCA) was conducted.

This paper describes the details of the skill analysis in laparoscopic surgery training on nephrectomy using cadavers.

II. THE MEASUREMENT SYSTEM

A. System configuration

The authors have developed a system to measure the movements of all surgical instruments used in simulated surgery by attaching individual-recognition infrared reflective markers to the surgical instruments. In the systems developed so far, six cameras have been placed around the surgeon to track the markers of the surgical instruments. However, in actual surgery, surgical assistants, endoscopic operators, and nurses stand around the patient, and these personnel become obstacles to the cameras placed around them, making it impossible to track the markers of the surgical instruments. In laparoscopic surgery, the surgeon operates while looking at the endoscopic monitor, so the line of sight between the surgeon and the endoscopic monitor is always maintained (Fig. 1).

In this study, an optical trinocular motion capture camera (OptiTrack V120: Trio) was placed above the endoscope monitor to track surgical instrument markers. The optical trinocular motion capture camera used has three built-in cameras and their positions are fixed, so dynamic calibration is not required. Infrared reflective markers were attached to the surgical instruments, and the marker arrangement was different for each surgical instrument, enabling simultaneous recognition and tracking of multiple surgical instruments. The measurement frequency of the motion capture was 120 Hz. The average errors in the tip position and orientation of the grasping forceps with this measurement system were 3.28 mm and 0.86°, respectively [9]. The errors for other surgical instruments were approximately the same.

B. Target tasks[1]

With regularly conducting cadaver surgical training (CST), participants performed laparoscopic radical left or right nephrectomy (transperitoneal approach) using laparoscopic surgical instruments with infrared reflective markers attached for individual recognition in this study. Grasping Forceps (GF), Scissors Forceps (SF), Right-angle Dissection Forceps (DF), Clip Applier Forceps (CA), Energy Devices (ED) and Suction Tubes (ST) were used (Fig. 2).

The surgeon used Grasping Forceps, Scissors Forceps, and Energy Devices (LigaSure) to make a sharp/blunt dissection incision during the mobilization of the colon (Part 1). The posterior surface of the kidney is then dissected, the tissue surrounding the renal artery and vein is dissected, and each vessel is clipped using a Clip Applier to block blood flow (Part 2), after which the vessel is divided. The kidney is then released, leaving the ureter intact (Part 3).

Mocap data was recorded in 51 training sessions. Among the 51 data, excluding the five cases due to insufficient embalming condition (one case), most of the procedure being performed by the mentor (one case), or video-recording failure (three cases), 46 data were utilized in the surgical skill analysis. The data was collected from a total of 36 participants (4 novices and 2 experts joined the training two times, and 2 novice urologists participated in the training three times).

[1] This experiment was conducted by the Department of Urology, Hokkaido University Graduate School of Medicine, with the approval of the Medical Ethics Committee of the Hokkaido University Faculty of Medicine.

The measurement of the behavior of the surgical instruments using the motion capture device during CST was carried out in compliance with the 'Guidelines for cadaveric autopsies in clinical medicine education and research' and with respect for the cadaver in the clinical autopsy practice room. The CST was carried out in the clinical autopsy room with respect for the deceased.

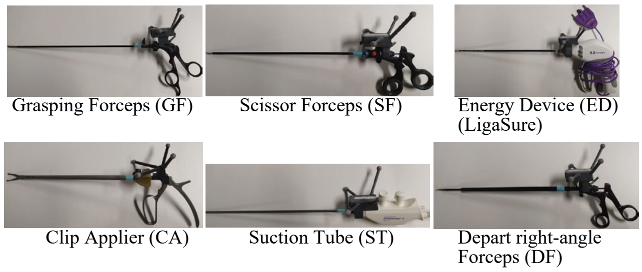


Fig. 2 Surgical instruments in training

TABLE. 1 Measurement rate of 6 surgical instruments

Surgical instrument	Measurement rate
Grasping Forceps (GF)	92.74 (89.88-95.75)
Scissors Forceps (SF)	93.72 (88.91-96.36)
Right-angle Dissection Forceps (DF)	97.49 (89.55-99.86)
Clip Applier Forceps (CA)	98.87 (93.61-99.90)
Energy Devices (ED)	94.22 (97.60-88.65)
Suction Tubes (ST)	97.66 (90.40-98.95)

Median (1st quartile – 3rd quartile)

Since the measurement data contained a lot of noise and abnormal values due to the misrecognition of surgical instruments, exclusion processing of abnormal measurement values, interpolation of missing values, and smoothing [9] were carried out. The motion capture software Motive® 3.0.3 was used to recognize and track each surgical instrument, which led to a high successful measurement rate (average above 90%) as listed in TABLE. 1.

C. Features extracted from the motion of surgical instruments

The following features were extracted from the movement data of the surgical instruments regarding the surgical skill evaluation study using porcine organs [10].

(1) Overall task: operating time (OT), the ratio of the path length of a surgical instrument in both hands (RPL), and using time for each instrument (UT).

(2) Quickness features: average velocity (v), acceleration (a), jerk (j), mean velocity in depth direction (V_d).

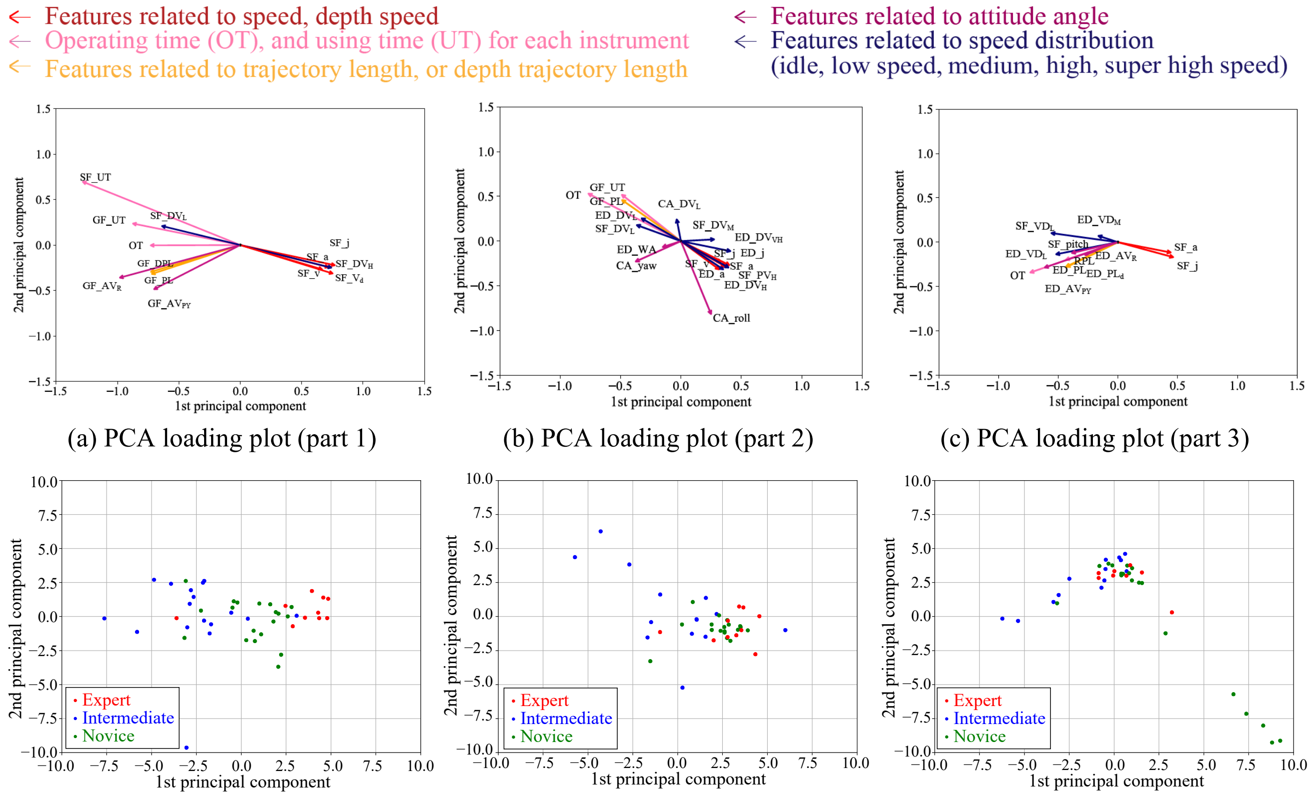
(3) Percentage of distribution of velocity range: idle (DV_I) (<0.5 cm/s), low velocity (DV_L) (0.5 ≤ to < 2.0 cm/s), medium velocity (DV_M) (2.0 ≤ to < 5.0 cm/s), high velocity (DV_H) (5.0 ≤ to< 12.0 cm/s), very high velocity (DV_{VH}) (≥ 12.0 cm/s).

(4) Efficiency feature: path length (PL), total path length in depth direction (PL_d).

(5) Attitude angle features mean change of angles (roll, pitch, yaw), the sum of changes in roll axis attitude angle (AV_R), sum of Pitch-Yaw attitude change angles (AV_{PY}).

(6) Spatial feature: Horizontal working area (WA).

They were extracted for each of the 6 surgical instruments



(a) PCA loading plot (part 1) (b) PCA loading plot (part 2) (c) PCA loading plot (part 3)

(d) PCA score plot (part 1) (e) PCA score plot (part 2) (f) PCA score plot (part 3)

(Fig. 2). The total number of features was 111.

D. Classification of surgeons

The 46 surgeons were classified according to the number of surgical experiences into the following three groups:
(a) Novice (N) (number of surgeries: 0-9): 17 surgeons
(b) Intermediate (I) (number of surgeries: 10-49): 19 surgeons
(c) Expert (E) (number of surgeries: 50 or more): 10 surgeons

A significance difference test was conducted on the above features among the three groups. The Kruskal-Wallis test was used to evaluate the difference among the three groups, and Mann-Whitney's U test was used for each of the two pairs within the three groups (between N-I, I-E, and E-N).

Laparoscopic surgery consists of several surgical processes. In this study, the movements of the surgical instruments were separately analyzed in each part.

III. Results & Discussion

A. Surgical process part 1: colon mobilization

Using the features that showed significant differences ($p < 0.05$) among the three groups, principal component analysis (PCA) was carried out to investigate which features were significant in differentiating the skills of experts, intermediates, and novices. The loading plots of the first principal components (PC1) and second principal components (PC2) are shown in Fig. 3 (a), (b) and (c). The score plots of PC1 and PC2 of each surgeon are plotted in Fig. 3 (d), (e), and (f).

As shown in the PCA loading plot in part 1 (Fig. 3 (a)), the features related to the operating time (OT) and the using time (UT) of Grasping Forceps (GF) and Scissor Forceps (SF), features related to efficiency such as path length (PL) and path length in depth direction (PL_d) of the Grasping Forceps, and the features related to attitude angle such as sum in roll (AV_R) and sum in pitch and yaw (AV_{PY}) of the Grasping Forceps showed a large contribution in the negative direction in PC1. On the contrary, the features related to the quickness such as mean velocity (v), acceleration (a), jerk (j), mean velocity in the depth direction (V_d), the high-velocity range (DV_H) of Scissor Forceps, showed a large contribution in the positive direction.

Comparing Fig. 3 (a) with (d), it is found that experts move the Scissor Forceps quickly and novices took a long time for an operation and largely moved the surgical instruments, which suggests that the principal component in part 1 is mainly related to the efficiency of the operation in Grasping Forceps and the velocity related in Scissor Forceps.

As shown in the score plots of PCA in part 1 (Fig. 3 (d)), experts (red dots) and novices (blue dots) are clearly separated, which means that efficiency is the key feature to evaluate the surgical skill in colon mobilization.

B. Surgical process part 2: renal vascularization

As shown in the PCA loading plot in part 2 (Fig. 3 (b)), the features related to operating time (OT), the using time (UT) of Grasping Forceps (GF), the features related to efficiencies such as path length (PL) of the Grasping Forceps (GF) and the features related to percentage of low-velocity range (DV_L) of the Scissor Forceps (SF) and Energy Device (ED) showed a large contribution in the negative direction in PC1. On the contrary, the features related to the quickness (velocity (v), acceleration (a), jerk (j), mean velocity in the depth direction (V_d)), percentages of the middle-velocity range (DV_M) and the high-velocity range (DV_H) of Scissor Forceps (SF) and Energy Device (ED), and the mean change in roll of clip applier (CA_roll) showed a large contribution in the positive direction in PC1.

Comparing the PCA score plot in part 2 (Fig. 3 (e)), it is concluded that most of the novices could not efficiently and quickly move the surgical instruments GF, SF, and ED. This suggests that the principal component in part 2 is mainly related to the usage of surgical instruments. Because the features related to the operating time and percentage of the low-velocity range contribute significantly to the negative direction in PC1, larger values imply higher efficiency. In the same way, because the features related to the quickness and the mean changes of clip applier contribute significantly to the positive direction in PC1, larger values imply quickness in operation.

As shown in the score plot of PCA in part 2 (Fig. 3 (e)), different from the score plot in part 1, experts (red dots) and intermediates (green dots) are not very clearly separated, although novices tend to take time to complete the task. This suggests that there is no clear difference between the surgical skills of experts and intermediates in the renal vascularization process.

C. Surgical process part 3: dissection of the remaining tissue

Seeing the PCA loading plot in part 3 (Fig. 3 (c)), it is found that the features related to operating time (OT), the ratio of the path length of a surgical instrument in both hands (RPL), and the features related to efficiencies such as path length (PL) and path length in depth direction (PL_d) of the Energy Device (ED), the features related to the percentage of low-velocity range (DV_L) of the Scissor Forceps (SF) and Energy Device (ED) showed a large contribution in the negative direction in PC1. On the contrary, the features related to quickness such as acceleration (a) and jerk (j) of Scissor Forceps (SF) showed a large contribution in the positive direction in PC1. This suggests that the principal component in part 3 is mainly related to the overall task efficiency and quickness.

As shown in the score plot of PCA in part 3 (Fig. 3 (f)), some intermediates (green dots) moved Scissor Forceps (SF) very quickly. There was a possibility that the movement of SF was significantly related to the state of each cadaver rather than the level of skill in the process of dissection of the remaining tissue.

D. Overall analysis

The fact that the expert surgeons are distributed in the first quadrant in the PCA score plot in part 1 and part 2, indicates that the components are related to the efficiency of the operation and the speed of the operation which mainly influences the difference in skill. A similar trend was observed in the previous study done by the authors in wet lab training using pig organs [9] and was confirmed to be consistent in the more practical CST.

IV. CONCLUSIONS

In this study, the features of the movement of the surgical instruments were extracted from the data obtained in cadaver training, and principal component analysis was performed on the extracted features to understand the difference in surgical skill among experts, intermediates, and novices. The data divided into 3 parts showed a better result in the number of features with significant differences when compared with before the study (without dividing).

Among the three groups: experts, intermediates, and novices, significant differences were seen in the efficiency features such as path length (PL) and features related to quickness such as mean velocity (v), mean acceleration (a), mean jerk (j), and velocity range in distribution (DL) of the main forceps. Principal component analysis was performed on the features that showed significant differences among the three groups especially in part 1. The differences between experts and intermediates were not very clear in parts 2 and 3, although novices were separated.

The efficiency in movement of surgical instruments and features related to quickness were the key features that influenced the differences in skill. In future, Mocap outcomes should be compared according to a global skill assessment such as Global Operative Assessment of Laparoscopic Skills (GOALS) [11]. Prospects include the analysis of each part of the operation and the establishment of a technique evaluation method using machine learning.

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