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Research Paper

Surgical skill analysis focused on tissue traction in laparoscopic wet lab training

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ABSTRACT

Background: Tissue handling is one of the pivotal parts of surgical procedures. We aimed to elucidate the characteristics of experts' left-hand during laparoscopic tissue dissection.

Methods: Participants performed tissue dissection around the porcine aorta. The grasping force/point of the grasping forceps were measured using custom-made sensor forceps, and the forceps location was also recorded by motion capture system (Mocap). According to the global operative assessment of laparoscopic skills (GOALS), two experts scored the recorded movies, and based on the mean scores, participants were divided into three groups: novice (<10), intermediate (10≤ to <20), and expert (≤20). Force-based metrics were compared among the three groups using the Kruskal-Wallis test. Principal component analysis (PCA) using significant metrics was also performed.

Results: A total of 42 trainings were successfully recorded. The statistical test revealed that novices frequently regrasped a tissue (median total number of grasps, novices: 268.0 times, intermediates: 89.5, experts: 52.0, $p < 0.0001$), the traction angle became stable against the aorta (median weighted standard deviation of traction angle, novices: 30.74°, intermediates: 26.80, experts: 23.75, $p = 0.0285$), and the grasping point moved away from the aorta according to skill competency [median percentage of grasping force applied in close zone (0 to 2.0 cm from aorta), novices: 34.96 %, intermediates: 21.61 %, experts: 10.91 %, $p = 0.0032$]. PCA showed that the efficiency-related (total number of grasps) and effective tissue traction-related (weighted average grasping position in Y-axis and distribution of grasping area) metrics mainly contributed to the skill difference (proportion of variance of first principal component: 60.83 %).

Conclusion: The present results revealed experts' left-hand characteristics, including correct tissue grasping, sufficient tissue traction from the aorta, and stable traction angle. Our next challenge is the provision of immediate and visual feedback onsite after the present wet-lab training, and shortening the learning curve of trainees.

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Introduction

Due to the widespread nature of laparoscopic surgery, which provides high-resolution images of anatomical structures and facilitates faster postoperative recovery, surgeons are required to gain advanced surgical skills including depth perception, bimanual coordination, and gentle tissue handling by utilizing specific surgical devices via TV monitor guidance. While surgical skill training was traditionally conducted through on-the-job training, the recent demand for improved medical safety and decreased case-loads due to working-hour restrictions have encouraged off-the-job training outside daily clinical practice. In order to improve core laparoscopic surgical skills for trainees, verbalize experts' surgical skills, and develop efficient laparoscopic training program, we regularly organized wet-lab simulation trainings using cadaveric swine organs, and continued motion capture (Mocap) analysis of surgical forceps [1–4]. For example, we previously reported that experts (≥50 laparoscopic surgeries) had shorter efficiency-related metrics, such as path length and angular length, and faster speed-related metrics, such as average velocity/acceleration/jerk. There were also significant differences in depth perception-related metrics, such as depth path length, and in the metrics related to bimanual dexterity [4]. These results suggest that experts have good depth perception and cooperative movement of both hands.

Tissue dissection is one of the key surgical steps, and gentle and effective tissue traction, usually managed by the left-hand, should be mandatory for efficient surgery. Through discussion in our research group, we hypothesized that experts grasp the tissue at the tip of the forceps and apply effective traction to the tissue, while novices show unstable tissue traction. During our past data collection, a subset of participants utilized grasping forceps with strain gauges, which could measure the grasping force and point of grasping forceps. Our forceps also had infrared reflective markers for Mocap analysis, which enabled us to analyze the grasping force and location data simultaneously. In the current study, we aimed to clarify experts' "left-hand" characteristics during tissue dissection. Furthermore, in order to enrich feedbacks to trainees, we aimed to visualize left-hand characteristics, combining instrument trajectory and the distribution of grasping positions through a heat map or other data visualization techniques.

Materials and methods

This study was approved by the Ethical Review Board for Life Science and Medical Research of Hokkaido University Hospital (No. 018-0257). We previously reported the present wet-lab simulation training model and Mocap analyses using cadaveric porcine organs [2–4]. Briefly, participants performed tissue dissection around the porcine aorta (tissue dissection task), and suturing/knotting on the incised porcine kidney. During our past data collection, 44 participants utilized grasping forceps with strain gauges during the tissue dissection task, which we focused on in the present study. Two participants were excluded due to the technical failure of force measurement, and 42 participants were included in the present analysis. Written informed consent was obtained for the use of their data for research purposes.

Training task and measurement system

Fig. 1A shows an overview of the training environment. The porcine aorta was placed in a box trainer (Endowork ProII®, Kyoto Kagaku, Japan, Fig. 1B) and one of the four authors (TA, MH, JF, or NI) served as a scopist using the endoscopic video system (VISERA Pro Video System Center OTV-S7Pro, Olympus, Japan). Participants were asked to remove the tissues surrounding the porcine aorta (Fig. 1C), dividing any encountered mesenteric vessels after applying Hem-o-lok (Fig. 1D). All participants were asked to use the grasping forceps with sensors, scissors forceps, and vascular clip applier (Hem-o-lok) and performed the task. The area to be dissected was designated in advance by the position of the golden ribbon (Fig. 1B). The dissection length was approximately 17 cm, and there were usually five to seven mesenteric vessels in the area. All trainings were video recorded for future analyses. Regarding our Mocap system, the tip position (X, Y, and Z), orientation (Roll, Pitch, and Yaw), sheath rotation angle, and opening angle of the forceps (Fig. 2A) were measured by tracking an infrared reflective marker attached to the handle of the forceps using the optical Mocap system (OptiTrack Prime 41, NaturalPoint Inc., USA). Since each marker set has a unique marker-placement pattern, this system can measure multiple surgical instruments simultaneously. Fig. 2B shows an enlarged view of our custom-made sensor forceps, and we previously reported the basic structure and accuracy experiments [5]. Briefly, the forceps had two strain gauge sensors (BF350-3AAN®, Elecrow Technology, Co., Ltd. China) attached on the back of the forceps tip, and we recorded the grasping forces and points, according to the principle of stereo measurement. The two sensors were placed 7 mm apart, and the grasping force and point were calculated from the two sensors' metrics. If the surgeon grasped a tissue at the base of the forceps (0 to 7-mm region from the base where the proximal sensor was only available for measurement), the grasping point was defined as 3.5 mm. A strain gauge amplifier (TP09®, 3PEAK Inc., China) was also used to amplify the signal, and sensor values were read by a microcomputer (Arduino Pro

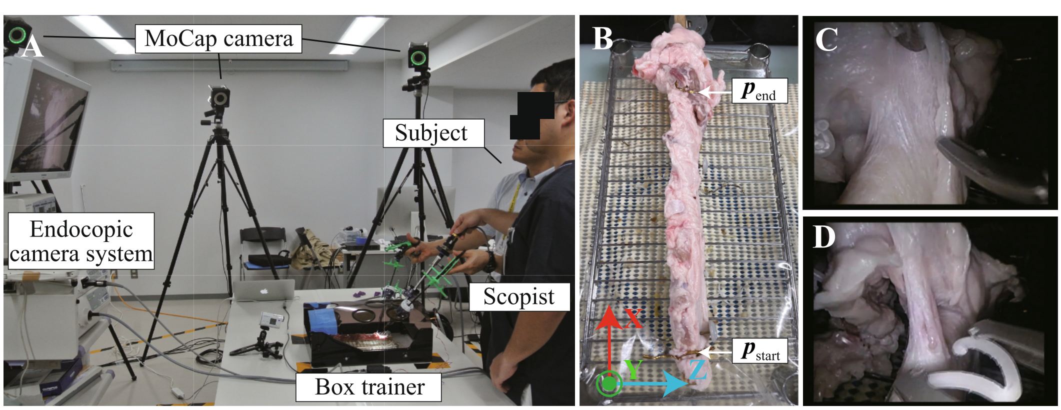

Fig. 1. An overview of simulation training.
A: An overview of the measurement environment in simulation training. The movement of surgical instruments and grasping force/point of grasping forceps were measured simultaneously by the MoCap system and our custom-made sensor forceps.
B: Appearance of the porcine aorta used in the training.
C: A view of tissue dissection.
D: A view of applying Hem-o-lok.

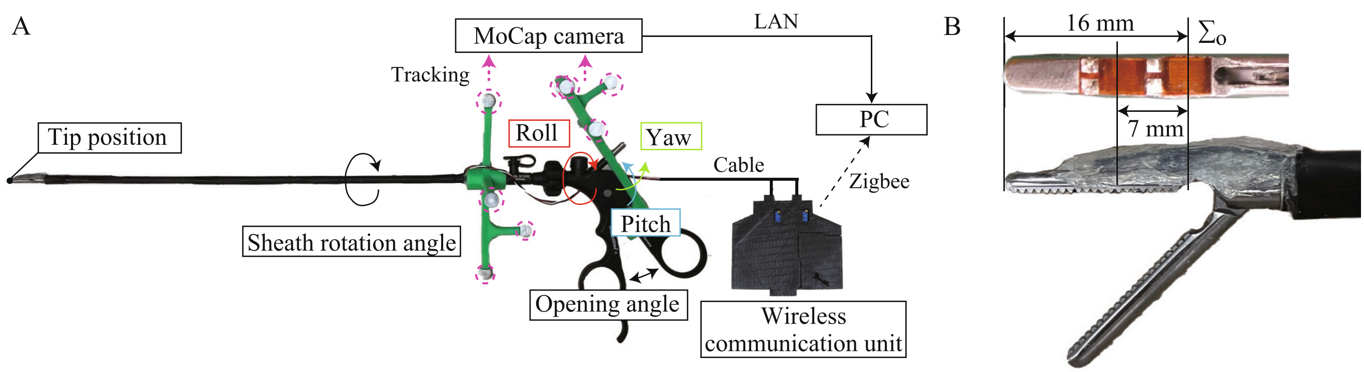

Fig. 2. Grasping forceps with markers and sensors.
A: An overview of grasping forceps. Infrared reflective marker sets were attached to the sheath and handle of the forceps, and the three-dimensional forceps tip position (X, Y, and Z), orientation (Roll, Pitch, and Yaw), sheath rotation angle, and opening ratio were measured.
B: An enlarged view of the tip of the forceps with sensors. Two strain gauge sensors were attached to the back of the grasping forceps at 0 and 7-mm points, respectively. If the surgeon grasped tissue in the 0 to 7-mm region between the two sensors, the grasping point was considered to be 3.5 mm. The grasping point l was defined as the distance from the origin Σ_o to grasping point.

Mini 328®, SparkFun Electronics, USA) and transmitted to a PC via ZigBee wireless communication. The forceps movement data and grasping force/point data were measured simultaneously at 30 Hz, and the mean absolute error of the measurement data was 0.186 N for grasping force, and 0.59 mm for the grasping point in the region from 7 to 16 mm on the forceps tip.

Movie assessments

Two experts (TA and KH) watched the recorded endoscopic videos after anonymization by the author (KE), and rated the surgical skill levels according to the formula of global operative assessment of laparoscopic skills (GOALS) [6]. Anonymized information was maintained only by KE, and video scoring was conducted completely independently by TA and KH. To minimize bias of the reviewers, their average scores were used to categorize the participants. The participants were categorized into 3 groups: novice (<10, n = 7), intermediate (10≤ to <20, n = 20), and expert (≤20, n = 15), and this categorization was utilized for subsequent statistical analysis.

Analysis and statistics

To verify our hypothesis regarding the grasping point and stability of the tissue traction, the following metrics were calculated by the grasping force and grasping point data. We consider that composite features based on instrument location and force data can indicate where the grasp/traction was mainly applied. The total number of grasps, metrics related to distribution and stability of the grasping position, and those related to the traction angle were also calculated. Fig. 3 outlines the definition of the metrics and positional relationship of the aorta.

1. Average grasping force $\bar{f}$ (N)

$$\bar{f} = \frac{1}{N_{\text{valid}}} \sum_{i=1}^{N} f(i)$$

where N is the total number of frames, $f(i)$ is the grasping force in frame i, and N_{valid} is the number of frames that satisfy $f(i) > 0$. That is, $\bar{f}$ means the average force while grasping tissue.

2. Average grasping point $\bar{l}$ (mm)

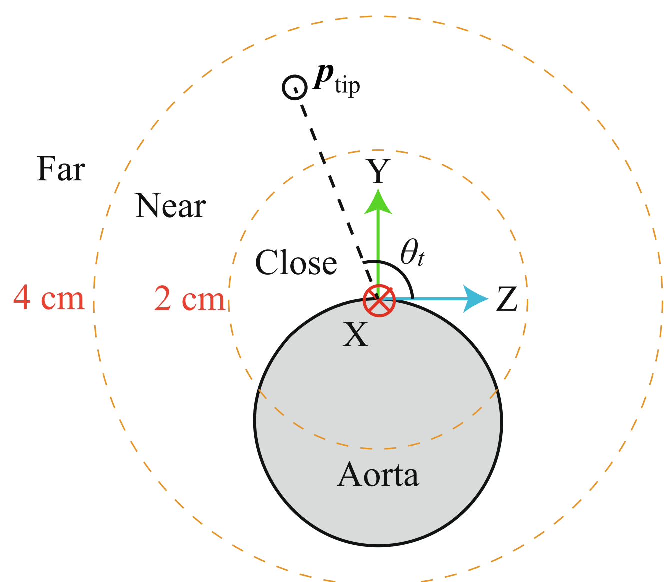

Fig. 3. Definition of the traction angle and zone metrics.
This is the projected view of the plane orthogonal to the aorta (Y-Z plane) from the closer side of Fig. 1. The traction angle refers to the angle formed by the line connecting the top of the aorta and forceps tip position $\boldsymbol{p}_{\text{tip}}$, and the Z-axis. Distributions of the grasping area were calculated in the three categories according to the distance from the aorta: (a) Close [0≤ to <2.0 (cm)], (b) Near [≤2.0 to <4.0 (cm)], and (c) Far [4.0≤ (cm)].

$$\bar{l} = \frac{1}{N_{\text{valid}}} \sum_{i=1}^{N} l(i)$$

where $l(i)$ is the grasping point in frame i. The grasping point l was defined as the distance from the origin at the root of the grasper ($\Sigma_o$in Fig. 2B) to the grasping point. That is, $\bar{l}$ means the average grasping point while grasping tissue.

3. Maximum grasping force $f_{\max}$ (N)

$$f_{\max} = max(f(i))$$

$f(i)$ and $l(i)$ were smoothed by the Savitkzy-Golay filter (window size: 15, order: 3).

4. Average of derivative of grasping force $\overline{df}$ (N/s)

$$\overline{df} = \frac{1}{N_{\text{valid}}} \sum_{i=1}^{N} \dot{f}(i)$$

where $\dot{f}(i)$ is the derivative of grasping force in frame i calculated from the Savitzky-Golay filter.

5. Ratio of grasping period to the total task time P_{grasp} (%)

$$P_{\text{grasp}} = \frac{N_{\text{valid}}}{N} \times 100$$

6. The total number of grasps N_{grasp} (–)
7. Standard deviation of grasping force σ_f (N) and grasping point σ_l (mm)
8. Skewness S_f, S_l (–)

It is a statistical measure that indicates the degree of deviation from the normal distribution, representing the degree of symmetry. This metric was calculated for grasping force (S_f) and grasping point (S_l), respectively.

9. Kurtosis K_f, K_l (–)

It is a statistical measure that indicates the degree of deviation from the normal distribution, representing both the peakedness and asymmetry of the distribution. This metric was calculated for grasping force (S_f) and grasping point (S_l), respectively.

10. Traction angle θ_t

The traction angle refers to the angle formed by the line connecting the top of the aorta and forceps tip $\boldsymbol{p}_{\text{tip}}$, and the Z axis, as outlined in Fig. 3.

(a) Weighted average $\overline{\theta_t}$ ($^\circ$)

Weighted average of θ_t by the grasping force f, as shown below:

$$\overline{\theta_t} = \frac{\sum_{i=1}^{N} f(i)\theta_t(i)}{\sum_{i=1}^{N} f(i)},$$

where $\theta_t(i)$ is the traction angle in frame i.

(b) Weighted standard deviation σ_t ($^\circ$)

Weighted standard deviation of θ_t by grasping force f, as shown below:

$$\sigma_t = \sqrt{\frac{\sum_{i=1}^{N} f(i)(\theta_t(i) - \overline{\theta_t})}{\sum_{i=1}^{N} f(i)}}.$$

(c) Skewness S_θ (–)

(d) Kurtosis K_θ (–)

11. Distribution of grasping area

The percentage of total grasping force applied in the zone to total grasping force. This feature was calculated in the following three categories according to the distance from the aorta:

(a) Close (%) [$0 \leq$ to <2.0 (cm)].
(b) Near (%) [$2.0 \leq$ to <4.0 (cm)].
(c) Far (%) [$4.0 \leq$ (cm)].

12. Weighted average of grasping position

Weighted average of forceps tip position by the grasping force f. This feature was calculated along two coordinate axes, the Y-axis and Z-axis defined in Fig. 1B.

(a) $\overline{y_w}$ (cm)
(b) $\overline{z_w}$ (cm)

13. Weighted standard deviation of grasping position

Weighted standard deviation of grasping position by the grasping force f. This feature was also calculated along the Y-axis and Z-axis.

(a) σ_{yw} (cm)
(b) σ_{zw} (cm)

Measurements were compared among the three groups (novice vs. intermediate vs. expert, above-defined), and the Kruskal-Wallis test was utilized to assess the differences since the normality of data was not assured. The Wilcoxon rank sum test was also used for paired comparison for significant metrics identified by the Kruskal-Wallis test ($p < 0.05$). The features with significant differences ($p < 0.05$) based on the Kruskal-Wallis test were employed in principal component analysis (PCA), a data reduction method. By performing PCA for significant features, it was possible to summarize the data and determine which factors mainly contributed to skill differences. Before PCA, data were normalized using a robust z-score to reduce the impact of outliers. The normalized data z_i were calculated as follows:

$$z_i = \frac{x_i - x_m}{NIQR},$$

where x_i refers to original data, x_m is the median of data, and $NIQR$ is the normalized interquartile range. Analyses were performed using JMP Pro 17 (SAS, Japan), and PCA was conducted using Scikit-learn, a machine-learning library for python [7].

Results

Table 1 summarizes the backgrounds of the 42 participants. Twenty-two urologists, 9 gastroenterological surgeons, 3 gynecologists, 3 junior residents, and 5 medical students joined the training sessions. Supplementary Fig. 1 shows a scatter plot of GOALS scores as evaluated by the two experts in an anonymous video review. The intraclass correlation coefficient of case 2 was 0.8258, showing good inter-rater reliability.

Supplementary Fig. 2 shows representative examples of line plots of grasping forces and points, and Fig. 4 shows a representative heat map of the distribution of the grasping force on the plane orthogonal to the aorta (Y-Z plane) for a novice, an intermediate, and an expert surgeon. As the proficiency increased, the area of the stronger grasping force shifted upwards from the aorta. Supplementary Table 1 summarizes the overall results of force-based metrics and combined metrics of force and Mocap data according to skill proficiency. Fig. 5 shows boxplots of $\bar{f}, \bar{l}$,

N_{grasp}, σ_t, Close, Far, and $\overline{y_w}$. As shown in Fig. 5, contrary to our hypothesis regarding the grasping point, there was no significant difference ($p < 0.05$) in $\bar{f}$ and $\bar{l}$ among the three groups. On the other hand, there was a significant difference was observed in N_{grasp}, σ_t, Close, Far, and $\overline{y_w}$. In other words, the total number of grasps decreased, tissue traction became sufficiently tense, and traction angle became stable.

Fig. 6 shows the results of PCA. The cumulative proportion of the 1st and 2nd principal components was 78.30 %. Fig. 6A shows the loadings of the first and second principal components, and the efficiency-related (N_{grasp}) and grasping position-related metrics ($\overline{y_w}$, Close, Far) contributed mainly to the 1st principal component (proportion of variance: 60.83 %), while the stability of the traction angle (σ_t) contributed to the 2nd principal component (proportion of variance: 17.47 %). Fig. 6B shows a scatter plot of the principal component score. The distribution was mainly along the first principal component in the order of experts, intermediates, and novices.

Discussion

In the present study, we developed unique grasping-forceps which could simultaneously record the grasping force/point and motion features, and recorded data during tissue dissection simulation training. Before the present study, we preliminarily compared the force/point and Mocap data among the 42 participants according to previous caseloads of laparoscopic surgery, but did not find differences in the characteristics, other than a higher ratio of the non-grasping period to total task time and larger number of grasps in novices [8]. Because previous caseloads do not always reflect skill competency, the two experts performed video-review assessments, and, using the mean GOALS score as a surrogate of skill proficiency, we conducted the present thorough analysis. We finally observed experts' "left-hand" characteristics in the tissue traction procedure. To our knowledge, this is the first study to measure and analyze the grasping point, force, and motion-related metrics of grasping-forceps simultaneously.

As shown in Supplementary Table 1 and Fig. 5, the total number of grasps was decreased according to skill competency. Standard deviation of the traction angle, σ_t, was significantly different among the three groups ($p = 0.0285$). These observations suggest correct tissue grasping and stable tissue traction in skilled surgeons. Significant differences were also observed in the "Close" and "Far" zones of the grasping area, and in the weighted average of the grasping position on the Y-axis $\overline{y_w}$, ($p < 0.0187$). These observations may reflect the effective tissue traction by experts. Regarding the grasping point, although we initially hypothesized that expert surgeons would grasp a tissue at the tip of the forceps, we did not observe this tendency. Overall, as shown in Fig. 6A (PCA results), the metrics related to efficiency and sufficient tissue traction contributed to the 1st principal component, while the stability of traction contributed to the 2nd principal component.

Several researchers performed grasping force measurements in different training situations. In a dry lab, Olivas-Alanis et al. measured the forceps tip position (X, Y, and Z) and grasping force in a peg/object transfer task or pea on peg task, and reported that expert surgeons had a high mean/maximum grasping force [9]. Timothy et al. also measured the forceps tip position (X, Y, and Z), tool roll angle, grasper jaw angle, and grasping force in peg transfer, cutting, and suturing tasks, and reported that the peak grasping force did not correlate with the task time or an FLS score [10]. In a wet lab, Araki et al. assessed the grasping force, grasping angle, and acceleration when elevating a kidney during live porcine simulation training (laparoscopic nephrectomy), and observed that expert surgeons showed a lower mean and standard deviation of the grasping force [11]. Richards et al. also measured the operating force/torque at the tip of forceps (X, Y, Z, Rx, Ry, and Rz), and grasping force in laparoscopic cholecystectomy and Nissen fundoplication in live porcine surgery. They observed that experts applied greater force/torque during tissue dissection, while novice surgeons applied greater force/torque during tissue manipulation [12]. However, in this study, there was no significant difference in grasping force between experts and novices. These inconsistent findings among previous studies may be due to differences of the training task. Also, we measured metrics during the entire training procedure, while previous studies mainly focused on a single motion, such as elevating the porcine kidney.

Limitations of this study include the small sample size and heterogeneity, including differences in the background (urologist/gastroenterologist/gynecologist) and inclusion of two left-handed surgeons. Porcine organs were not completely identical; for example, they showed a difference in the number of mesenteric vessels encountered. Regarding the GOALS score evaluation, to minimize human bias, this study utilized the mean score of two experts who independently rated the anonymized videos, but that was not entirely free from human bias. Another limitation of this study was that the force measurement data include an error (grasping force: 0.186 N, grasping point: 0.59 mm), although we believe it is small enough to be acceptable. Our forceps could not be used to accurately measure the base of the forceps tip (0 to 7-mm region in Fig. 2B) due to sensor placement, although the tissue was mainly grasped at the tip, as shown in Supplementary Fig. 2 and Supplementary Table 1. Nevertheless, we believe that our composite analysis of forceps motion and grasping force/point revealed experts' left-hand characteristics during tissue dissection, and may be helpful to develop objective

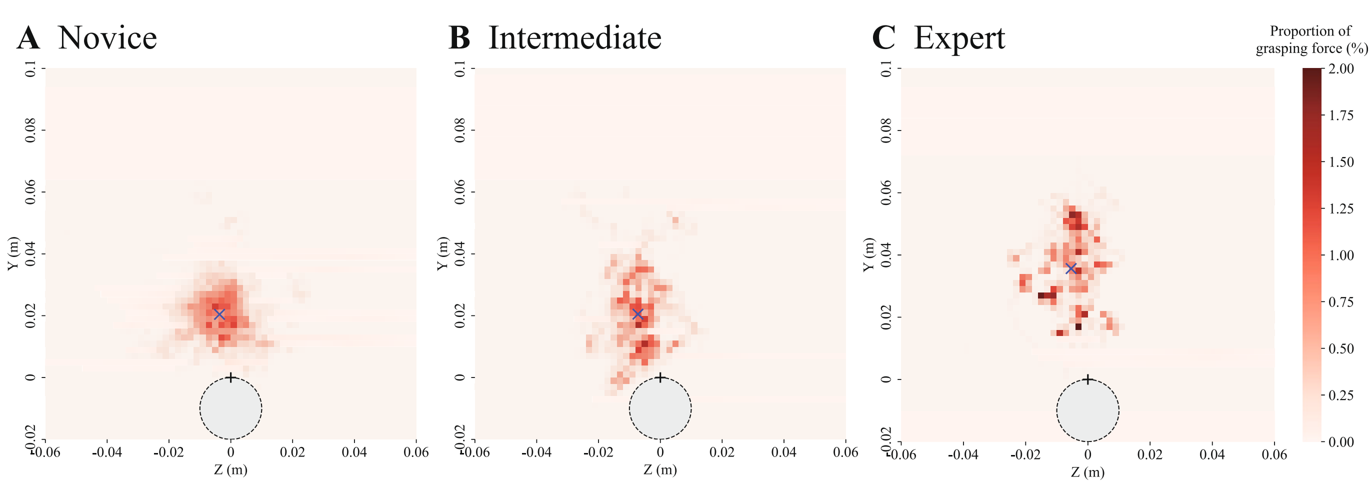

Fig. 4. Representative heat map of the distribution of grasping force.
Each pixel in the figure was set to 2 mm square, and the proportion of the sum of the grasping forces applied in the pixel to the total grasping force (%) was displayed in the plane orthogonal to the aorta (as in Fig. 3).

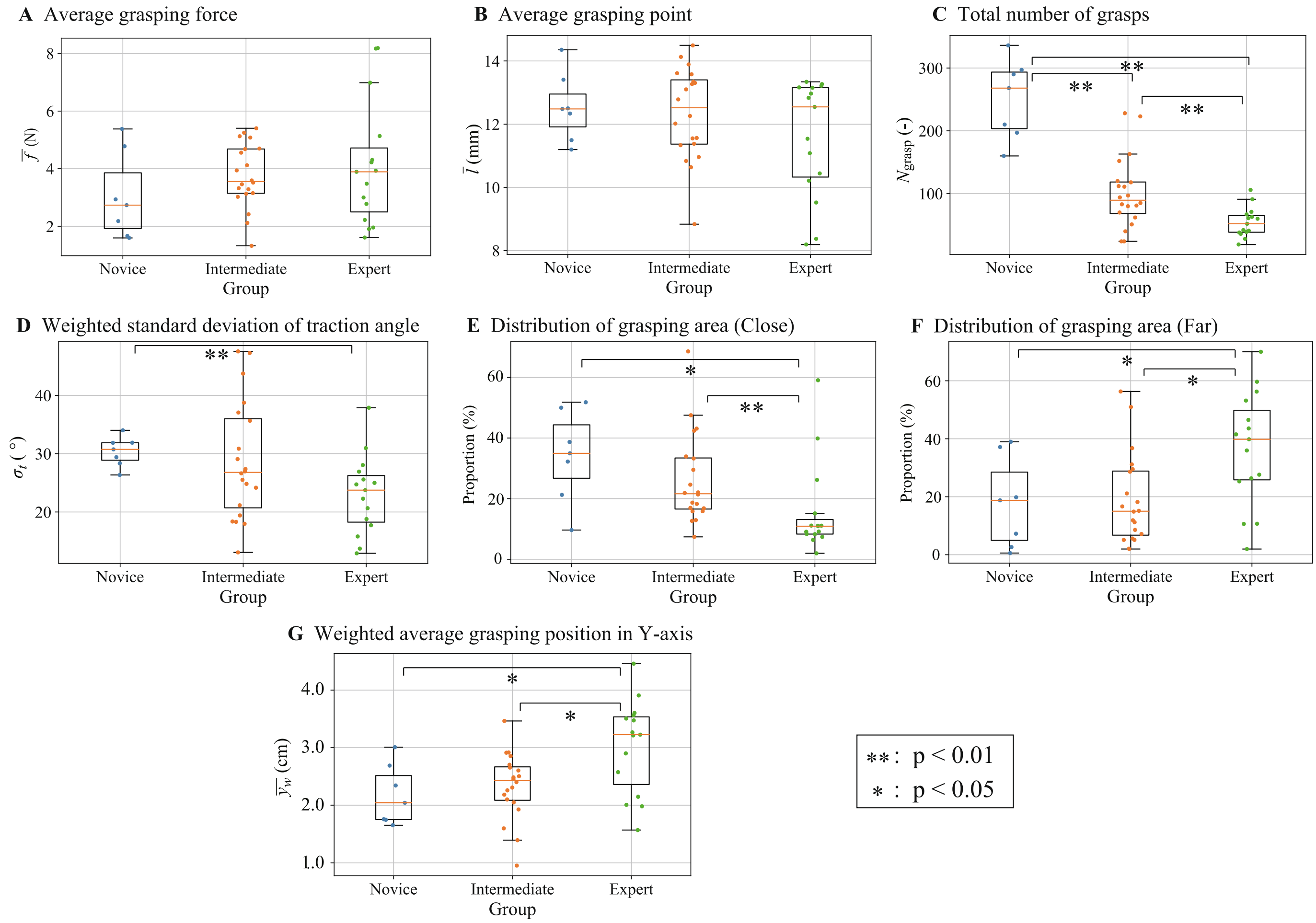

Fig. 5. Box plot of representative calculated metrics.
A: Average grasping force.
B: Average grasping point.
C: The total number of grasps.
D: Weighted standard deviation of traction angle.
E: Distribution of grasping area (Close).
F: Distribution of grasping area (Far).
G: Weighted average of grasping position in Y-axis.
The Kruskal-Wallis test was used to assess differences between the three groups (novice, intermediate, and expert). The Wilcoxon rank-sum test was also used for paired comparisons.

Table 1
Participants' backgrounds.

	n = 42
Background	Urologic surgeon, n = 22
	Gastroenterological surgeon, n = 9
	Gynecologic surgeon, n = 3
	Junior resident, n = 3
	Medical student, n = 5
Age, years	Median 38.5 (range, 23–52)
Sex	Male/female = 38/4
Experience of laparoscopic surgery	0–9, n = 9
	10–49, n = 11
	50–99, n = 4
	100–499, n = 13
	≥500, n = 5
Dominant hand	Right/left = 40/2

feedback for trainees. Because we are developing a Mocap-based objective feedback method both in porcine organ-based laparoscopic training and cadaveric training (laparoscopic radical nephrectomy), our future challenge is to integrate the present force measurement system into our training program, and provide objective feedback to trainees, ideally onsite immediately after training.

Conclusion

The simultaneous analysis of grasping force and device location revealed the experts' left-hand characteristics, including correct tissue grasping, sufficient tissue traction from the aorta, and a stable traction angle. Our next challenge is how to provide immediate and visual feedback onsite after the present wet-lab, and shortening the learning curve.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sopen.2024.08.002.

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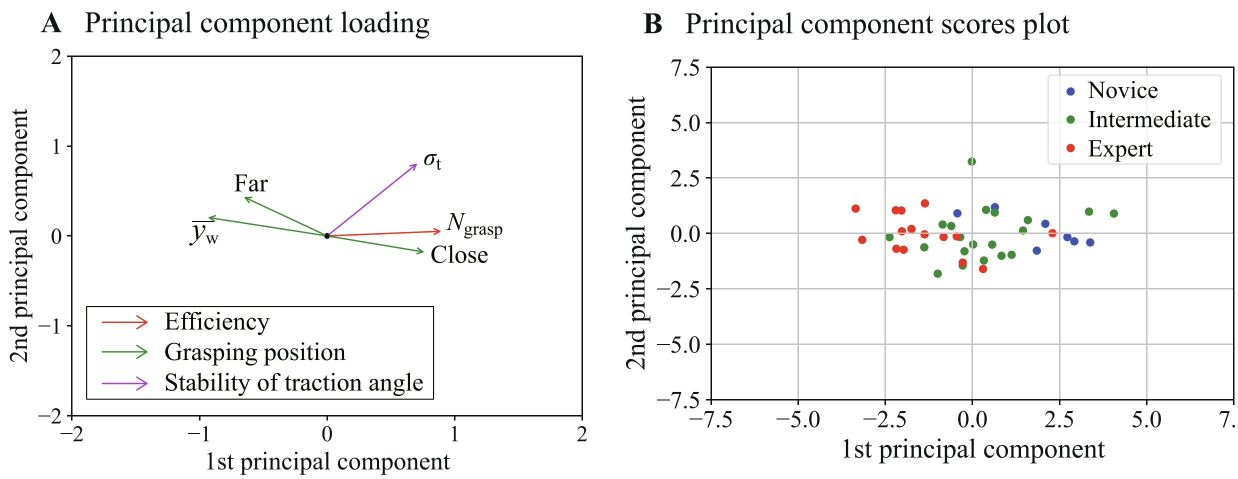

Fig. 6. The results of PCA.
A: Principal component loading plot on 1st and 2nd principal components. Based on the characteristics of each metric, they were categorized as follows: "Efficiency": total number of grasps (N_{grasp}), "Grasping position": Close, Far, and Weighted average of grasping position in Y-axis ($\overline{y_w}$), "Stability of traction angle": Weighted standard deviation (σ_t). The cumulative proportion of the 1st and 2nd principal components was 78.30 %.
B: Principal component score plot for 1st and 2nd principal components. The plots were color-coded based on the subject's grouping (novice, intermediate, and expert).

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Ethics approval

This study was approved by the Ethical Review Board for Life Science and Medical Research of Hokkaido University Hospital (No. 018-0257). All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Research Committee and the Declaration of Helsinki of 1964 and its subsequent amendments or comparable ethical standards.

CRediT authorship contribution statement

Koki Ebina: Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis. **Takashige Abe:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Madoka Higuchi:** Methodology, Investigation. **Kiyohiko Hotta:** Investigation, Data curation. **Jun Furumido:** Investigation. **Naoya Iwahara:** Investigation. **Taku Senoo:** Supervision. **Shunsuke Komizunai:** Supervision, Software, Methodology, Investigation. **Teppei Tsujita:** Supervision. **Kazuya Sase:** Supervision. **Xiaoshuai Chen:** Supervision. **Yo Kurashima:** Resources. **Hiroshi Kikuchi:** Investigation. **Haruka Miyata:** Investigation. **Ryuji Matsumoto:** Investigation. **Takahiro Osawa:** Investigation. **Sachiyo Murai:** Investigation. **Atsushi Konno:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Nobuo Shinohara:** Supervision, Resources, Project administration.

Declaration of competing interest

None of the authors have a conflict of interest, financial or otherwise.

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