

Assessment of Force Thresholds Perceived as Safe by Expert Surgeons in Surgical Procedures

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Abstract. Although excessive force on organs is known to cause injury, learning how to safely apply force during surgery is one of the most difficult skills for young doctors to master. Based on their experience, expert surgeons have their own safety thresholds and operate within these thresholds. In this study, we investigated these “safety thresholds.” The experiment was conducted after obtaining approval of the Ethics Committee of the Animal Experiment Facility (IVT24-50). We performed experiments in the same setting as laparoscopic surgery using a laboratory pig. Two expert surgeons who are responsible for teaching and supervising surgery at their respective institutions compressed the pig’s kidney for a few seconds at the appropriate safety threshold strength used in actual surgery. The force was measured using surgical forceps equipped with a three-axis force sensor at the tip. The measured force was graphed and the mean force over a 1-second interval following the first peak was calculated (1sMean). The median of 1sMean in 337 sessions was 0.79 N (interquartile range: 0.62–1.04 N). The logarithmic transformation of 1sMean became the normal distribution. The exponentially transformed mean, +1SD and +2SD were 0.80 N, 1.19 N and 1.76 N, respectively. In minimally invasive kidney surgery, expert surgeons are taught to target a force of about 0.80 N, with a safety margin of 1.19 N and a safety limit threshold of 1.76 N. The results of this study can be used as basis for future studies on the forces applied to the organs

Keywords: Safety Force, Force Measure, Porcine Kidney, Minimally invasive surgery

1 Introduction

1.1 Requirement for Force Measurement

Recently, minimally invasive surgical techniques, including² laparoscopic and robot-assisted surgery, have become widespread worldwide. Compared with traditional open

surgery, minimally invasive surgical techniques offer numerous advantages, including enhanced visualization, shorter hospital stays, and reduced readmission rates [1]. However, despite these advantages, minimally invasive surgical techniques have unique problems, particularly in the precise application of force during procedures. Compared with open surgery, where direct tactile feedback is available, minimally invasive surgical techniques rely on the use of surgical instruments (e.g., forceps), which limits direct contact with the organs. This limitation makes it difficult to accurately perceive the amount of force being applied. The organs often need to be manipulated or held in place during surgery. Although excessive force can result in tissue damage or injury, insufficient force may impede the surgical procedure. Thus, mastering the appropriate application of force is one of the most challenging but important skills for novice surgeons. Currently, as there are no standardized protocols for teaching how to control force application, controlling of force application is typically learned through subjective guidance from experienced surgeons. Furthermore, few studies have defined the thresholds of safe versus dangerous force application during surgery [2,3]. Moreover, studies that have quantitatively measured the forces applied during routine minimally invasive procedures are limited [4].

1.2 Safety thresholds of expert surgeons

In a previous study, a porcine kidney ruptured when a closed blade tip was applied with a force of 4.5 N, highlighting the potential dangers associated with excessive force[4]. Although this force level is considered dangerous, the precise thresholds for safe versus dangerous force application remain unclear. Establishing a “safety threshold” requires demonstrating that no injury occurs, even in rare cases. However, defining these thresholds objectively poses significant challenges.

Currently, expert surgeons rely on their clinical experience to apply force within their perceived safety thresholds during surgical procedures. These self-defined safety thresholds, which have been developed through years of hands-on experience, serve as informal guidelines but lack standardization or empirical validation. In the present study, we focused on these “safety thresholds” for kidney manipulation, because the kidney is a solid organ that is frequently encountered in urological surgery. This study aimed to quantify the forces applied during surgical procedures and assess their implications for patient safety.

2 Preparation for the Experiment

2.1 Ethical Committee

The experiment was conducted after obtaining approval of the Ethics Committee of the Animal Experiment Facility of Kyoto University (IVT24-50).

2.2 Preparation of the Force-Measuring Forceps

Laparoscopic forceps that are capable of measuring the force at the tip were needed to perform this experiment. However, there were no such forceps available commercially. Thus, we previously developed custom forceps that can measure the force and reported their use in a dry box environment [5]. These custom-designed forceps were equipped with a three-axis force sensor (USLG10-5N: Tec Gihan Co., Ltd.), which allowed for the precise measurement of forces in the x, y, and z directions. The design of the forceps replicated the shape and functionality of the forceps used in robotic surgery, ensuring relevance to clinical applications (Fig. 1a, b). The force data in the x, y, and z directions were collected during the experiment. The Z-axis represents the axial direction of the forceps (aligned with the shaft), the Y-axis corresponds to the opening and closing direction of the tip of the forceps, and the X-axis is perpendicular to both the Z-axis and the Y-axis (Fig. 1c). The resulting force values were calculated using the following equation:

$$\text{Force} = \sqrt{F_x^2 + F_y^2 + F_z^2}$$

This setup enabled the accurate quantification of forces applied during simulated surgical procedures, providing the basis for assessing safety thresholds.

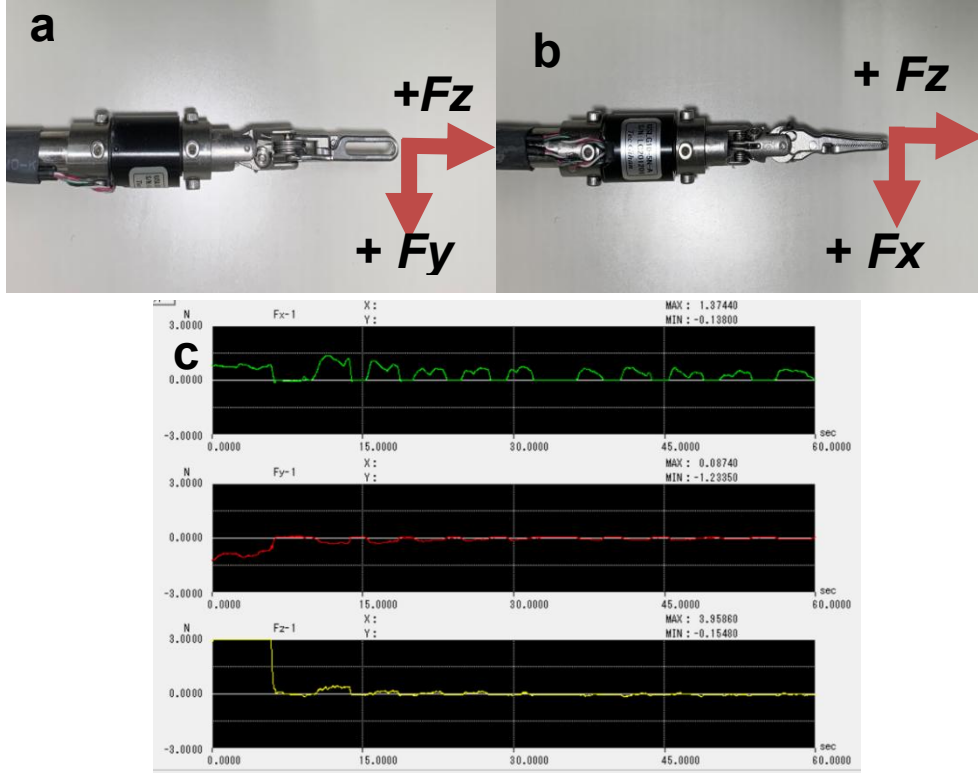


Fig. 1. a), b) Forceps with the three-axis force sensor. c) example of result of force measurement.

2.3 Pre-measurement Preparation

The force measurement system was calibrated to ensure accuracy prior to the experiment. A weight of 100 g was suspended and 0.98 N was measured. The experiments were performed in a laparoscopic surgery setup using a laboratory pig. A pig was selected as the experimental model because of its anatomical similarity to humans, making it suitable for experimental and surgical training purposes. Two expert surgeons with extensive experience in teaching and supervising surgical procedures at their respective institutions, participated in the study.

After the pig was laterally positioned on the operating table, the peritoneal cavity was accessed under general anesthesia following the standard protocol for conventional left kidney surgery. After exposing the kidney surface, the surgeons applied compressive force to the left kidney using the custom-designed laparoscopic forceps. A fixed camera was included in the experimental setup to ensure consistent visualization, and the forceps were introduced through a single port during the procedure (Fig. 1a).

The surgeons incrementally applied force for a few seconds, aiming to reach the “safety threshold” that they deemed appropriate for actual surgical practice (fig.2). Once this was achieved, the force was maintained at a constant level to simulate real surgical conditions and allow for accurate data collection.

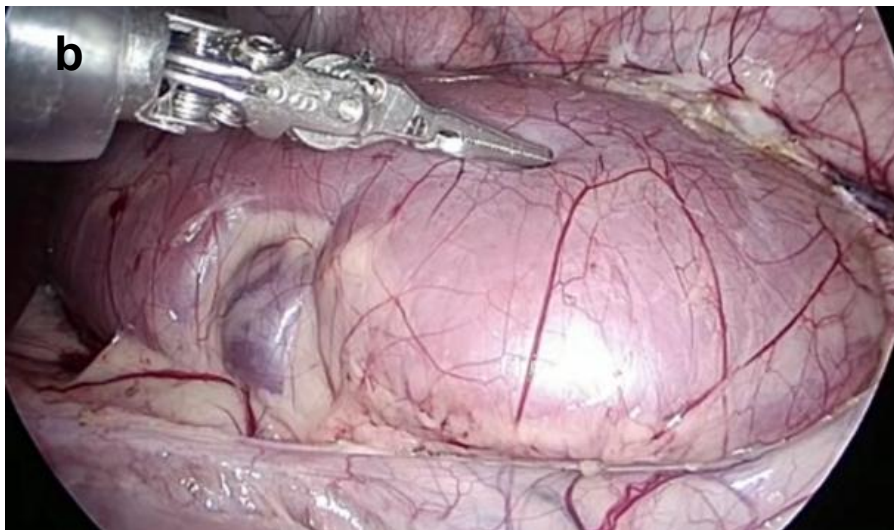
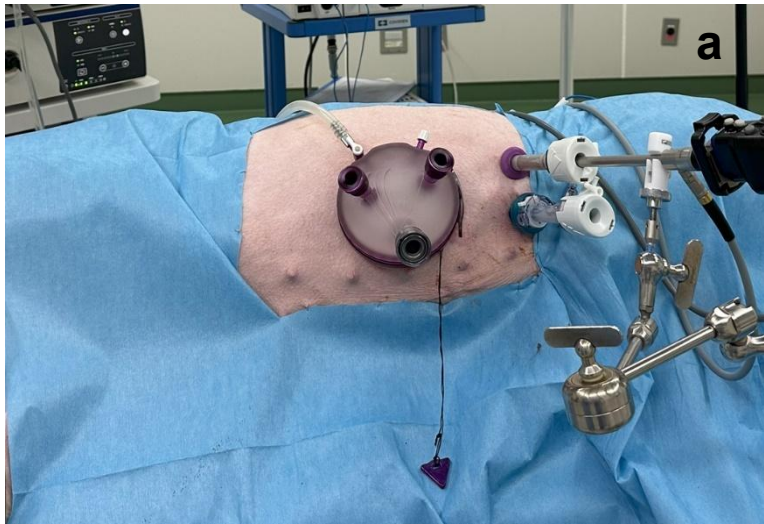


Fig. 2. a) The pig was secured in the lateral position under general anesthesia as in conventional left kidney surgery. b) the surgeons applied force to kidney aiming to reach the safety threshold imaging actual surgery.

2.4 Definition of Valuables

In an ideal scenario, the maintained force should remain perfectly constant, allowing for the straightforward determination of the “safety threshold” (fig. 3a). However, in practice, the applied force exhibited variability during maintenance (Fig 3b). Consequently, the “safety threshold” was defined as either the first peak value or the average force measured after the first peak. The measured force data were graphed, and the mean force over a one-second interval following the first peak (1sMean) was calculated (Fig. 3c). The first peak was defined as the initial point at which the measured force value began to decline. To ensure precision, this peak was identified by reediting the data in 0.2-seconds increments, as a single decline was insufficient to define a peak (a continuous decline was needed for validation).

This calculated value was considered as the “safety threshold” for each session. Subsequently, the statistical safety threshold was determined through repeated measurements of these session-specific thresholds. The sessions were excluded from the analysis if force measurements were not recorded or if the force was not maintained for a minimum of one second.

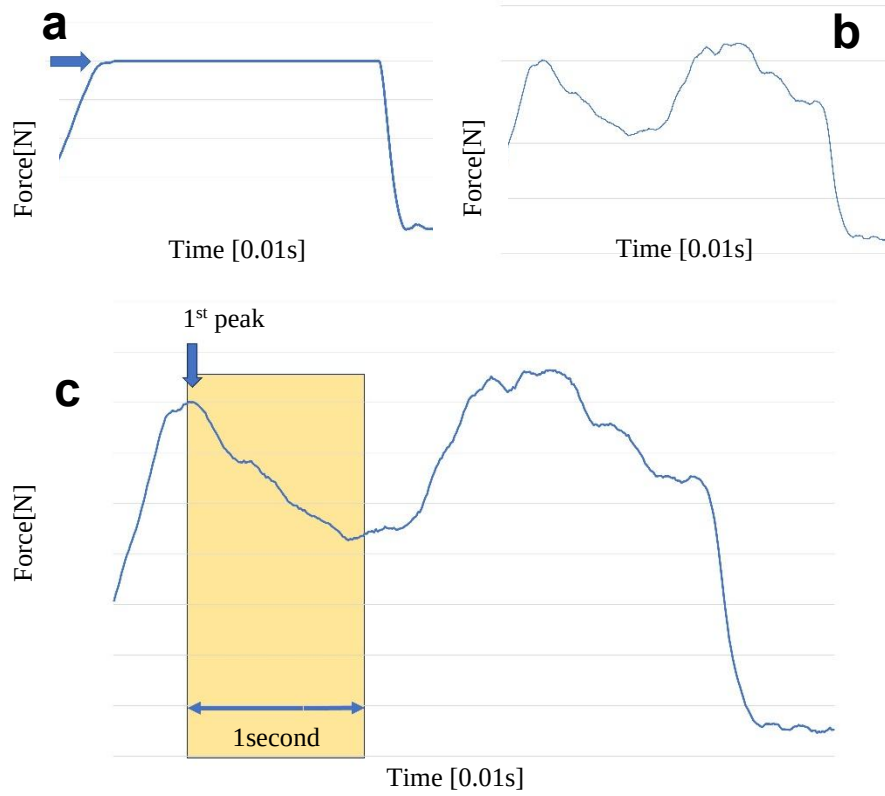


Fig. 3. the graph of measured force. a) If the maintained force was completely constant, blue arrow was “safety threshold” b) Actually, the maintained force was not constant. c) 1sMean was defined as 1 second means from first peak.

3 Result

3.1 Measuring Force with The Forceps in Porcine Kidney

After excluding nine sessions with insufficient data, 337 sessions were included in the analysis. The distributions of the 1sMean and first peak values are illustrated as histogram in Fig. 4a and Fig. 4b, respectively. The median and interquartile range (IQR) for 1sMean were 0.79 N (interquartile range: 0.62–1.04 N), with a 95th percentile value of 1.54 N. and 1.54 N, respectively. Similarly, the median and IQR for the first peak value were 0.83 N (IQR: 0.66–1.12 N), with a 95th percentile value of 1.59 N. In addition, the maximum and minimum force values recorded during the sessions were analyzed. The median (IQR) for the maximum force was 0.88 N (IQR: 0.71–1.17 N), while the median (IQR) for the minimum force was 0.68 N (IQR: 0.51–0.92 N). These results

provide a quantitative foundation for understanding the variability and thresholds of force applied during laparoscopic manipulation of a porcine kidney.

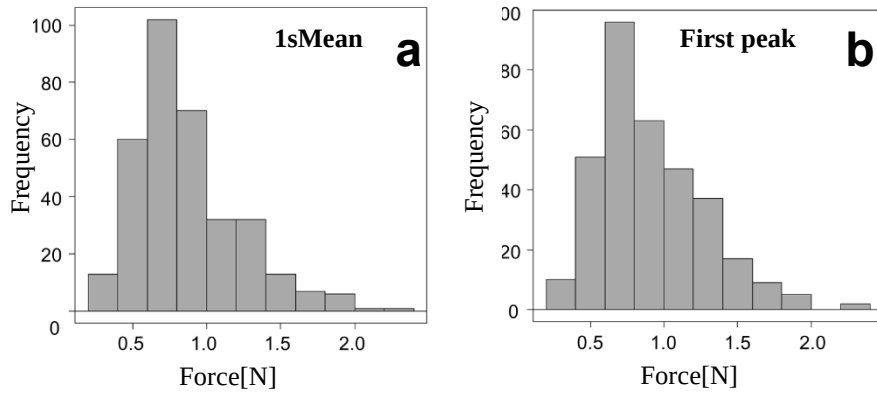


Fig. 4. a) The distributions illustrated as histogram, a) 1sMean b) first peak.

3.2 Comparing 1sMean and First Peak Value

The Mann-Whitney U test revealed no significant difference between the first peak and the 1sMean values (Fig. 5a, $p = 0.060$). However, a strong correlation was observed between these two variables, with a correlation coefficient of 0.97 ($p < 0.001$) (Fig. 5b). These findings suggest that expert surgeons typically apply force to the kidney until reaching the “first peak” value and then slightly reduce the force to maintain it at a stable level. Given that the first peak value may be slightly excessive for defining “safety thresholds,” the 1sMean value is considered a more appropriate metric for determining a safe force application threshold.

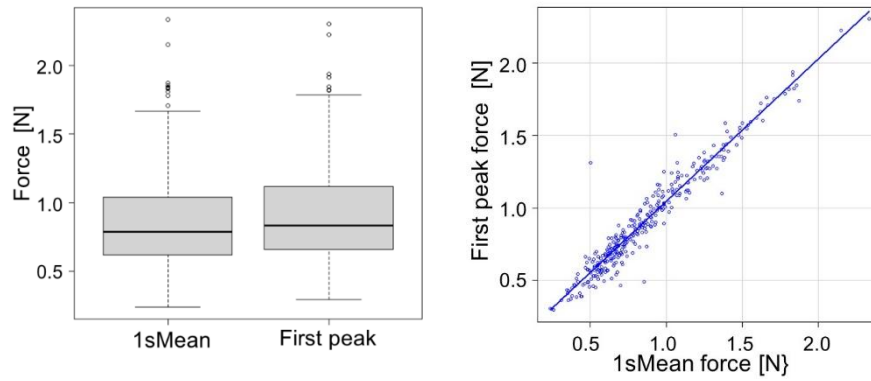


Fig. 5. a) comparing 1sMean and first peak, a) box plot by Mann-Whitney U test, b) scatter plot.

3.3 Logarithmic Transformation

The logarithmic transformation of the 1sMean resulted in data distributions that conformed to normality (Fig. 6). The Shapiro-Wilk normality test yielded $p = 0.26$ for the 1sMean, while the Kolmogorov-Smirnov test showed $p = 0.49$, further supporting normal distribution.

The mean, +1 standard deviation (SD), and +2 SD for the logarithmic-transformed 1sMean were -0.0954, 0.0752, and 0.246, respectively. After exponential transformation, these corresponded to 0.80 N, 1.19 N, and 1.76 N.

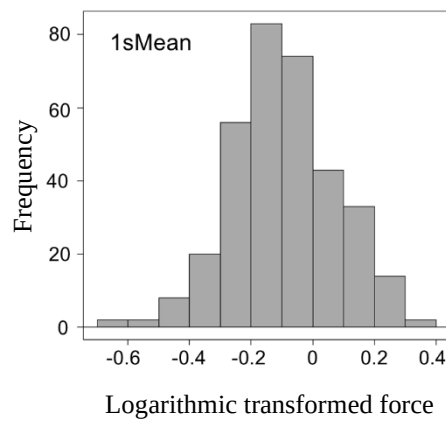


Fig. 6. The distribution of 1sMean illustrated as histogram.

3.4 Dangerous Force

During the application of forces within the defined safety thresholds, no hematoma or bleeding was observed. However, to explore the impact of excessive force, we intentionally applied forces significantly higher than the typical safety thresholds, defined as “obviously dangerous force.”

At 8th session, a hematoma was observed on the kidney surface (Fig. 7a, b). The corresponding force measurements for this session were as follows: the 1sMean was 3.60 N, the first peak was 3.56 N, the maximum force was 3.81 N, and the minimum force was 3.32 N. These results suggest that forces exceeding 3.5 N represent a threshold beyond which organ damage becomes evident.

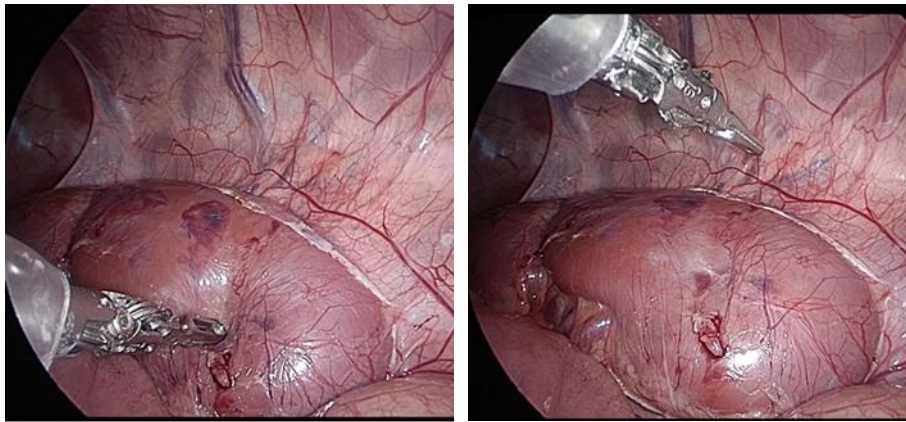


Fig. 7. a) applying force to kidney as strong as possible. b) hematoma was observed (white arrow).

4 Discussion

This study demonstrated that expert surgeons typically applied approximately 0.8 N of force when compressing the kidney during laparoscopic procedures. Accounting for the variability in force application, the statistical safety threshold was determined to be 1.8 N. This upper limit represents the threshold that should not be exceeded to ensure patient safety. Unlike previous studies that primarily focused on direct tissue damage to define dangerous forces, the present study is the first to establish safety thresholds based on repeated measurements of the force applied by expert surgeons during routine surgical practice. This research provides a practical and empirically derived guideline for safe force application by leveraging the experiential knowledge of expert surgeons.

These findings are significant as they offer an objective reference point for training novice surgeons and refining surgical techniques in minimally invasive procedures. Moreover, further research could build upon these results by exploring the thresholds for other organs and surgical conditions to enhance the generalizability of the findings.

As previously mentioned, the safe and dangerous force thresholds for organ manipulation during surgery remain unclear. Few studies have quantified the forces applied to organs, primarily because of the lack of commercially available forceps that can

measure the force. To address this gap, previous studies have developed custom-designed force-measuring forceps to address this gap. For example, Yatabe et al. [2] reported a 0% incidence of gross hemorrhage, hematoma, or external longitudinal muscle injury at the microscopic level when a maximum grip strength of 15 N was applied during small-intestine grasping experiments in 10 dogs. This discrepancy between their findings and our results may reflect fundamental differences between luminal and parenchymal organs. Similarly, Barrie et al. [3] investigated the histological changes in porcine colon tissue resulting from varying gripping forces and durations by using a mechanical grasper. They found that the applied gripping force was correlated with the degree of tissue injury, as evaluated pathologically. These findings are consistent with our clinical experience, suggesting that a similar relationship may exist for the kidney. This reinforces the importance of understanding the interplay between force application and tissue response to establish safety thresholds across different types of organs.

Compared with previous studies, the present study did not include pathological evaluation. This decision was driven by several factors. First, the number of trials posed a significant limitation. Conducting pathological evaluations repeatedly in a living porcine model is impractical. Although the length of the intestine allows for multiple locations to be tested, the kidney presents a more constrained environment, with limited space for applying force. Consequently, the scope for pathological examination under varied conditions was inherently restricted. Second, the uncertainty of damage rendered the pathological evaluation less practical. We believe that the relationship between organ damage and applied force is stochastic, lacking a clear deterministic threshold. A single instance without observable pathological changes does not guarantee absolute safety. Third, pursuing a precise threshold at which organ damage occurs was deemed unnecessary in the context of this study. In actual surgical practice, forces approaching such “dangerous thresholds” are rarely applied, because there is usually a significant margin of safety. Furthermore, the thresholds determined through pathological evaluation may not be suitable for novice surgeons, who are less adept at regulating force during procedures.

In a previous study, the kidney ruptured when a closed blade tip was applied with a force of 4.5 N to the organ. Although this finding demonstrates that a force of 4.5 N is dangerous, it does not imply that forces below 4.5 N are universally safe for other porcine kidneys [4]. In the present study, a mean force of 3.6 N was observed in a session where a hematoma occurred, suggesting that forces in this range may also be dangerous.

Given these considerations, we opted to measure the “safety threshold” as defined by the subjective judgment of expert surgeons rather than through pathological evaluation. The extensive experience of these surgeons effectively substitutes for a large number of trials, providing a practical and reliable reference for novice surgeons who are learning to regulate force during surgical procedures.

Aside from the absence of pathological evaluation, this study has several limitations beyond the absence of pathological evaluation. First, this study was conducted using data from only two expert surgeons. Although their extensive experience provides valuable insights, collecting data from a larger cohort of expert surgeons would enhance the robustness and generalizability of the findings. Second, whether these results can

be directly extrapolated to human patients remains uncertain. Although pigs are anatomically similar to humans and are widely used in surgical training and experiments, physiological and structural differences may limit the applicability of the findings. Nonetheless, the results serve as a useful reference for novice surgeons who are practicing on porcine models. Finally, the experiments were conducted under consistent conditions. The findings may not apply to scenarios where the forceps are used at different angles or orientations. For example, applying force at a sharp angle or in a pricking direction with the forceps may lower the safety threshold. However, such techniques should be avoided whenever possible. In this study, the force application closely reflected the manner typically used to manipulate the kidney during laparoscopic procedures. In addition, this study focused on a scenario where the renal surface of the kidney was fully exposed. However, in actual surgery, the kidney is surrounded by perinephric fat, through which manipulation often occurs. This difference in conditions could influence the force thresholds and warrants further investigation. Despite these limitations, the study provides a foundational understanding of the force application thresholds, offering practical guidance for surgical training and safety.

This study specifically focused on the magnitude of the force applied by expert surgeons during direct renal compression. Of note, a greater force may be required in actual surgery depending on specific conditions, including the presence of adhesions. Future research should investigate how the application strategies used by surgeons vary under different conditions, including changes in the direction and angle of pressure or when operating on different organs. These expanded insights could provide a broader understanding of safe force application and inform surgical training programs. The findings of this study have practical applications, particularly for novice surgeons, and could serve as a foundation for the developing advanced surgical simulators designed to replicate realistic force thresholds.

In conclusion, expert surgeons typically aim to apply a force of approximately 0.8 N during minimally invasive kidney surgery, with a statistical safety threshold of 1.8 N to avoid potential organ damage. These results offer valuable insights into the forces applied to organs during minimally invasive surgery, providing a reference point for future studies and surgical training protocols.

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Disclosure of Interests. authors have no competing interests.

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