Luo et al. BMC Medical Education (2025) 25:677
https://doi.org/10.1186/s12909-025-07242-3

BMC Medical Education

RESEARCH

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Enhancing laparoscopic surgery training: a comparative study of traditional models and automated error detection system

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Abstract

Background Although beneficial for patients through its minimally invasive nature, laparoscopic surgery creates unique training challenges due to limited instrument maneuverability, absence of stereovision, and inadequate real-time feedback. Traditional training models rely on subjective instructor evaluations, which are time-consuming and lack objective error detection. This study evaluates the efficacy of an Automated Error Detection System (AEDS), designed to provide real-time feedback on mistouch error counts, in improving laparoscopic skill acquisition compared to conventional methods.

Methods Forty novice participants were recruited and randomized into Group A (AEDS-enhanced training) and Group B (traditional training). Group A underwent a crossover design: 10 min of baseline training without AEDS followed by 10 min with AEDS. Group B completed 20 min of traditional training. The training program encompassed standardized laparoscopic tasks designed to simulate real surgical procedures. Performance metrics, including task completion time and the number of errors made, were recorded for each participant through AEDS. Confidence levels were assessed through self-reported questionnaires. Furthermore, statistical analysis was performed to evaluate the effectiveness of AEDS. A paired t-test was utilized to assess error reductions within the AEDS group, and Bland-Altman analysis was used to analyze the self-estimate error bias. Also, a Wilcoxon signed-rank test evaluated improvements in confidence levels attributable to the system, while a Mann-Whitney U test was conducted to compare performance metrics between the AEDS and traditional training groups.

Results Group A demonstrated a 24% reduction in errors post-AEDS (mean: 78.1 to 59.4, $p < 0.001$), outperforming Group B (mean: 67.4, $p < 0.001$). Participants significantly underestimated errors without AEDS (mean bias: +9.9 errors). Confidence levels in Group A increased from 2.4 to 3.6, significantly surpassing Group B's improvement (median: 3) ($p < 0.001$). Real-time feedback bridged perceptual gaps, enhancing both technical precision and self-assessment accuracy.

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Conclusion The integration of AEDS into laparoscopic training significantly reduces operational errors, accelerates skill acquisition, and boosts trainee confidence by providing objective feedback. These findings advocate for adopting AEDS in surgical education to standardize training outcomes, mitigate overconfidence, and improve patient safety. Future studies should explore AEDS scalability across advanced procedural modules and diverse trainee cohorts.

Clinical trial number Not applicable.

Keywords Laparoscopic surgery, Medical training, Simulations, Surgery error reduction

Introduction

Currently, laparoscopic surgery is widely applied and a primary surgical innovation direction [1, 2], which offers advantages such as shorter hospital stays, fewer wound-related complications, improved aesthetics, and reduced incision pain [3–5].

However, all laparoscopic instruments need to be inserted into the abdominal cavity through an incision channel, which limits their freedom and flexibility [6, 7]. Additionally, laparoscopic surgery lacks stereovision and refined haptic feedback compared to traditional open surgery [8]. Therefore, laparoscopic skills training has become a required course for many surgeons [9]. However, the trainee's process feedback on the operation training only comes from the two-dimensional image on the screen while the operator cannot detect any possible errors because of no information feedback mechanism [10]. Moreover, the laparoscopic surgery training instructors typically need to repeatedly watch and evaluate a large number of training and operation videos of students, costing a lot of time and leading to a waste of human resources.

Based on this, numerous studies have focused on optimizing laparoscopic training outcomes by improving training models. Some research has specifically aimed at enhancing simulation-based models and discussed how virtual reality simulation training can aid doctors and medical students in developing their laparoscopic surgery skills [11–13]. For example, Abinaya and Manivannan developed a haptic extension of the fundamental laparoscopic surgery program for VR, which improves laparoscopic skill training by incorporating enhanced force feedback [14]. In contrast, Shen et al. focused on enhancing conventional models by providing tactile feedback, creating an innovative 3D-printed model that significantly enhanced skill acquisition and clinical transferability [15]. Additionally, Both Zhou et al. and Salvador et al. concluded that visual feedback is particularly effective for accelerating the learning process and enhancing proficiency in tissue handling for novices via prospective randomized controlled trials [16, 17]. This research had considered these prior efforts to incorporate feedback into these students and decided to optimize the physical apparatus by adding an Automated Error Detection System (AEDS). This AEDS comprises two primary components. One is the automatic embedded contact device, which can collect the operator mistakes in training and record the corresponding number of errors. The other is an error feedback system, which will add an interface on the screen displaying the surgical procedure, showing the cumulative number of current operational errors as well as the total duration of the operation. The purpose is to facilitate the operator to change or adjust their mode of operation at any time after receiving feedback information on the screen, which we hypothesized to achieve a more rapid and efficient improvement of the trainer's laparoscopic surgery level effect [18, 19]. Moreover, after the training ends, the operator can view the time of each operational error and a line chart analysis from the tables exported by the AEDS (Fig. 1).

In order to verify the training effect of the AEDS for the students and the accuracy of the system itself for the collection of operational data, we also conducted comparative experiments on the students to test the impact of this system on the training results. To examine the system's shortcomings or improvement direction, as well as improve the system's usability, participants were asked to fill out a survey of their subjective feelings about using this system.

Methods

Participant details and demographics

For this experiment, a convenient sample of 40 novice undergraduate students (age range: 18–22 years; 20 female and 20 male) was recruited for this study. All participants were enrolled in our institution and had no prior formal training in laparoscopic procedures or exposure to simulation-based or clinical surgical practice. Before the experiments, all participants were randomly allocated to either Group A (AEDS training) or Group B (traditional training), with 20 individuals in each group. This study is conducted in accordance with guidelines of the Declaration of Helsinki. All the participants were aware of their rights and the study design and provided informed consent before joining the study. This study is approved by the Institutional Review Board of Sichuan University (IRB2019-1071).

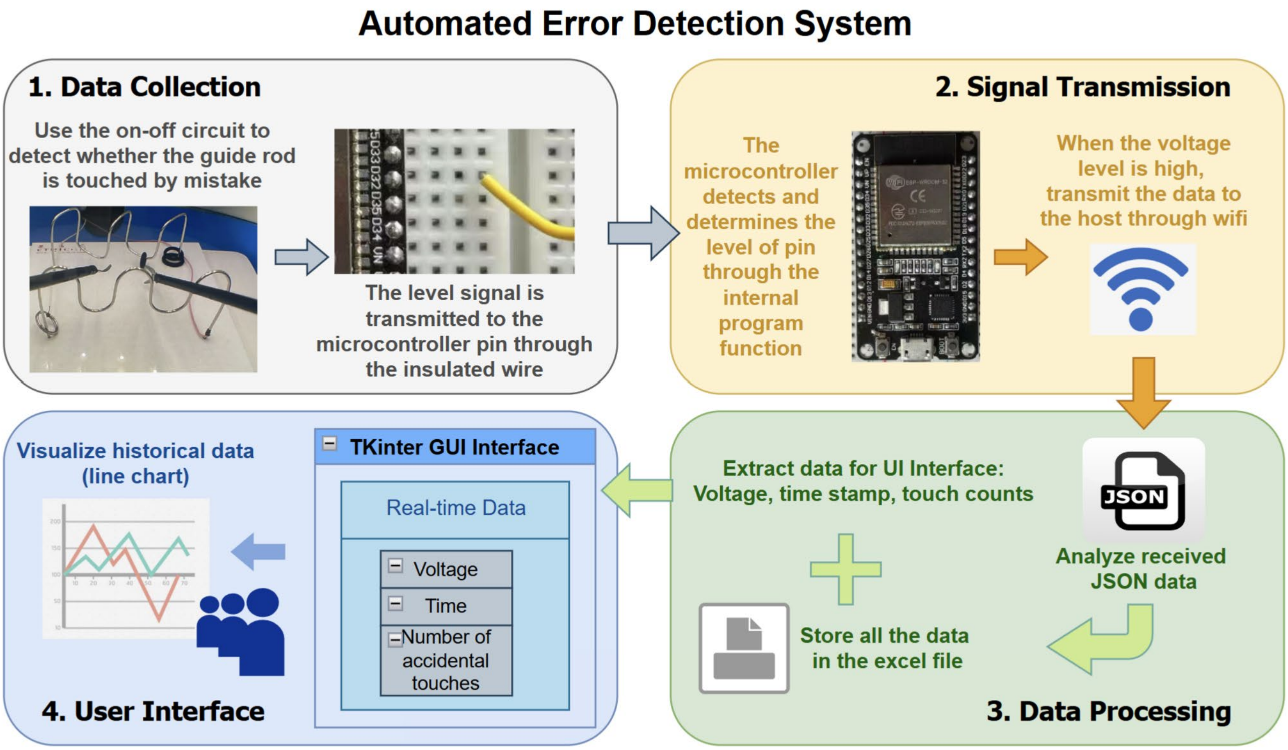

Fig. 1 Schematic diagram of AEDS design and operation

Fig. 2 Laparoscopic simulation training setup for participants

Apparatus

The experimental equipment incorporates an all-encompassing assemblage of laparoscopic simulation training apparatuses, traditional laparoscopic training models, and an AEDS. The laparoscopic simulation training equipment encompasses the laparoscopic simulation training box, the specialized forceps for laparoscopic simulation training, and the display screen (Fig. 2). The moving mock-up is constituted of small rings situated on irregular rails (Fig. 3). This system was specifically designed to train object delivery in laparoscopic surgery, similar to peg transfer tasks, and has been used for years. Ideally, the students are asked to move the rings from one side of the rail to the other without touching the ring to the rail, using only the traditional model for one session. In another session of the experiment, AEDS is activated as a comparative model. As shown in Fig. 3, the external differences between models with or without AEDS are minimal to reduce the potential confounding effects introduced by variations in appearance. During the experiment when AEDS is activated, the moving object model was linked to the AEDS via wires. Once the AEDS was actuated, the subject was enabled to discern distinctly and in real-time whether erroneous operations of the rail's contact with the small rings were engendered during the participants' operation.

Experiment design

In this experiment, participants were guided to complete laparoscopic simulation training tests and evaluations within a controlled environment, with a preparatory period before each assessment (Fig. 2). The task required

(a) (b)

Fig. 3 Training model Prototype: (**a**). Traditional training model and (**b**). Training model with AEDS

participants to use laparoscopic forceps to hold a ring and transfer it from one end to the other without touching an irregular rail. Each participant was tested individually in an isolated setting to ensure data independence and eliminate potential peer influence. This setup prevented external factors, such as observational learning or competition, from affecting performance, allowing for a more accurate assessment of each participant's skill development and response to the intervention.

20 participants in Group A practiced employing the traditional moving object model and deactivated the AEDS during the 10-minute practice preparation before the first assessment and activated the AEDS during the 10-minute practice preparation before the second assessment. Both assessments in Group A were conducted using the AEDS for error detectionBefore using the AEDS in Group A, we provided a demonstration for all participants to ensure they understood its purpose and functionality.

The two-phase design for Group A (10 min without AEDS followed by 10 min with AEDS) served two key purposes: (1) Baseline Establishment: The initial 10-minute session without AEDS provided a baseline measurement of participants' intrinsic skill levels and error rates, controlling for individual variability in prior experience. (2) Intervention Isolation: By immediately transitioning to a second 10-minute session with AEDS-activated feedback, we ensured that observed improvements could be attributed to real-time error correction rather than long time practice or task familiarity from traditional training system. This within-subject crossover design allowed direct comparison of performance under both conditions.

Another 20 Participants in Group B practiced with the traditional moving object model and deactivated the AEDS during the 20-minute practice preparation before the assessment. However, during the assessment, participants in Group B utilized the AEDS for error detection. After the assessment, they completed an experience questionnaire to gather their sentiments regarding the training process and utilization of the system.

The total training duration (20 min for Group A vs. 20 min for Group B) was standardized to ensure parity in task exposure. Group B's single 20-minute session without AEDS served as a control for natural skill progression unrelated to the system.

Based on this setting, this experiment is intended to examine whether the optimized AEDS can effectively assist students to locate errors in operation, so as to enhance students' learning efficiency and improve their learning outcomes. By analyzing the performance of the subjects, the effect of the system on the simulation training of laparoscopic surgery was evaluated.

Data collection

Experimental data

During the assessments, the following objective metrics were recorded through: (1) Task completion time: Total duration (seconds) required to complete each task. (2) Self-estimated errors: Participants were asked to report their perceived number of errors immediately after each session. (3) AEDS-recorded errors: The automated system objectively quantified errors in real time by detecting mistouches between instruments and the simulated anatomy.

For Group A, data were collected twice: during the baseline phase (pre-AEDS) and after the intervention (post-AEDS), while Group B underwent a single assessment after traditional training. Identical task protocols, including rail complexity and ring size, were maintained across phases to ensure consistency. Data collection intervals were synchronized with the experimental workflow, as illustrated in the Fig. 4.

Questionnaire survey

Subjective feedback was systematically collected at defined intervals (see Fig. 4 for experimental workflow). For Group A, participants completed validated questionnaires immediately after the second assessment. The questionnaire assessed their (a) confidence levels: Rated on a 5-point Likert scale (1 = Not confident to 5 = Very confident), (b) Satisfaction: Perceived usefulness of AEDS feedback (5-point scale), (c) Usability: Ease of system interaction (e.g., clarity of error notifications), and (d) Willingness to recommend: Likelihood of endorsing AEDS to peers. As for Group B, participants completed the same questionnaire but do not answer question related to AEDS usage. This questionnaire was specifically developed for the present study following established questionnaire design principles to ensure its relevance and validity in assessing the targeted aspects of laparoscopic surgery training. An English version of the questionnaire is provided as supplementary material (see Supplementary File 1).

Data analysis

In this study, we employed a comprehensive statistical approach to assess the effectiveness of the AEDS compared to the original training model in enhancing laparoscopic task performance. The primary analyses included a paired t-test to evaluate the reduction in the number of actual errors within Group A before and after AEDS implementation, reflecting improvements due to the system. To mitigate the confounding influence of practice effects inherent to repeated training, the study adopted a controlled crossover design. For Group A (AEDS intervention), baseline performance (pre-AEDS) served as an internal control for post-AEDS measurements, isolating the incremental impact of real-time feedback by directly comparing performance improvements within the same cohort. In contrast, Group B (traditional training without AEDS) underwent the same total training duration as Group A but without the crossover repetition, ensuring comparable exposure to task mechanics while eliminating repeated-measurement biases. To further validate that improvements in Group A were attributable to AEDS rather than practice alone, Group A's post-AEDS performance was systematically compared against Group B's single-session performance, ensuring that observed differences reflected the AEDS intervention rather than repetition-driven learning.

Additionally, self-reported confidence levels and error estimates were analyzed alongside objective

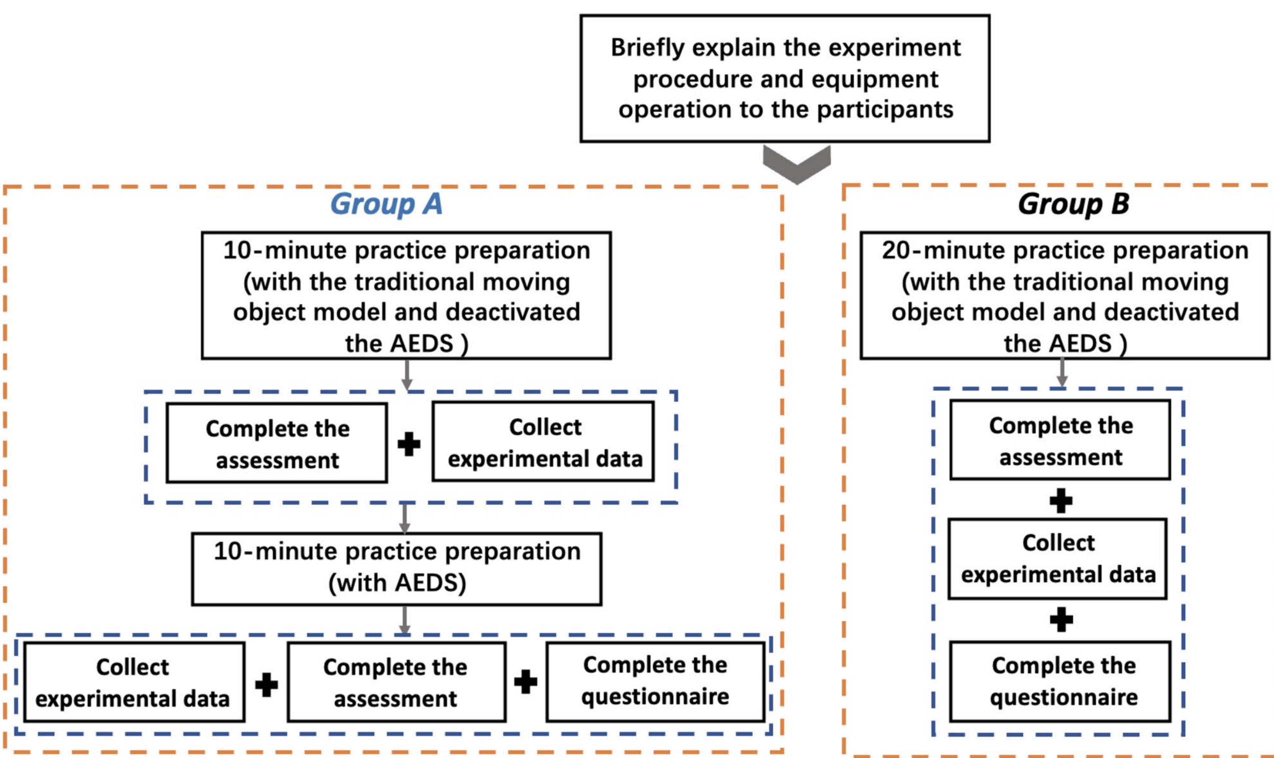

Fig. 4 Experimental Workflow

AEDS-recorded metrics to evaluate alignment between subjective perceptions and objective outcomes, with discrepancies interpreted as limitations of self-reported data. This multi-faceted approach strengthened causal inference while addressing potential confounders. For the self-reported error counting estimation, Bland-Altman analysis is used, which indicates systematic underestimation by participants. And for the non-normally distributed confidence data, a Wilcoxon signed-rank test was used to assess changes in participants' confidence levels, highlighting the psychological impact of AEDS.

Lastly, a Mann-Whitney U test was utilized for between-group comparisons of error counts to investigate the differential effects of AEDS usage across different training conditions. All results were reported as means or medians with their respective variability measures, and a p-value of less than 0.05 was considered statistically significant, supporting the strong efficacy of the AEDS in improving both the precision and confidence of participants performing laparoscopic tasks.

Results

Reduction of errors with AEDS

In exploring the efficacy of the AEDS in laparoscopic simulation training, our primary objective was to determine whether our system could significantly reduce operational errors before and after AEDS within Group A. To this end, we applied a paired t-test, a statistical approach suitable for comparing two related samples or repeated measurements on a single sample. This choice was supported by the verification of data normality through the Shapiro-Wilk test first, which indicated that the distribution of error counts both before and after AEDS intervention adhered to normalcy.

Based on the Shapiro-Wilk test results, both the p-value before and after using AEDS within Group A (before: $p = 0.316$, after: $p = 0.418$) indicating that we fail to reject the null hypothesis that the data is normally distributed. Based on this, we further conduct the paired t-test and the statistical analysis yielded a t-value of 8.57 and an extremely small p-value ($p < 0.001$), firmly establishing the reduction in errors. Specifically, the mean number of errors decreased significantly when participants engaged with the AEDS during their second session of laparoscopic tasks. This outcome is illustrated by the decline in errors across participants from an average of 78.1 errors initially to 59.4 errors post-intervention, highlighting a notable enhancement in precision. More detailed information is presented in Fig. 5 below.

Discrepancy between self-reported and AEDS-recorded error counts

The comparison between objective AEDS-recorded errors and students' subjective self-reported estimates revealed a clinically concerning pattern of systematic underestimation and unwarranted confidence. As shown in Fig. 6, the median self-reported error count was substantially lower than the AEDS median, with the AEDS distribution exhibiting a wider range (13–92 vs. 10–80) and a pronounced right skew (e.g., outliers > 80 errors). This indicates that many students not only significantly underestimated their errors ($p < 0.05$), but also failed to recognize critical high-error episodes that objectively occurred.

In the meantime, Fig. 7. further quantified this discrepancy, demonstrating that 70% of participants (14/20) fell below the zero-difference line, reflecting pervasive underestimation. The mean bias of + 9.9 errors (95% limits: − 28.0 to + 47.9) highlights that more than half of students showed confidence in their performance as safer than reality—a trend exacerbated in high-error scenarios (e.g., AEDS = 92 vs. self-reported = 80; difference = + 12). Notably, even when students committed severe errors (AEDS > 60), their self-reports rarely exceeded 50 errors, suggesting a cognitive disconnect between perceived and actual technical precision.

Improvement of confidence with AEDS

In addition to performance metrics, changes in participants' confidence levels were also documented, providing further insight into the training impact. Quantitatively speaking, the average confidence level of participants before the training was 2.4 (SD = 1.05), which increased to 3.6 (SD = 1.14) after the training sessions. This significant improvement ($p < 0.001$) in average confidence underscores the positive psychological impact and enhanced skill perception provided by the AEDS.

To better analyze the impact of the AEDS on participants' confidence levels during laparoscopic simulation training, we utilized the Wilcoxon signed-rank test, a non-parametric test well-suited for ordinal data and used specifically because the Shapiro-Wilk test indicated a non-normal distribution of the confidence scores (before: $p = 0.0024$, after: $p = 0.0071$).

The results of the Wilcoxon test showed a statistically significant increase in confidence levels after the use of AEDS ($p < 0.001$). This analysis was based on the transformation of categorical confidence levels into ordinal values, where "Not confident" was coded as 1 and "Very confident" as 5. The median confidence score improved notably from a median of 3 (Normal) before the intervention to 4 (Relatively confident) afterward, with the proportions of participants identifying as "Very confident" increasing significantly post-intervention. This shift is quantified by the movement of scores, where the proportion of higher confidence ratings ("Relatively confident" and "Very confident") increased from 5% before AEDS usage to 50% afterward.

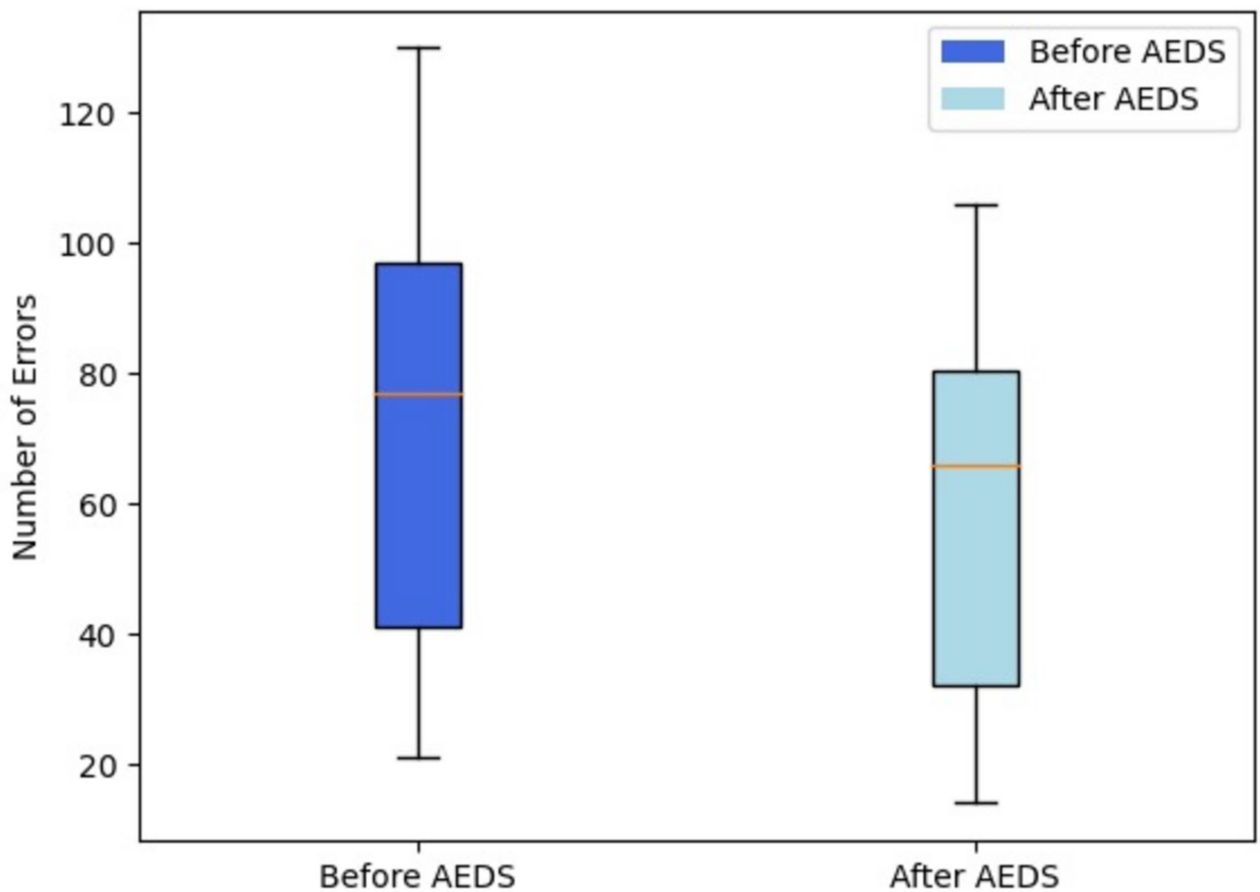

Fig. 5 Boxplot for number of errors before and after using AEDS within Group A

Critically, while both groups exhibited confidence gains, the AEDS group (Group A) demonstrated substantially greater improvements compared to the traditional training group (Group B). Post-training confidence levels in Group A (median = 4) were significantly higher than those in Group B (median = 3). This divergence suggests that the error feedback mechanisms unique to AEDS contributed to a more robust confidence-building effect beyond mere task repetition. For instance, 50% of Group A participants rated themselves as "Very confident" post-training, compared to only 15% in Group B—a 3.3-fold difference attributable to AEDS-enhanced self-assessment accuracy.

Between-group comparison on error reduction

To rigorously assess the efficacy of the AEDS, we further performed a two-phase between-group comparative analysis. Group A underwent a crossover design, first completing laparoscopic tasks using the traditional training model (baseline phase, without AEDS) followed by a second session with the AEDS-activated system (intervention phase). In contrast, Group B served as a control cohort, completing all training and assessments exclusively with the traditional model. By comparing Group A's post-intervention performance (with AEDS) against Group B's single-assessment results (without AEDS), this design isolated the impact of real-time AEDS feedback while controlling for confounding variables such as task familiarity.

Given the error data in Group B is not normally distributed, as indicated by the Shapiro-Wilk test ($p = 0.0019$), we employed the Mann-Whitney U test, a non-parametric test suited for comparing medians of two independent samples in this case. Since Group B's data is not normally distributed, the Mann-Whitney U test is more appropriate as it does not assume a normal distribution. This test will allow us to compare the medians of the two independent samples to see if there's a statistically significant difference in the number of errors between the two groups.

The Mann-Whitney U test revealed a statistically significant difference in the number of errors between the groups, with a U-statistic of 92.6 and a p-value of 0.0001. This significant result highlights that the median number of errors was substantially lower in Group A after the intervention compared to Group B as shown in Fig. 8. below, who did not use AEDS. Specifically, the average number of errors reduced in Group A from a pre-intervention average of 78.1 to a post-intervention average of

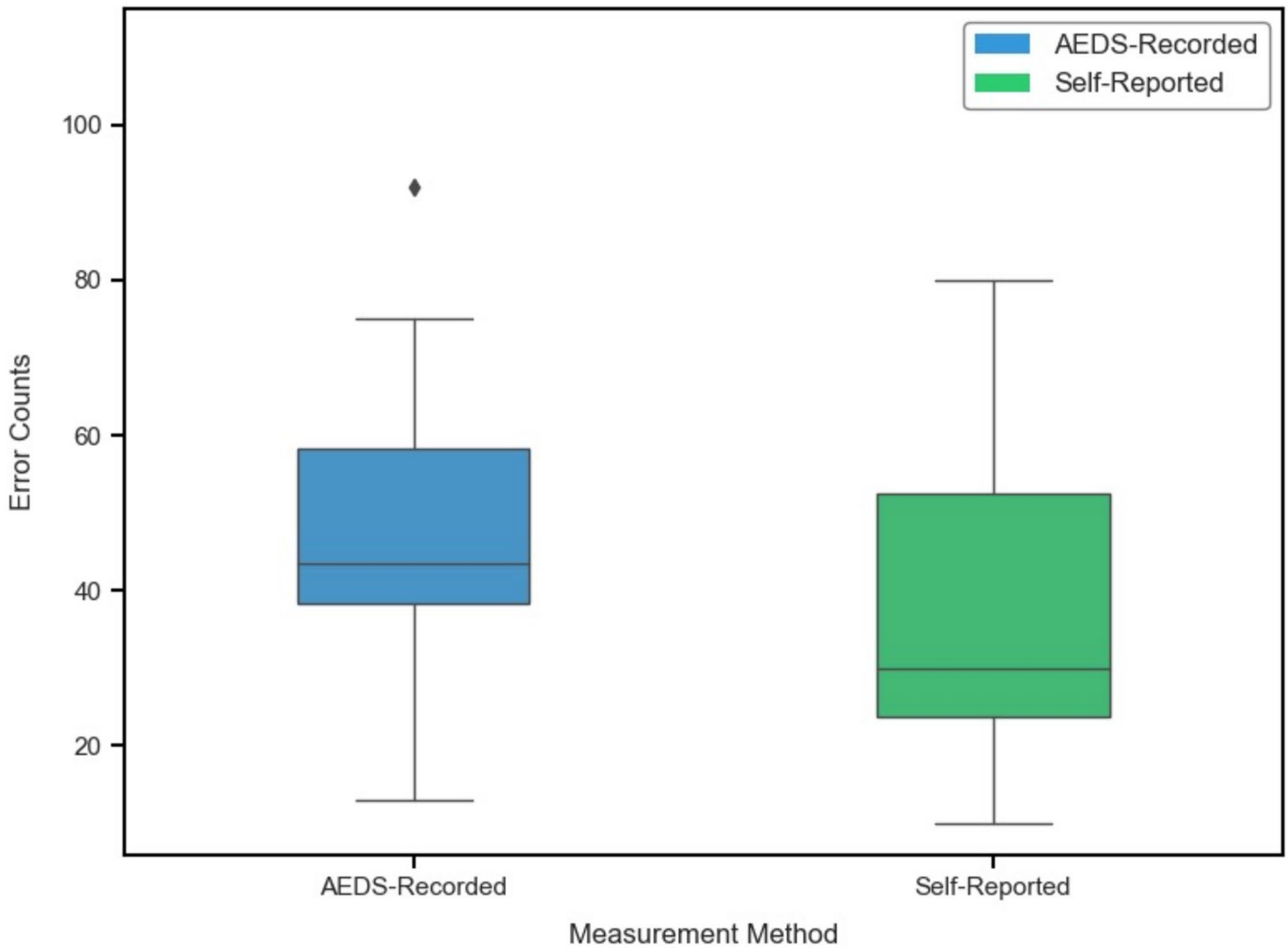

Fig. 6 Boxplot for distribution comparison in error counts

59.4, whereas Group B maintained a higher error average than participants in Group A with AEDS of 67.4 throughout the training period.

Discussion

Discussion for principle results

The substantial reduction in errors observed in this study can largely be attributed to the real-time feedback provided by AEDS. The system's mechanisms likely enhanced participants' control and spatial awareness—critical skills in laparoscopic procedures where depth perception and fine motor precision are paramount. By effectively reducing errors, AEDS demonstrates its potential as a training aid while suggesting broader applicability for improving the safety and efficacy of surgical procedures.

However, the marked discrepancy between students' self-assessed errors and objectively measured errors raises concerns. This overconfidence is alarming in the context of laparoscopic surgery, where unacknowledged mistouches could translate to risky instrument movements in real procedures, potentially leading to complications such as bowel perforation or vascular injury. For instance, the mean bias of 9.9 errors indicates that students underestimated nearly 10 errors, equivalent to 10 unrecognized risky actions in a clinical setting. These findings underscore AEDS's critical role in bridging perceptual gaps, as subjective self-assessment alone inadequately prepares students to mitigate intraoperative risks.

Notably, participants exhibited significantly improved confidence after AEDS training, likely stemming from enhanced performance accuracy and perceived control during simulations. While higher confidence among students may optimize training effectiveness, it is important to contextualize these results: the study involved undergraduates, not clinical students. Future research must evaluate whether similar confidence gains persist in surgical residents, where decisiveness and precision directly influence clinical decision-making and operational outcomes.

Moreover, the between-group disparity not only underscores the direct impact of AEDS in reducing errors but also illustrates the potential broader applicability of such feedback systems in enhancing training protocols across various settings. By significantly minimizing errors in

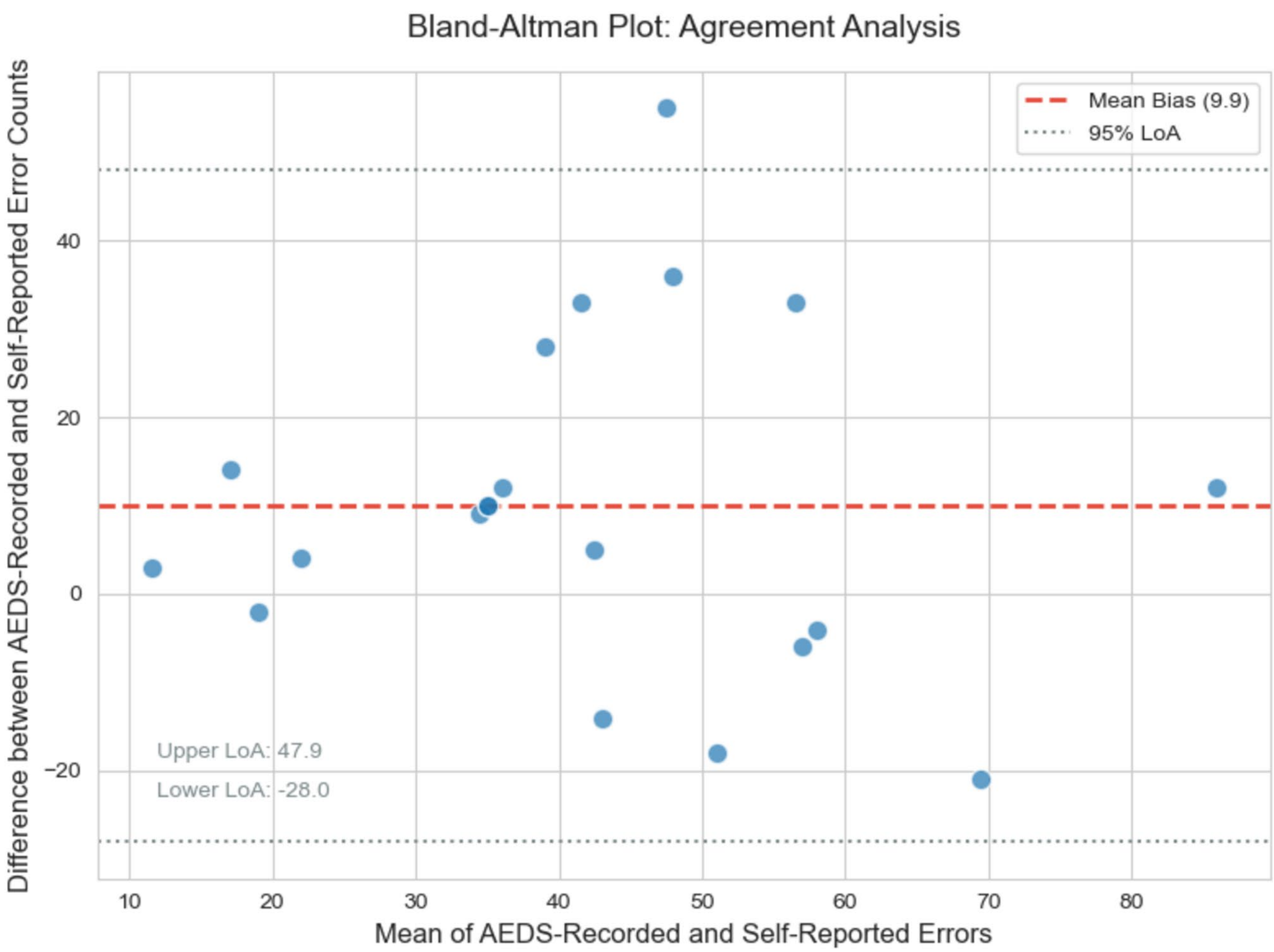

Fig. 7 Agreement Analysis of Bland-Altman Plot

Group A, AEDS has demonstrated its value as an essential tool for improving precision and safety in laparoscopic training.

In short, the results presented above (**Sect. 3**) demonstrate the significant benefits of the AEDS in enhancing laparoscopic simulation training. Our results clearly show that AEDS effectively reduces the number of operational errors ($p < 0.001$) and significantly boosts participants' confidence levels ($p < 0.001$), highlighting its dual impact on both technical proficiency and psychological assurance. The between-group comparison further reinforces the value of AEDS, with Group A exhibiting significantly lower error rates than Group B, which did not use the feedback system ($p < 0.001$). All these findings underscore the potential of integrating tactile feedback mechanisms like AEDS into surgical training programs, suggesting they could play a crucial role in improving training outcomes and ultimately enhancing surgical safety and efficacy. This research advocates for broader implementation and further investigation into tactile feedback systems, promising significant strides in medical education and patient care.

Implications, limitations and future work

The integration of feedback mechanisms into laparoscopic training systems has gained significant attention due to the inherent limitations of conventional training methods. Traditional laparoscopic training relies primarily on two-dimensional screen displays, which often obscure errors and oversights during simulation exercises [20, 21]. This deficiency is particularly evident in the training model we have selected and developed, where the restricted field of view and difficulty in accurately rendering curved trajectories lead to suboptimal feedback for students. Moreover, conventional box trainers, including the one we have been dedicated to improving, lack objective assessment of skill acquisition [22]. These challenges highlight the need for enhanced feedback systems that can provide real-time, accurate, and objective error detection to improve training outcomes.

To address these limitations, our team developed an automatic sensing contact device that captures operational errors and their occurrence times with real-time precision. This device leverages the model's conductivity and the binary switching characteristics of the circuit to

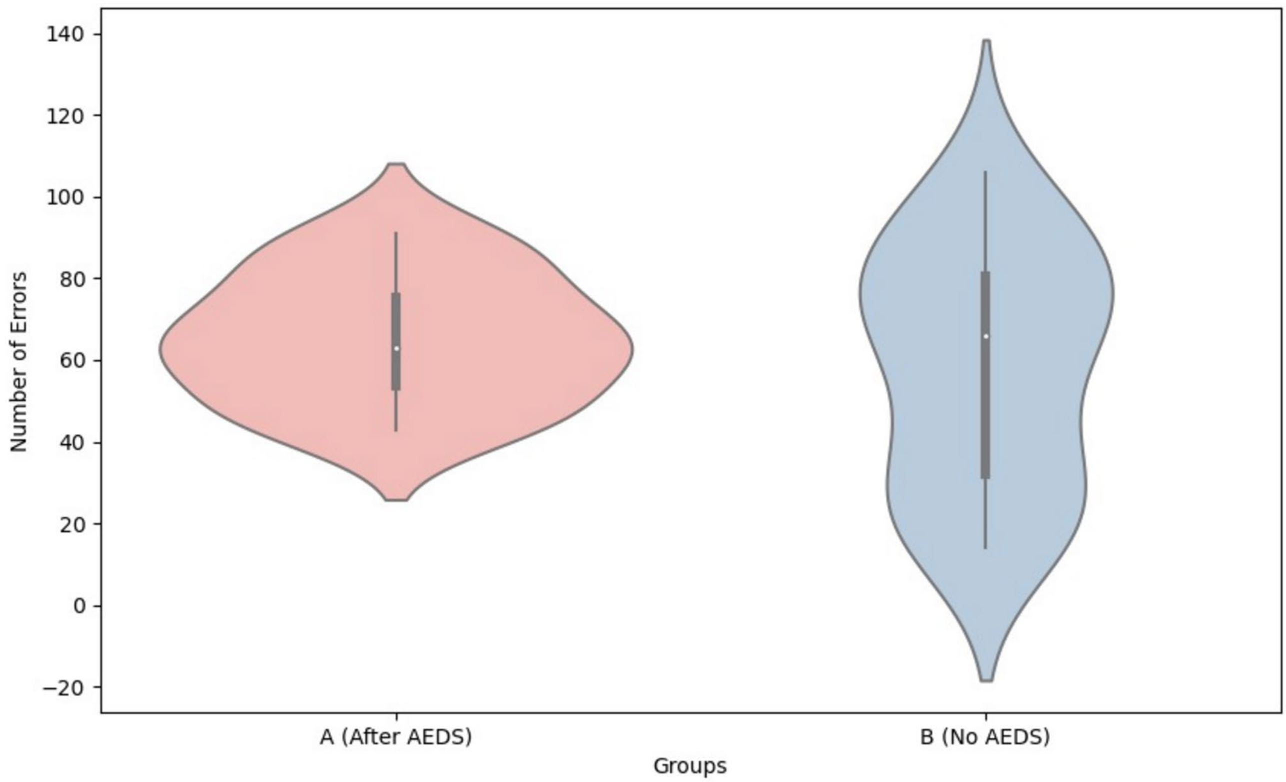

Fig. 8 Violin Plot for Number of Errors within Group A and Group B

detect errors more accurately than traditional methods, which rely on visual inspection or post-training video review before [20]. Our study also highlights the importance of objective assessment in laparoscopic training. The model we developed provides students with metrics such as success rate and the number of mistouches, offering a more objective evaluation than traditional methods [22]. Research has shown that deliberate practice with both high- and low-frequency intermittent feedback significantly enhances early procedural skill acquisition [23]. By providing consistent reminders of mistakes, our system reinforces the skills necessary for laparoscopic training. As evidence has shown, the skills required for laparoscopic surgery differ from those of open surgery and are more akin to endoscopy [24, 25]. Through laparoscopic training, surgeons can acquire these skills in a controlled environment, free from the pressures associated with operating on real patients [26]. Enhancing training effectiveness is crucial for developing the specialized skills required for laparoscopic surgery, and our immediate feedback system better prepares students for future surgical operations [15].

One limitation of this study is that the subjects were undergraduate students with no prior laparoscopic experience, rather than novice surgical students or residents. As a result, the findings primarily reflect the early stages of skill acquisition rather than the training outcomes of individuals already familiar with laparoscopic techniques. Additionally, the limited number of training sessions constrained the study to assess initial performance differences between the traditional and optimized models, without capturing the effects of prolonged practice. Given that skill acquisition follows a learning curve—where performance initially improves rapidly before stabilizing—the restricted training duration may have prevented subjects from reaching a plateau, potentially influencing the results. Future studies should consider extending the training period or including more experienced participants to provide a more comprehensive assessment of long-term training effectiveness. Moreover, stratified analysis or mathematical modeling could help control for learning curve effects and reduce confounding biases. A thorough discussion of these potential confounders is necessary, along with appropriate strategies to mitigate their impact.

Another limitation pertains to the scope of error analysis in this study. Errors were defined based on contact between the AEDS rings and the rail, an analogy for unintended contact with non-target tissues during laparoscopic surgery. While this metric is relevant, it does not encompass other critical error types that can impact surgical outcomes, such as excessive force application, misidentification of anatomical structures, or improper instrument manipulation. These errors are particularly significant in clinical practice, as they are associated with iatrogenic complications and patient safety risks. A more holistic evaluation of AEDS training effectiveness should include these additional error types to better understand its potential advantages and limitations. Future research should employ advanced tracking technologies or force sensors to capture a broader range of errors, providing a more accurate reflection of real-world surgical challenges.

Furthermore, it is important to recognize that the traditional laparoscopic training model used in this study primarily focused on object manipulation, specifically the "picking up" skill. While this is a fundamental aspect of laparoscopic procedures, it does not fully represent the complexity of actual surgical tasks. Laparoscopic training is typically divided into three key skill modules: picking up, suturing, and cutting. The findings of this study may not directly translate to these more advanced tasks. Future research should investigate how AEDS can be adapted and optimized for these additional training modules, potentially enhancing its applicability to broader surgical education.

Finally, this study relied on self-reported measures for confidence and error estimation, which introduces potential biases. Self-assessment can be influenced by subjective perception, over- or under-estimation of performance, and variability in individual confidence levels. To improve the reliability of training evaluations, future studies should incorporate objective performance metrics, such as motion analysis, force measurements, or direct expert assessment, to complement self-reported data and provide a more comprehensive understanding of training effectiveness.

Conclusions

This study conclusively demonstrates that the integration of an AEDS into laparoscopic training significantly enhances both the technical performance and confidence of medical students compared to traditional training methods. The marked reductions in task completion time and error rates and substantial increase in trainee confidence, show the effectiveness of AEDS as a superior training tool. Moreover, AEDS effectively eliminates the cognitive discrepancies caused by the lack of feedback in traditional training, enabling students to accurately recognize and correct their mistakes in real time. These findings are significant for medical education, suggesting that adopting AEDS can help students master the laparoscopic skills more efficiently and sophistically. The relevance of this study lies in its potential to transform surgical training paradigms, advocating for the widespread implementation of automated technologies to foster higher standards of surgical competence and reduce the incidence of procedural errors in clinical practice.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12909-025-07242-3.

Supplementary Material 1

Acknowledgements
Not applicable.

Author contributions
Conceptualization, RY, YH, and XW; methodology, YL, YF and RY; Data curation, YL and JW; formal analysis, YL JW, ZY, JH, LF and SW; investigation, YL, JW and NL; Funding acquisition, KL and DP; writing—original draft preparation, YL, JW, ZY, JH and LF; Visualization, YL and JW; writing—review and editing, all authors; supervision, RY, DP and KL; project administration, RY, DP and KL; All authors reviewed the manuscript and agreed to the published version of the manuscript.

Funding
Part of this study is supported by the Sichuan University Postgraduate Education and Teaching Reform Project (grant ID GSSCU2024028); Part of this study is supported by the Science and Technology Department of Sichuan Province, China (grant ID 24KJPX0119); Part of this study is supported by the 1·3·5 project for disciplines of excellence (grant ID ZYYC21004), West China Hospital, Sichuan University.

Data availability
The datasets used and analysed during the current study may be available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study is approved by the Institutional Review Board (IRB2019-1071) of West China Hospital of Sichuan University. All participants are consent to participate in this study. This study adhered to the Declaration of Helsinki.

Consent for publication
All the data collected are anonymized and deidentified.

Competing interests
The authors declare no competing interests.

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Received: 16 January 2025 / Accepted: 25 April 2025
Published online: 08 May 2025

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