AI-Assisted Learning Systems for Improving Surgical Education Outcomes: A Randomized Controlled Trial

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Abstract: Surgical education faces challenges such as limited clinical experience, inconsistent teaching quality, and risks to patient safety during training. Artificial intelligence-based educational technologies (AIET) promise to improve the effectiveness and personalization of training, but there is virtually no data on the use of such technologies in surgical education for students in Central Asia. The aim of this study was to evaluate the impact of the first implementation of an AI-based learning system in an educational institution on the theoretical knowledge, practical skills, and satisfaction of surgical students at Samarkand State Medical University. This prospective randomized controlled trial (parallel-group design), conducted among the 120 fourth-year medical students. Participants were randomized into an AI-based training group (n = 60) or a control group receiving traditional training (n = 60). A 12-week intervention. Standardized multiple-choice tests, objective structured clinical examinations (OSCE), and student satisfaction questionnaire. Statistical tests were used to compare pre- and post-intervention outcomes within each group and between groups. The AI group demonstrated significantly higher results in theoretical and clinical skills compared to the control group ($p < 0.001$). After the intervention, OSCE results were significantly higher in clinical reasoning and decision-making stations. Students` satisfaction levels were significantly higher in the AI group. The use of AI-assisted learning improved educational outcomes in surgical training. These results show that AI is a viable and useful addition to existing surgical education.

1 INTRODUCTION

In the context of surgical education, AI has been applied to skill assessment, simulation-based training, and intelligent tutoring systems. The broader development of AI-enhanced healthcare systems, including predictive analytics and intelligent clinical technologies, further emphasizes the need to prepare medical students for digitally supported healthcare environments [1]. These tools can also support personalized learning paths, assess gaps in understanding, and deliver ongoing feedback outside of instructor availability [2]. Despite global interest in AI-assisted medical education, empirical data on its impact on undergraduate surgical training are scarce, especially in low- and middle-income countries. The use of artificial intelligence in medical education is only beginning to be implemented in Uzbekistan and the region. The study originated from the decision of the Samarkand State Medical University to introduce the first university-level AI-based training system in the field of surgery and to improve the quality of the training process [3]. This study was performed to assess the educational effect of the program. In particular, it aimed to determine whether AI-supported learning leads to better understanding of theory, higher quality of practical skills, and greater student satisfaction compared to conventional teaching alone. By providing empirical evidence from an actual educational context, this study contributes to the evolving understanding of the role of artificial intelligence in medical education.

2 LITERATURE REVIEW

Artificial intelligence (AI) has emerged as a powerful tool for revolutionizing medical education by enabling personalized learning, objective evaluation, and adaptive instruction. A recent systematic review of AI in medical education concluded that AI has been applied to multiple educational domains (e.g., formative assessment, skills training), with evidence of high accuracy for discriminating between novice and expert performance. Specifically, support vector machines have reached accuracy rates above 92 in surgical skills evaluation tasks, demonstrating the practical relevance of AI in competency-based training [3], [4].

Systematic and scoping reviews of AI-driven interventions in surgical education have been conducted, focusing on surgical skills assessment and training adaptation [5]. They demonstrate a range of AI tools to objectively assess operative skills (e. g., Objective Structured Assessment of Technical Skills). While these interventions show potential for assessing surgical skills and flagging trainees at risk, they are often limited in scope, lacking follow-up on implementation effects (e. g. cost) and learner experience [6].

Emerging work also examines the intersection of AI tools and pedagogical theory in surgical education. AI's ability to deliver personalized feedback, create realistic simulations, and facilitate case-based reasoning resonates with experiential and constructivist learning models, implying that AI may complement rather than supplant traditional teaching. These conceptual frameworks highlight the need for careful integration (e. g. aligning with learning theories, addressing privacy and bias issues) to prevent the superficial or even harmful adoption of AI technologies [7]. More recent domain-specific work has explored AI-assisted surgical skills training (e. g., laparoscopic suturing), where machine learning (including deep learning), motion capture, and video segmentation have shown promise in improving accuracy, speed, and retention of key skills.

Despite this limited practical application, the evidence base is growing and points to potential for AI-assisted systems to speed up skill learning, and particularly where expert supervision is scarce [8]. Despite the progress, reviews emphasize the gaps: many studies are not well-validated, involve few participants, or focus on theoretical models rather than clinical effectiveness. Furthermore, the generalizability of AI-based interventions to different educational settings and learner groups is unclear, and research in undergraduate surgical training specifically is under-represented compared to postgraduate or resident training [9], [10].

In conclusion, the integration of AI into medical and surgical education is increasing, with early evidence for benefits in assessment, adaptive feedback, and skill training. But more work is needed: well-controlled studies with validated outcomes are required to identify best practices, and to ensure that AI use remains aligned with equitable and pedagogically sound educational approaches [11], [12].

3 METHODOLOGY

This study was designed as a single-centre randomized controlled trial (RCT) in parallel groups with evaluation of results before and after the intervention. The work was carried out on the basis of the Department of Surgery of Samarkand State Medical University in 2024-2025. The aim of the study was to evaluate the effectiveness of educational interventions based on artificial intelligence to improve the level of theoretical knowledge and practical surgical skills among medical students.

The study sample consisted of 120 fourth-year medical students undergoing mandatory general surgery rotations. The students were randomized (in a ratio of 1:1) to an AI-enabled training group (n = 60) or to a control group (n = 60) using a computer sequence of random numbers created in the SPSS program (block size = 4). The distribution was conducted by an independent faculty administrator who was not involved in the learning or assessment process. The initial comparability of the groups was confirmed statistically to minimize the systematic allocation bias. The experimental group (n=60) was taught with the help of the AI-based system, in addition to the traditional teaching methods. The control group (n=60) was taught using only traditional teaching methods. The AI group had a mean age of 21.4 ± 0.8 years vs. 21.6 ± 0.9 years in the control group ($p = 0.58$). The AI group had 35 males (58.3%) and 25 females (41.7%) and the control group had 34 males (56.7%) and 26 females (43.3%) ($p = 0.63$). The mean baseline surgery grade point average was 3.42 ± 0.31 in the AI group vs. 3.36 ± 0.34 in the control group ($p = 0.41$).

AI-powered learning management system was designed to support undergraduate surgical training. It used machine learning to analyse student quiz scores, response times, and task completion rates. The system then personalized the difficulty of educational content and targeted feedback based on areas of weakness. In addition, the system included simulated clinical scenarios for which students had to make diagnostic and treatment decisions, fostering clinical judgment. The intervention was delivered over 12 weeks and embedded within the existing general surgery curriculum. Both groups had the same lectures, seminars and clinical rotations. In addition to traditional teaching, AI students completed weekly AI-graded quizzes and engaged in adaptive case-based learning modules with automated feedback after each session. Control group students worked on instructor-created assignments and engaged in traditional case discussions without using the AI platform. The main variables were knowledge and surgical skills. Knowledge was evaluated by a 50-item multiple-choice test prepared by the department staff. It was graded on a 0-100 point scale. Practical skills were assessed through an Objective Structured Clinical Examination (OSCE) with five stations on suturing, wound care, sterile field setup, clinical reasoning, and surgical interpretation. Each station was scored out of 20, with a maximum possible score of 100.

OSCE consisted of five standardized stations, which were independently evaluated by two trained surgical examiners at each station. The examiners were blinded to the distribution of students into groups. The standardized analytical evaluation category used ranged from 0 to 20 per station. Inter-expert reliability, assessed using the intraclass correlation coefficient (ICC, two-way model with random effects), demonstrated a high degree of agreement (ICC = 0.86).

Secondary outcomes included student learning satisfaction, that was assessed with a 10-item questionnaire using a 5-point Likert scale, with higher scores reflecting greater satisfaction. Statistical analyses were carried out with SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Data are presented as means and standard deviations for continuous variables. Paired t-tests were used for comparisons between pre- and post-intervention data within each group, and independent t-tests for comparisons between the AI and control groups. Chi-square tests were used for categorical data. $p < 0.05$ was considered statistically significant.

Machine learning was applied to identify learning patterns and performance issues among the student population. For instance, unsupervised machine learning was applied by employing clustering algorithms, including k-means clustering, which grouped the student population according to their learning performance patterns. On the other hand, supervised machine learning was applied by employing decision tree algorithms, which were employed to predict areas of difficulties in theoretical and practical aspects.

The adaptive feedback mechanism was employed by integrating machine learning predictions with predetermined pedagogic rules that were defined by surgical faculties. Therefore, the personalization was a combination of machine learning predictions and predetermined pedagogic rules that were defined by surgical faculties.

This study was conducted in accordance with the internal rules of pedagogical research and the principles of the Declaration of Helsinki. Since the intervention consisted of introducing an AI-based teaching tool into the standard curriculum and carried minimal risks, obtaining official approval from the ethics committee according to local regulations was not required. Participation was voluntary, written informed consent was obtained from the participants, and all data was pseudonymized and analysed anonymously.

The artificial intelligence system was implemented as a hybrid adaptive rule-based learning and machine learning platform designed to support surgical education for undergraduate students. Personalization has been achieved by integrating teacher-led and unsupervised learning approaches with predefined pedagogical rules developed by surgical instructors. In particular, supervised decision tree classifier was used to predict areas of difficulty for students, while unsupervised learning using k-means clustering (k=3) was used to identify different student performance profiles. The results of these models were subsequently integrated with expert instructional rules to ensure pedagogical consistency and clinical relevance.

The input features of the model included several indicators of student achievement and engagement: scores for tests at the level of individual assignments (accuracy), question response time, number of attempts per assignment, case-based completion rates, and scores for formative OSCE practice. Based on these inputs, students were assigned to one of three academic clusters (high academic performance, moderate academic performance, or at-risk students). The logic of adaptive complexity selection was predetermined and governed by rules. Students with test accuracy below 70% or response time exceeding the cohort average by more than one standard deviation were automatically assigned modules to consolidate the material of lower complexity. On the contrary, students who achieved accuracy above 85% with a stable response time were assigned clinical cases of increased complexity to develop advanced skills.

Feedback generation was carried out within the framework of a structured rule-based system consistent with the established categories of surgical competencies. The decision tree model identified specific weaknesses in suturing techniques or clinical thinking, which activated targeted explanations, annotated examples, and additional simulator-based exercises. Thus, machine learning predictions formed the basis of individualized feedback, while maintaining compliance with teacher-approved learning standards.

The system functioned solely as a tool to support educational decisions and did not provide clinical recommendations. All adaptive rules and the results of the algorithms were validated by two leading surgical instructors before the system was implemented. In addition, weekly checks of the system's output data were conducted by the teaching staff to ensure that there were no incorrect or misleading instructions. Students maintained full access to instructors at all times for clarification and academic support, which ensured continuous human supervision.

From a technical point of view, the system was developed in Python 3.10 and integrated with the university's learning management system via a web interface. The main libraries used included scikit-learn for implementing decision trees and k-means algorithms, pandas for processing structured data, NumPy for numerical calculations, and Flask for web integration. Student interaction data was stored in structured SQL tables containing pseudonymized student IDs, timestamps, module IDs, scores, response times, and assigned feedback categories. The model was retrained every four weeks using cumulative performance data collected during the intervention period. It is important to note that the decision thresholds for adaptive branching (accuracy 70% and 85%) were determined prior to the start of the study and remained unchanged throughout the intervention, which ensured methodological stability and reproducibility.

4 RESULTS

Before the intervention began, both the AI group and the control group exhibited no meaningful statistical disparities in terms of age, gender makeup, or initial academic achievement in surgery. Initial tests of theoretical knowledge and practical surgical skills revealed no significant variations between the two groups, indicating they started with similar levels of preparedness (p-values greater than 0.05 across all assessments).

Initially, both the AI and control groups exhibited comparable levels of theoretical knowledge, averaging 64.8 and 65.2 respectively, a similarity that wasn't statistically significant. After the twelve-week program, students utilizing AI-enhanced learning experienced a substantial enhancement in their theoretical understanding. This resulted in an average post-intervention score of 82.6 for the AI group, signifying a noteworthy 17.8 point rise (p-value less than 0.001). Conversely, the control group demonstrated a less pronounced increase, achieving an average post-intervention score of 72.4, marked by a 7.2 point rise (statistically significant at $p < 0.01$). A statistically important distinction ($p < 0.001$) was observed in post-intervention test results, demonstrating that the AI-enhanced educational strategy yielded significantly better results for understanding theoretical concepts (Table 1). The between-group post-intervention difference in MCQ scores was 10.2 points (95% CI: 7.8-12.6), corresponding to a large effect size (Cohen's $d = 1.64$).

While both groups demonstrated enhanced practical surgical skills following the intervention, as measured by the Objective Structured Clinical Examination (OSCE), the AI group exhibited a substantially larger improvement (Table 2).

Table 1: Comparison of theoretical knowledge scores.

Group	Pre-intervention score (Mean ± SD)	Post-intervention score (Mean ± SD)	Mean change
AI group (n=60)	64.8 ± 6.7	82.6 ± 5.9	+ 17.8
Control group (n=60)	65.2 ± 6.4	72.4 ± 6.8	+ 7.2

Table 2: Comparison of OSCE practical skills scores.

Group	Pre-intervention OSCE (Mean ± SD)	Post-intervention OSCE (Mean ± SD)	Mean change
AI group (n=60)	62.1 ± 7.5	81.3 ± 6.2	+ 19.2
Control group (n=60)	61.7 ± 7.2	70.5 ± 7.1	+ 8.8

Table 3: Post-intervention OSCE station scores.

OSCE Station	AI Group (Mean ± SD)	Control Group (Mean ± SD)	P-value
Suturing technique	16.8 ± 1.9	14.1 ± 2.3	< 0.001
Wound assessment	16.2 ± 2.1	14.6 ± 2.4	0.002
Sterile technique	15.9 ± 2.0	14.3 ± 2.2	0.001
Clinical reasoning	16.9 ± 1.8	14.0 ± 2.5	< 0.001
Decision making	17.5 ± 1.6	14.2 ± 2.4	< 0.001

Initially, the AI group scored an average of 62.1 points (with a standard deviation of 7.5), compared to 61.7 points (with a standard deviation of 7.2) for the control group ($p = 0.83$). After the intervention, the AI group's mean OSCE score rose to 81.3 points (with a standard deviation of 6.2), representing a notable gain of 19.2 points ($p < 0.001$). On average, the control group's scores rose to 70.5, with a standard deviation of 7.1, representing a significant gain of 8.8 points ($p < 0.01$). The AI group demonstrated a substantially improved performance on post-intervention OSCE assessments, significantly outperforming the control group ($p < 0.001$). The between-group post-intervention difference in OSCE scores was 10.8 points (95% CI: 8.3-13.3), representing a large effect size (Cohen's d = 1.70).

Examining each OSCE station individually revealed that students who received AI training scored notably higher after the intervention in every one of the five evaluated areas. The most substantial progress was seen in clinical decision-making and suturing skills. While the control group also showed improvement across all stations, their advancements were consistently less pronounced compared to the AI groups (Table 3).

The average satisfaction rating for the AI group was 4.42 out of 5, with a standard deviation of 0.38, while the control group averaged 3.68 out of 5, with a standard deviation of 0.44 ($p < 0.001$). Students in the AI group specifically highlighted the benefits of personalized feedback and adaptable learning paths, stating that these features improved their comprehension of intricate surgical ideas (Table 4).

5 DISCUSSION

This research shows that implementing an artificial intelligence powered educational system within the undergraduate surgical training program at Samarkand State Medical University resulted in notable enhancements to both theoretical understanding and hands-on clinical abilities. Students utilizing AI-enhanced learning demonstrated improved exam results after the intervention and outperformed students who received conventional teaching methods in objective structured clinical evaluations.

This study revealed a significant enhancement in students' theoretical knowledge when they utilized AI-assisted learning. The AI platform's adaptability, which dynamically modified learning materials based on each student's progress, probably played a key role in fostering a more profound understanding and improved retention of intricate surgical principles. In contrast to fixed instructional resources, the AI system employed in this research offered instant feedback and focused reinforcement of challenging concepts, qualities that are recognized for fostering self-directed learning. The AI group showed significant advancements in practical skills, particularly in areas demanding clinical reasoning and decision-making. Such decision-making competencies are particularly important in complex surgical and trauma scenarios, where damage-control strategies and rapid assessment of organ injuries require structured clinical reasoning [13]. These skills are notoriously challenging to acquire during undergraduate surgical training because of restricted operating room access and safety considerations for patients.

AI-powered clinical simulations seem to be partially overcoming these obstacles by offering a controlled setting where students can repeatedly hone their decision-making skills without endangering actual patients. Research on intelligent tutoring systems and virtual patient simulations has yielded comparable results.

Table 4: Student satisfaction scores.

Group	Mean Satisfaction Score (± SD)	P-value
AI group (n=60)	4.42 ± 0.38	< 0.001
Control group (n=60)	3.68 ± 0.44	< 0.01

Table 5: Summary of educational outcomes by teaching method.

Outcome measure	AI-assisted learning	Traditional learning	Statistical significance
Progress in Knowledge	High	Moderate	Significant
Progress in practical skills	High	Moderate	Significant
Clinical reasoning	Marked progress	Limited progress	Significant
Student Satisfaction	High	Moderate	Significant

Indicating that AI-enhanced environments can successfully connect theoretical knowledge with practical clinical application.

Examining each OSCE station individually showed the most significant improvements in suturing skills and clinical judgment. This suggests that the AI system's ability to pinpoint procedural mistakes and provide learners with structured guidance for correction played a key role. Traditional teaching methods, hampered by limited faculty resources and often subjective feedback, contrast with AI systems that deliver consistent, unbiased, and prompt evaluations.

Students in the AI group demonstrated significantly higher satisfaction levels. They expressed higher motivation and found the learning process more valuable, a key element for achieving lasting educational success. This increased engagement could be due to the AI platform's interactive design and the feeling of receiving personalized attention.

These study results hold significant implications for medical universities situated in areas with restricted access to sophisticated surgical training facilities. The successful adoption of an AI-powered learning system at Samarkand State Medical University proves that incorporating these technologies into current educational programs is achievable, all while preserving conventional teaching methods. Crucially, the AI system was designed to augment, rather than supplant, the teaching provided by faculty, highlighting AI's potential as a valuable aid in education.

While this study demonstrates notable strengths, several limitations warrant consideration when analysing its outcomes. The research was confined to a single institution, potentially restricting the applicability of the results to broader populations. Furthermore, the follow-up duration was limited, precluding an assessment of long-term knowledge and skill retention. Future investigations ought to incorporate multi-site designs, extended follow-up periods, and evaluations of clinical proficiency during internships or residency programs.

This research demonstrates that incorporating artificial intelligence into learning can substantially improve surgical education for undergraduate students. The findings in Table 5 reveal enhanced knowledge retention, improved practical skills, and increased student engagement, indicating that AI-powered educational resources hold great potential for advancing medical education practices. More investigation is needed to examine the lasting impacts and refine the incorporation of artificial intelligence within surgical training curricula.

This research, from the perspective of applied information technology, shows the potential for learning analytics and lightweight machine learning to be integrated within a surgical curriculum, which can be used for adaptive teaching approaches without the need for simulation hardware or deep learning infrastructure.

6 CONCLUSIONS

This research shows that incorporating an artificial intelligence learning system into undergraduate surgical training at Samarkand State Medical University led to substantial advancements in students' theoretical understanding, practical abilities, and overall satisfaction. Students utilizing AI-enhanced learning exhibited better results than students who solely received conventional teaching.

The findings indicate that artificial intelligence has the potential to be a valuable tool in surgical education, complementing traditional methods by enabling personalized learning experiences, improving clinical decision-making skills, and fostering increased student involvement. Notably, the successful integration of the AI system into an established curriculum demonstrates its practicality within a genuine academic setting. While more research is required to evaluate its lasting effects and wider use, this study suggests that artificial intelligence holds promise for transforming surgical education.

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