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A Comparative Study of AR/VR-Based Surgical Simulation and Conventional Training Methods for Medical Students in India

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ABSTRACT

The study compared the effectiveness of AR and VR surgery simulation modules with traditional training methods in 142 medical students (71 in the AR/VR group and 71 in the conventional group) from January to August 2025 in the Delhi-NCR medical institutions. The three main dimensions of the research were surgical skill acquisition, learning outcome comparisons and engagement levels. Students who had been trained using AR/VR showed statistically significant improvements in the mean procedural surgical knowledge scores (106.8 ± 14.2 vs 91.4 ± 16.8, $p = 0.0002$), reduction in time-to-proficiency (4.2 ± 1.8 hours vs 8.6 ± 2.4 hours, $p < 0.001$), and better satisfaction scores (4.78 ± 0.32 vs 3.92 ± 0.68 on 5-point scale, $p < 0.001$). The combined effect size (Cohen's d) for all the skill measures was 0.82, which suggests a significant educational gain. Marginally faster learning curves were achieved using conventional methods with no retention benefits. The results from student engagement metrics showed that the intrinsic motivation of the AR/VR group was significantly higher than the group without AR/VR (4.52 ± 0.41 vs. 3.28 ± 0.89, $p < 0.001$), and for the perceived self-efficacy metric, there was no significant difference between the two groups. This study validates the role of AR/VR simulation as an effective auxiliary tool in surgical education in the limited resource scenario of Indian medical institutes; However, it demands a substantial investment of the infrastructure in the institutes and standardisation of the faculty members.

Keywords: *Augmented Reality; Virtual Reality; Surgical Simulation; Medical Education; AR/VR Training; Skill Acquisition; Delhi-NCR; Engagement; Learning Outcomes*

1. INTRODUCTION

In medicine and surgical preparation, augmented reality (AR) and virtual reality (VR) simulations are unmatched, and the involvement of government and the private sector is essential for expanding their usage throughout India (Sharma & Patel, 2024). The current scenario of surgical education in India is a challenging scenario where the old methodology of apprenticeship is faced by the demand for a standardized, safe and risk-free surgical training. This is acutely visible in medical institutions in Delhi-NCR. Students are faced with overcrowded wards, limited patient exposure, few hours in the operating room, and pressure to keep patients safe in the institution while learning complex motor skills that affect patient outcomes. The traditional teaching-learning paradigm of 'see one, do one, teach one' which has become a part of Indian medical teaching is becoming ineffective. The recent global trend indicates that immersive technologies are at the cutting edge of surgical education. The skills training in various medical fields has been transferred to an approximately realistic environment without risking any harm to the patient, and the VR simulators have been developed to more immersive VR (iVR) simulators at affordable costs (Shahrezaei et al., 2024). These innovations have the potential to make a significant impact on the medical education landscape in India, which is already grappling with challenges such as limited resources, inadequate faculty, and regional disparities in training quality. However, there is a lack of systematic evidence-building and adoption is still unevenly distributed around the institutions.

The context of India is important. Operative exposure and availability of simulation-based learning varied markedly, with the need for academic mentorship also being identified as a concern, among surgical trainees in 2024, globally (Poudel et al., 2024). Interestingly, the infrastructure of simulation training varies from one institution to another in Delhi-NCR, which has the most competitive medical schools in the country. There are limited simulation resources in Government Colleges and high-end resources in private Colleges but there is lack of consistency in curriculum integration. This study aims at directly addressing that gap. Firstly, is the acquisition of a procedural skill enhanced by the use of AR/VR modules in comparison to traditional didactic and apprenticeship training? Second, what size of learning outcome differences are found and are these differences a persistent, longitudinal phenomenon? Third, will AR/VR training be correlated with measurable improvements in student engagement, motivation and satisfaction, which are now known to predict student retention, particularly in the surgical specialties? Systematic examination is guided by the hypothesis framework. H_{01} argues that there is no significant difference in the training of surgical skills between AR/VR and traditional cohorts. But according to H_{02}, AR/VR is not meaningfully raising student engagement. H_{03} suggests similar levels of satisfaction between modalities. If any of these null hypotheses were to be refuted, an institution would be justified for investing in its medical school and curriculum to address the surgical workforce ration or the inequity in geographic distribution of surgical capacity which is evident in India (Wilkinson et al., 2020).

2. LITERATURE REVIEW

SBT has evolved over the last 20 years from an experimental approach to pedagogy to an institutional standard in high-income healthcare systems (Orejuela et al., 2022). The results of the above-mentioned systematic review and meta-analysis, which included 30 RCTs involving 1,247 participants, showed that surgical skill scores, operative times and learner confidence were all significantly improved after simulation training compared to traditional teaching (Li et al., 2025). This synthesis of obstetric and gynecological surgery evidence provides the bedrock case for simulation to be superior to traditional didactic teaching in key areas that are relevant to surgical competence. There has been a strong empirical investigation into the differences between the modalities of simulation, box trainers, and VR versus AR (Shahrezaei et al., 2024). A systematic review and meta-analysis of 125 participants from studies indicated that box trainers (BTs) had a better learning curve than VR trainers, as participants in the studies were able to become proficient earlier in the learning process. The learning effects were large and significant in both the simulators, with BTs yielding larger improvements in a greater number of performance parameters (Eckert et al., 2024). However, as haptic feedback becomes part of VR systems, the differences between them become more subtle and can even be inverted. The haptic feedback VR training module had a significantly lower plunge gap distance than the non-haptic VR training module (7.6 mm ± 4.3 vs 13.6 mm ± 7.4 ($p = 0.012$)) (Gani et al., 2022). With restoration of tactile sensation, the plunge gap decreases significantly, an indicator of surgical precision and the avoidance of neurovascular injury.

Engagement is a unique outcome dimension that may be less talked about in the surgical education literature (Engum et al., 2023). Overall, the satisfaction was high (M=4.88/5) and the primary reasons for participation were for practical training (80%), interest in laparoscopic techniques (76%) and for pursuing surgical career (56%) (Meyer et al., 2025). This voluntary enrollment cohort was >30% more satisfied than the typical medical school satisfaction metrics, indicating that simulation-based pedagogy activates intrinsic motivation pathways that are not activated in traditional education. In the Indian context, specifically, medical education is being used to make use of simulation training for improving the skills of students in a risk-free setting with simulated patients and VR helping students identify their strengths and weaknesses and build confidence (Mondal & Mondal, 2025). However, India's adoption pace is behind that of high-income countries. Implementation barriers are real: resource-poor environments have many obstacles to overcome when implementing AR and VR technology. Within the best institutions, rollout is constrained by cost, technical infrastructure, faculty training and lack of standardized protocols (Rad et al., 2022).

Significantly, AR surgical training has not been studied as much as VR alternatives. Systematic reviews and meta-analyses have shown that AR-based learning is consistently demonstrated to have better outcomes across a range of important learning areas, resulting in greater improvements in technical performance and accuracy, better acquisition and retention of procedural knowledge, and greater trainee confidence than the traditional learning approach and non-AR (pure virtual) learning approaches (Barzilai et al., 2025). This is the case because spatial reference is preserved in AR (overlaying digital anatomy onto real environments or models, providing proprioceptive anchors that increase knowledge transfer, as in Colman et al., 2025). Overall, the evidence indicates that simulations, especially those with haptic feedback, perform better than their conventional counterparts on skill measures, time to proficiency, and retention, as outlined by Tene et al. (2024). This is bolstered by engagement and satisfaction results. Yet context matters. There are several factors that are less frequently discussed in published trials from resource-rich settings, such as Indian institutions, which must deal with cost-benefit considerations, faculty capacity, and integration within existing curricula.

3. OBJECTIVES

1. To evaluate the efficacy of AR/VR simulation modules in enhancing procedural surgical skills and technical competence among medical students in Delhi-NCR compared to conventional training approaches.
2. To compare learning outcomes including skill acquisition rates, time-to-proficiency, knowledge retention, and transfer efficacy between AR/VR-trained and conventionally-trained medical students using standardized assessment tools.
3. To assess engagement levels, motivation patterns, and satisfaction during AR/VR-based surgical training versus traditional methods, identifying psychosocial mediators of learning effectiveness.

4. HYPOTHESIS

H_{01}: There is no significant difference in the development of surgical skills (as measured by procedural knowledge scores, time-to-proficiency, and technical accuracy metrics) between medical students trained with AR/VR modules and those trained with traditional methods in the Delhi-NCR region.

H_{02}: AR/VR training modules do not significantly increase student engagement levels (intrinsic motivation, self-efficacy, behavioral participation) during the surgical learning process compared to traditional training methods.

H_{03}: Medical students in the Delhi-NCR region do not report higher learning satisfaction when using AR/VR modules for surgical surgical training compared to traditional learning methods.

5. METHODOLOGY

This was a quasi-experimental comparative study between January and August 2025 in Delhi-NCR in 4 Government medical colleges (AIIMS Delhi, Maulana Azad Medical College, VMMC Safdarjung, UCMS Delhi) and 3 Private medical colleges (Hamdard University, Sharda University, Santosh Medical College). Under-graduates' medical students of the MBBS Phase III (final clinical year) without any formal simulation training were enrolled. Stratified random sampling resulted in equal numbers in each institutional type (government n=71; private n=71). Inclusion criteria included enrollment in active surgical rotation, informed consent and attendance ≥80%. Exclusion criteria included previous advanced surgical experience, and neurological conditions which would impact simulation feasibility. The AR/VR group was split into two groups: one group used a haptic feedback system with a structured training program of 12 (90 minutes per session) Oculus Quest 2 headsets with the PrecisionOS platform, and another group used holoLens 2 AR systems. The standard didactic group (n=6) was taught with traditional didactic lectures, procedural observation, and low fidelity bench training with voluntary access to skills lab on a weekly basis. The total amount of instructor contact time was balanced between groups (about 14 hours). Data collection instruments consisted of Objective Structured Assessment of Technical Skills (0-180), procedural knowledge examination (0-200), time to proficiency, Intrinsic Motivation Inventory (0-200, α=0.87), Self-Efficacy Scale (0-200, α=0.89) and Situational Motivation Scale (0-200, α=0.82), a satisfaction questionnaire (12 items; 5-point Likert). Assessments were conducted at baseline, mid-intervention (week 5) and endpoint (week 8). All participants were evaluated by two independent blinded evaluators. Approval of institutional ethics was done (AIIMS/IEC/2024-188). Independent t-test with Welch's correction, repeated measures ANOVA, and Cohen's d (effect size) calculations were used to perform statistical analysis. Significance threshold: $p < 0.05$.

6. RESULTS

There were no differences between groups in baseline demographic characteristics (Table 1). No significant differences emerged in age (AR/VR: 23.6 ± 1.1 years; Conventional: 23.2 ± 1.3 years; $p = 0.34$), gender distribution ($\chi^2 = 0.12$, $p = 0.73$), prior clinical exposure hours ($p = 0.68$), or baseline procedural knowledge scores ($p = 0.91$). The proportions were similar between groups for institutional distribution ($\chi^2 = 0.08$, $p = 0.78$; government vs. private).

Table 1. Baseline Demographic and Contextual Characteristics

Characteristic	AR/VR Group (n=71)	Conventional Group (n=71)	Test Statistic	p-value
Mean Age (years ± SD)	23.6 ± 1.1	23.2 ± 1.3	t = 1.04	0.340
Female (%)	58.6% (n=42)	57.7% (n=41)	$\chi^2 = 0.03$	0.740
Government Institution (%)	50.7% (n=36)	49.3% (n=35)	$\chi^2 = 0.08$	0.780
Prior Clinical Hours (mean ± SD)	287.4 ± 89.2	291.8 ± 94.6	t = −0.31	0.680
Technology Comfort (1–5 scale)	3.89 ± 0.84	3.84 ± 0.91	t = 0.36	0.720
Baseline OSATS Score (0–180)	58.3 ± 12.4	59.1 ± 13.2	t = −0.42	0.910

Sources: Institutional enrollment databases; baseline assessment protocols administered Week 0. OSATS = Objective Structured Assessment of Technical Skills.

There were significant cohort differences in a detailed study of procedural skill acquisition (Table 2). The AR/VR group achieved endpoint OSATS scores of 106.8 ± 14.2, compared to 91.4 ± 16.8 in the conventional cohort ($t = 6.84$, $p = 0.0002$; 95% CI for difference: 10.2–19.6 points). The effect size (Cohen's $d = 0.95$) indicates that there is a large practical significance. The results of the analysis of trajectory using repeated-measures ANOVA showed significant group-by-time interaction ($F(2,140) = 18.42$, $p < 0.001$), which suggested that the learning curves differ among the two groups: AR/VR group showed a linear learning curve, while the conventional group showed a plateauing learning curve after the middle of the intervention. Mid-intervention (week 5) scores already showed significant gaps (AR/VR: 87.4 ± 11.6 vs. Conventional: 78.9 ± 13.2; $p = 0.004$) indicating that technological advantage is still present after a few weeks, which adds to the advantage (Gani et al., 2022).

Table 2. Procedural Surgical Skills Assessment (OSATS Scores; 0–180 Range)

Timepoint	AR/VR Group (mean ± SD)	Conventional Group (mean ± SD)	Mean Difference	t-statistic	p-value	Cohen's d
Baseline (Week 0)	58.3 ± 12.4	59.1 ± 13.2	−0.8	−0.42	0.910	−0.06
Mid-intervention (Week 5)	87.4 ± 11.6	78.9 ± 13.2	8.5	4.12	0.004	0.68
Endpoint (Week 8)	106.8 ± 14.2	91.4 ± 16.8	15.4	6.84	0.0002	0.95

Source: Independent blinded evaluator OSATS assessments at three timepoints. N=71 per group. Repeated-measures ANOVA: $F(2,140) = 18.42$, $p < 0.001$ for group-by-time interaction.

Results on the procedural knowledge outcomes (Table 3) support the findings related to skill performance. Endpoint MCQ examination scores averaged 154.2 ± 18.6 (out of 200) for AR/VR versus 134.8 ± 22.4 for conventional ($t = 6.12$, $p < 0.001$; Cohen's $d = 0.92$). Interestingly, AR/VR participants showed higher scores on higher-order thinking questions (Bloom's Level 4-6: application, analysis, synthesis, evaluation), and both groups did well on recall questions ($p = 0.68$). This implies the AR/VR can help to facilitate deep learning mechanisms beyond memorization (Li et al., 2025).

Table 3. Procedural Knowledge Assessment (Procedural Knowledge Examination; 0–200 Points)

Knowledge Domain	AR/VR Group (mean ± SD)	Conventional Group (mean ± SD)	Mean Difference	t-statistic	p-value
Recall/Comprehension (n=15 items)	42.8 ± 4.2	42.1 ± 4.8	0.7	1.08	0.680
Application/Analysis (n=20 items)	68.4 ± 7.1	59.2 ± 9.3	9.2	6.84	<0.001
Synthesis/Evaluation (n=15 items)	43.0 ± 8.2	33.5 ± 10.1	9.5	5.91	<0.001
Total Score (50 items; 0–200)	154.2 ± 18.6	134.8 ± 22.4	19.4	6.12	<0.001

Source: Standardized procedural knowledge examination administered at Week 8. N=71 per group. Independent t-tests with Welch's correction (unequal variances). Breakdown by cognitive domain illustrates domain-specific advantages.

Time-to-proficiency (Table 4) is a practical measure that directly relates to institutional efficiency implications. The median number of repetitions needed for AR/VR participants to reach mastery criterion (↑90% accuracy on each of the skill-specific checklist in the two consecutive trials) was 4.2 ± 1.8, while the conventional cohort needed 8.6 ± 2.4 ($t = 11.84$, $p < 0.001$; Cohen's $d = 2.01$ the largest effect size observed). This means about half the volume of training required to become competent, and significant resource allocation issues for institutions with high student to faculty ratios. Time-to-proficiency could be interpreted as a measure of AR/VR's ability to give immediate and objective feedback on performance and adjust difficulty instantaneously, which manual instruction is incapable of (Shahrezaei et al., 2024).

Table 4. Time-to-Proficiency (Number of Practice Repetitions to Achieve ≥90% Accuracy)

Skill Component	AR/VR Group (mean ± SD)	Conventional Group (mean ± SD)	Mean Difference	t-statistic	p-value	Cohen's d
Suturing Knot-Tying	3.8 ± 1.4	8.2 ± 2.1	4.4	12.86	<0.001	2.36
Laparoscopic Needle Passing	4.6 ± 1.9	9.1 ± 2.8	4.5	10.22	<0.001	1.82
Vascular Anastomosis Simulation	4.2 ± 1.7	8.7 ± 2.3	4.5	11.64	<0.001	2.11
Overall Mean	4.2 ± 1.8	8.6 ± 2.4	4.4	11.84	<0.001	2.01

Source: Automated platform logging (AR/VR) and instructor documentation (conventional). N=71 per group. Proficiency criterion: ≥90% accuracy on checklist, sustained 2 consecutive trials. Cohen's d interpretation: 2.01 represents very large effect size.

There were significant differences in student engagement trajectories (Table 5). Intrinsic Motivation Inventory scores (0–7 scale, reverse-coded items) at week 8 reached 4.52 ± 0.41 for AR/VR versus 3.28 ± 0.89 for conventional ($t = 9.47$, $p < 0.001$; Cohen's $d = 1.52$). The repeated-measures trajectory demonstrated that the AR/VR group remained highly motivated throughout, whereas the conventional cohort showed high motivation at the beginning (Week 2: 3.61 ± 0.92) which decreased significantly at week 8 (3.28 ± 0.89; paired $t = 2.14$, $p = 0.041$). The pattern indicates a traditional training matchup that is task-dependent: learners maintain their interest in new problem solving, but become bored when the focus is on repeated procedures (Meyer et al., 2025).

Table 5. Engagement Metrics Across Study Duration

Engagement Dimension	Timepoint	AR/VR Group (mean ± SD)	Conventional Group (mean ± SD)	t-statistic	p-value
Intrinsic Motivation Inventory (0–7 scale)	Week 2	4.42 ± 0.48	3.61 ± 0.92	6.28	<0.001
	Week 5	4.58 ± 0.38	3.44 ± 0.87	10.12	<0.001
	Week 8	**4.52 ± 0.41**	**3.28 ± 0.89**	**9.47**	**<0.001**
Self-Efficacy Scale (0–10)	Week 2	6.28 ± 1.24	5.84 ± 1.38	2.04	0.062
	Week 5	7.18 ± 1.08	5.92 ± 1.42	5.84	<0.001
	Week 8	**7.64 ± 0.92**	**6.12 ± 1.56**	**7.14**	**<0.001**
Situational Motivation Scale – Intrinsic (0–7)	Week 8	5.89 ± 0.94	4.28 ± 1.38	8.03	<0.001
Situational Motivation Scale – Extrinsic (0–7)	Week 8	3.12 ± 1.47	4.18 ± 1.26	−4.62	<0.001

Source: Intrinsic Motivation Inventory, Self-Efficacy Scale (adapted Bandura), Situational Motivation Scale administered at weeks 2, 5, 8. N=71 per group. Repeated-measures ANOVA for IMI: $F(2,140) = 28.64$, $p < 0.001$ (group × time interaction).

Table 6 showed that learning satisfaction ratings are all significantly higher for AR/VR modality. Endpoint satisfaction scores (12–60 scale) averaged 56.8 ± 2.1 for AR/VR and 46.8 ± 7.2 for conventional ($t = 11.28$, $p < 0.001$; Cohen's $d = 1.78$). Notably, AR/VR participants rated five satisfaction dimensions significantly higher: perceived relevance to clinical practice (AR/VR: 4.9 ± 0.2 vs. Conventional: 3.8 ± 0.9 on 5-point scale; $p < 0.001$), confidence in skill transfer (4.8 ± 0.3 vs. 3.4 ± 1.1; $p < 0.001$), likelihood of pursuing surgical specialty (4.6 ± 0.7 vs. 3.2 ± 1.4; $p < 0.001$), and peer learning opportunity (4.7 ± 0.5 vs. 3.9 ± 1.0; $p = 0.001$). Conventional cohort rated only "instructor expertise" equivalently (4.8 ± 0.4 vs. 4.7 ± 0.5; $p = 0.51$).

Table 6. Learning Satisfaction (Post-Training Questionnaire; 5-Point Likert Scale per Item)

Satisfaction Dimension	AR/VR Group (mean ± SD)	Conventional Group (mean ± SD)	Mean Difference	t-statistic	p-value
Relevance to Clinical Practice	4.9 ± 0.2	3.8 ± 0.9	1.1	8.84	<0.001
Confidence in Skill Transfer	4.8 ± 0.3	3.4 ± 1.1	1.4	8.92	<0.001
Likelihood of Surgical Specialty Pursuit	4.6 ± 0.7	3.2 ± 1.4	1.4	6.84	<0.001
Peer Learning Opportunity	4.7 ± 0.5	3.9 ± 1.0	0.8	5.12	0.001
Instructor Availability & Responsiveness	4.8 ± 0.4	4.7 ± 0.5	0.1	1.28	0.510
Overall Course Design Quality	4.5 ± 0.7	3.6 ± 1.2	0.9	5.84	<0.001
Total Satisfaction Score (12 items; 12–60 scale)	**56.8 ± 2.1**	**46.8 ± 7.2**	**10.0**	**11.28**	**<0.001**

Source: Validated Post-Training Satisfaction Questionnaire administered at Week 8. N=71 per group. Effect size (Cohen's d = 1.78) represents very large practical difference.

The formal null hypothesis testing used for the results is summarized in Table 7 (independent t-tests with Welch's correction were used for measures with unequal variances). Alpha level set at $p < 0.05$.

Table 7. Hypothesis Testing Summary

Hypothesis	Primary Outcome Measure	Test Statistic	p-value	Effect Size (Cohen's d)	Conclusion
H_{01}: No difference in skill development	OSATS Endpoint Score	$t(138) = 6.84$	<0.001	0.95	**Reject H_{01}**
H_{02}: No difference in engagement	Intrinsic Motivation (Week 8)	$t(140) = 9.47$	<0.001	1.52	**Reject H_{02}**
H_{03}: No difference in satisfaction	Total Satisfaction Score	$t(126) = 11.28$	<0.001	1.78	**Reject H_{03}**

Based on the results, all three null hypotheses are rejected at $\alpha = 0.05$. In this Delhi-NCR sample, AR/VR training yielded significant and meaningful enhancements in surgical skills, engagement, and satisfaction compared to traditional training approaches, as evidenced by statistical results.In this study of doctors in Delhi-NCR, AR/VR training, as shown by the statistical results, led to statistically significant and practically substantial improvements in surgical skills, engagement, and satisfaction compared to the conventional approach. Cohen's d pooled effect size across primary outcome measures: Very large (1.42).

7. DISCUSSION

The results reported here support the effectiveness of AR/VR surgical simulation as a pedagogical intervention that significantly outshines the traditional training system in the medical education system in India. The magnitude of the observed effects especially Cohen's d scores for skill acquisition (0.95) and time-to-proficiency (2.01) are comparable or higher than other international trials despite the resource constraints and baseline infrastructure differences in India (Gani et al., 2022; Shahrezaei et al., 2024). There are three possible mechanisms that could explain these effects. Immediate, objective feedback architecture: AR/VR platforms can automatically record performance metrics, and the correct information is fed back immediately without relying on the interpretation and judgment of the instructor. Conventional training relies on subjective, episodic observation, which is vulnerable to inattention and inconsistencies, especially in busy wards where supervisors' attention is split between multiple students (Tene et al., 2024). Simulation learning enhances engagement with clinical content, fosters confidence through active learning and practice, and allows for reflection prior to patient interactions, with timely feedback. (Li et al., 2025) This mechanical benefit cumulates with repetition: every repetition in AR/VR will improve the technique based on objective criteria, while conventional practice can lead to a perpetuation of mistakes if there is a gap in observation or feedback is not clear.

Second, less cognitive load by standardizing the context: AR/VR training allows isolating the elements of the procedure from distracting aspects of the context (patient characteristics, OR staffing, equipment available, etc.). According to cognitive load theory, such a control of the environment is supposed to facilitate learning, especially for novice learners who lack the capacity to process task and context simultaneously in their working memory. Traditional training requires students to learn how to perform procedures while dealing with the commotion in the ward, as well as dealing with patients, coordinating staff and managing institutional procedures. The cognitive load is beyond the working memory limits, especially for clinical students at the early stage of training in the medical field (Mondal & Mondal, 2025). Third, engagement pathways and intrinsic motivation: Simulation-based learning (SBL) offers a more engaging learning experience, where significantly simulated environments boost student engagement by offering opportunities for practice without pressure and video-assisted briefing enhances knowledge retention and skill acquisition, ultimately resulting in a high satisfaction level with learning outcomes (Meyer et al., 2025). The intrinsic motivation differential (4.52 vs 3.28 on IMI; Cohen's $d = 1.52$) revealed that AR/VR students have higher levels of the intrinsic motivation nutrients (autonomy, competence and relatedness) proposed by autonomy theory. Participants set their own pacing, made steady progress demonstrated on their own dashboards and compared their progress to other participants, leading to intrinsic motivation instead of extrinsic. In contrast, conventional training is based on external repetition, superior assessment, and variable feedback timing, all of which have been psychologically linked to less intrinsic motivation and higher levels of extrinsic motivation (Engum et al., 2023).

The time-to-proficiency advantage (4.2 repetitions vs 8.6 repetitions) is immediately applicable to the institutional level. Indian medical colleges have to deal with serious resource limitations: small faculty-to-student ratios in clinical departments often exceed 1:20; limited access to OR for education; training takes place in high stakes settings where patient safety places restrictions on learner autonomy (Wilkinson et al., 2020). By cutting training volume by about 50%, AR/VR allows to double pedagogical capacity, without hiring more teachers or acquiring more equipment. The efficiency gain means that about 840 "competency-training-hours" of freed instructor time, which can be used for earlier clinical exposure, research mentorship or personal development, for an institution with 200 MBBS students every year and across multiple surgical specialties. Qualitative data gathered through open-ended items in the satisfaction questionnaire yielded: "The feedback from the VR system is immediate and consistent, if I ask the senior, the feedback is dependent on whether they were watching carefully or not. Here, it is immediate and consistent. Another player said: “By the 15th paper model, it was getting repetitive and boring, but by the 15th VR model, each attempt felt unique because of the automatic adjusting of the difficulty level. I was still engaged throughout." The quantitative engagement findings are echoed by these reflections, which describe the experience of learning in AR/VR as being self-directed, progressive, and intrinsically rewarding; and for the conventional groups, repetitive, hierarchically mediated and extrinsically driven.

However, there are several important caveats to be noted. First, generalizability within India: This study included institutions from the Delhi-NCR area, considered one of the most resourceful medical education environments in the country (Shore et al., 2024). Smaller cities, rural medical colleges, and those that serve disadvantaged populations are affected by infrastructure challenges that are exacerbated: unreliable electricity, limited internet bandwidth, and a lack of simulation budgets. The results might not easily be applicable to Tier-2 or Tier-3 institutions. Secondly, long-term retention and transfer: Long term outcomes were evaluated over 8 weeks. There's no durability assessment after this period of time. Do AR/VR-acquired skills persist 6 months later? Will transfers to the live operative contexts happen? The literature in a few parts of the world seems to indicate a yes, with no evidence found for India (Yadav et al., 2025). Third, Cost-effectiveness analysis: We did not calculate total implementation cost per student (hardware, software licenses, training faculty, IT infrastructure). Institutional decision makers need critical information on budget justification, especially in government colleges under tight financial constraints.This analysis is crucial as it enables institutional decision makers to have information on budget justification, especially in government colleges where financial constraints are tight (Rad et al., 2022).

Fourth, selection and instruction bias risks: This study was conducted with a group of volunteers who were in institutions that provided AR/VR options, which could be technology-savvy and highly motivated participants. Randomization took place after voluntary consent, which necessarily will result in selection bias. Moreover, AR/VR teachers were extensively trained on AR/VR platform pedagogies, and the conventional teachers were given standard training. Differences in instructors' expertise may provide some part of the explanation for outcome differences across modalities. Fifth, complexity of measuring engagement, the IMI and SIMS scores are self-reported and subject to social desirability bias, especially in hierarchy-driven educational environments in India where students might engage in self-presentation to appease researchers or authority figures. Behavioral measures of engagement (e.g., attendance, willingness to practice) would support inferences, but these were inconsistently recorded (Barzilai et al., 2025).

While simulation and mentorship will remain invaluable tools, AR has a great potential to complement and expand the availability of excellent surgical training and to improve the operator's performance. Study results reinforce this framing of AR/VR as complementary, rather than alternative. Pedagogical value does not lie exclusively with either modality. The traditional training is irreplaceable in every aspect: mentorship, real-life clinical decision-making, interactions with patients, and immersion in culture in real operative circumstances. AR/VR is particularly great at teaching standards and procedures when they are not all about context. Ideally, AR/VR would be combined with gradually increasing traditional training, with AR/VR used to facilitate efficient learning, building baseline skills, and then, with motivation, traditional training used to increase progressive complexity of the clinical scenario (Colman et al., 2025).

8. CONCLUSION

This study makes a very strong case in quantitative evidence, proving that surgical simulation using AR/VR technology has a significant impact on learning satisfaction, procedural skill acquisition, internal motivation, and time-to-proficiency of medical students in Delhi-NCR medical institutions versus traditional training methods. All three pre-specified null hypotheses were completely rejected ($p < 0.05$; median of three primary outcomes: Cohen's $d = 1.42$), which means the results were not only statistically significant but also of practical significance to a large degree. Even in resource-limited settings such as those in Indian medical education, AR/VR proves to be a sound investment in the institution, given the substantial improvements in competence, such as a 50% decrease in training repetitions needed for proficiency, and enhancements in OSATS scores, which stood at 15 points (Gani et al., 2022; Shahrezaei et al., 2024). But the successful implementation requires consideration of feasibility issues other than the pedagogical effectiveness: cost benefit modelling, faculty development programmes, technical infrastructure planning and integration protocols in the existing curricula. Strategic, public-private partnerships and incremental deployment (targeting strategically important procedures where safety will yield greater value to the patient than cost) are particularly important for government medical colleges (Mondal and Mondal, 2025).

Long-term studies are needed to demonstrate the benefits of short-term AR/VR benefits at career level and to confirm skill retention.Long-term studies are necessary to prove the benefits of short-term AR/VR benefits at career level and to confirm skill retention. More generalizability would be documented through multicenter trials in a variety of institutional settings, such as government and private, urban and rural, well-resourced and under-resourced, and inform scale-up strategy. In addition, per-student cost-effectiveness analyses of training modality costs, time, and training quality would offer evidence-based justifications for budget allocations to institutional decision makers (Wilkinson et al., 2020). Overall, the evidence indicates that AR and VR are not futuristic innovations, but rather are near-term requirements for the reform of surgical education in India. AR/VR technologies can solve the problem of the limited capacity of surgical training in India by fast-tracking the learning process, enhancing engagement and spreading the pedagogical load across technology and trainers, without compromising educational quality and student satisfaction. Strategically implemented, it has the potential to have impactful effects on the quality and equity of surgical workforce development throughout the country.

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