

A study comparing a magnifying box, a 3D laparoscope, and a wearable head-mounted display glasses for laparoscopic surgery skills training.

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Abstract

Objective: This study aimed to conduct a prospective, randomized, single-blinded comparative evaluation of three distinct laparoscopic visualization modalities—a low-cost magnifying box, a standard 3D laparoscope, and wearable display glasses—to determine their effects on operational efficiency and psychomotor proficiency during a structured surgical skills curriculum.

Methods: Thirty-six surgical novices (medical students) were randomized into three visualization cohorts: Magnifying Box (n=14), Standard 3D Laparoscopic Camera Simulator (n=11), and Wearable Visual Display Glasses (n=11). Participants completed a 4-week structured curriculum comprising three Fundamentals of Laparoscopic Surgery (FLS) tasks of increasing complexity: peg transfer, circle cutting, and intracorporeal suturing. Primary outcomes included task completion times and technical quality assessed via Global Objective Assessment of Laparoscopic Skills (GOALS) scores over four sequential attempts. Data were analyzed utilizing Repeated Measures ANOVA, Kruskal-Wallis H tests, and Analysis of Covariance (ANCOVA).

Results: All cohorts demonstrated significant performance improvements across the four trials, producing parallel learning trajectories with no significant Group $\times$ Time interactions ($p > 0.05$). The Magnifying Box cohort completed peg transfer and intracorporeal suturing significantly faster than both the Laparoscope and Display Glasses cohorts ($p < 0.05$). Furthermore, the Magnifying Box group consistently achieved significantly higher overall endpoint (T4) GOALS scores compared to both alternative modalities. Conversely, the Laparoscope and Display Glasses cohorts did not differ significantly from each other on any task completion time or technical quality measure (all pairwise $p > 0.40$).

Conclusion A low-cost, mechanically simple magnifying box achieves superior early skill acquisition outcomes compared to substantially more expensive, technologically complex visualization systems. The equivalent learning rates across all modalities suggest that structural practice and deliberate repetition, rather than visualization technology, remain the primary drivers of surgical skill acquisition.

Introduction

Until the 21st century, the predominant method of general surgery education was apprenticeship-based training conducted directly in the operating room (1). However, with the rise of minimally invasive surgery, surgical trainees are now required to master not only open surgery but also inimally invasive surgery, which includes; laparoscopic, endoscopic and robotic surgery. Laparoscopic surgery has become the gold standard approach for several procedures due to its lower postoperative pain, infection rates, and hospital stay (2, 3). Over the years it has become increasingly evident that achieving competence in all these MIS techniques solely through operating room training is impractical. Increased recognition of legal and ethical patient safety concerns (4), limitations on trainee working hours (5, 6), hospital efficiency pressures (7), and technological innovations (8) are culminating in a changing training environment. This has created a need for more comprehensive educational methods that focus on

improving surgical skills. In response, novel approaches, such as simulation training, virtual reality, and augmented reality, have been adopted in surgical education (9, 10). Among these, simulation training, including bench models, laparoscopic simulation boxes, 3D printed models and animal models, has already been widely utilized as an effective method for surgical trainees to practice basic MIS skills (11–14).

With these methods multiple laparoscopic training programs have been created. With each curriculum showing marked improvement of technical skills in a simulated scenario and also demonstrated successful transfer of the skills to the operating room (11, 12, 15–17). Despite all of this, there is still a lack of a universal curriculum to be followed. The most widely used laparoscopic skills training program is the Fundamentals of Laparoscopic Surgery (FLS), which was developed by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) and released to the public in 2004 (18). In 2008, successful completion of the FLS program became a requirement for board certification by the American Board of Surgery, reflecting its importance in surgical education (19). Simulation is a valuable tool for surgical training, offering safe and controlled environments for learners to practice repeatedly. However, high-quality simulators are costly, inaccessible, require significant resources, and onsite feedback to be effective. Moreover, voluntary use of simulators by trainees is poor (20, 21). These limitations underly the pursuit for an inexpensive, accessible, scalable alternative which trainees are likely to engage with. Common training difficulties include three-dimensional tasks while viewing a two dimensional (2D) monitor. This is exacerbated by the fulcrum effect, where instrument movements outside the body are counterintuitive to the motion of the instrument tip inside. Furthermore, long instruments and the lack of direct contact lead to a profound attenuation of haptic and tactile feedback, critical sensory information that guides tissue handling and dissection (22, 23).

Surgical simulators vary in cost and complexity, ranging from low-tech, low-cost options such as the FLS trainer to hightech, high cost haptic-based trainers. The cost of low-fidelity simulators ranges from under 10 dollars to approximately 230 dollars USD, while commercial systems can cost hundreds to many thousands of dollars (24). A key feature of low-cost trainers is portability, which requires a compact and durable design. This characteristic is particularly essential for enabling remote surgical training in underserved or rural areas (12). These low-cost innovations hold great promise for laparoscopic skill training by making it more accessible. The Wearable Head Display Glasses is a new imaging monitor that has been proposed for laparoscopic surgery, its quality is modern in terms of resolution, wearability, and weight. This wearable display glass is a 330-g binocular Display Glasses composed of 0.7-inch organic light-emitting diode (OLED) screens (resolution: 1,280 × 720 pixels) for each eye, which provides the wearer with sharp and high-contrast images (25).

Visual feedback is fundamental to psychomotor skill acquisition in surgery. In laparoscopic procedures, the visualization system fundamentally alters the visuomotor transformation available to the trainee (16). Specifically, the spatial relationship between instrument movement and visual feedback, stereoscopic depth perception, and the first-person versus external monitor perspective (26). These differences in visual information processing may substantially influence learning efficiency, learning

trajectory velocity, and technical proficiency development. However, whether these differences are sufficiently large to justify the substantial cost differential between visualization modalities. Despite the emergence of multiple visualization technologies applied in laparoscopic surgical training such as Display Glasses, Laparoscope tower and Magnifying glass box trainers no prior prospective comparative studies have directly evaluated their comparisons. The specific effects of visualization modality on both the rate of skill acquisition and endpoint technical proficiency remain unclear. This information is critical for determining whether low-cost visualization alternatives can provide equitable surgical training access without sacrificing learning outcomes.

The primary objective of this study was to conduct a prospective, randomized, single-blinded comparative evaluation of three distinct laparoscopic visualization modalities to determine their effects on operational efficiency and psychomotor proficiency during a structured surgical skills curriculum.

Materials and Methods

Study Design.

This was a prospective, randomized, single-blinded comparative study conducted from April, 2026, to May, 2026 (4-week structured protocol) at Zhejiang Provincial Peoples Hospital. The study was approved by the institutional review board IRB number: KT2026113. All participants provided written informed consent prior to enrollment. The methodological design was adapted from established validation frameworks and modified to compare three distinct visualization modalities: the magnifying box, laparoscope, and wearable display glasses. The study adheres to CONSORT guidelines. The study methodology followed the framework outlined by Seymour et al. (27) and Van Sickle et al. (28), with later modifications in Sidney A. et al. (11), to incorporate the novel visualization comparison, As summarised on Fig. 1.

Participant Recruitment and Randomization.

Thirty-nine medical students in their 3rd to 6th academic years were assessed for eligibility. Inclusion criteria required absolute zero or negligible prior baseline experience in formal laparoscopic simulation training or live laparoscopy surgery. Exclusion criteria included: (1) prior completion of laparoscopic surgical skills modules; (2) functional manual dexterity limitations (self-reported); (3) inability to complete the entire 4-week training sequence. Three participants met exclusion criteria. All 36 eligible participants were enrolled and randomized to one of three visualization cohorts using a computer-generated block randomization sequence with unequal allocation ratios designed to match real-world equipment configurations: Magnifying Box (n = 14), Laparoscope Simulator (Laparoscope, n = 11), and Wearable Visual Display Glasses (Display Glasses, n = 11). The use of surgical novices was intentional, as it allowed for a clear assessment of skill acquisition from a true baseline without confounding prior experience.

Sample size calculation.

Based on previous laparoscopic skills performance study which demonstrated an effect size of approximately 1.3 (11), we employed similar statistical parameters including an alpha value of 0.05 and a power threshold of 0.80 and established a minimum requirement of nine participants per experimental group to detect meaningful differences between the three training approaches.

Baseline Standardization and Pre-Training Preparation.

All participants completed an identical pre-training standardization protocol to ensure equivalent knowledge and procedural understanding across cohorts. This protocol consisted of three sequential components: (1) a standardized didactic lecture (60 minutes) covering fundamental laparoscopic instrument ergonomics, instrument identification (laparoscopic graspers, dissectors, needle drivers, and endoscopic scissors), and mechanical fulcrum mechanics; (2) compulsory viewing of instructional benchmark videos demonstrating optimal execution of the three target psychomotor tasks (Peg Transfer, Circle Cutting, and Intracorporeal Suturing); and (3) a supervised baseline familiarization trial on each trainee's assigned visualization modality, conducted to eliminate cognitive misunderstandings of task rules and technical platform operation before formal data collection commenced.

Training Devices.

Modality A: Magnifying Box (Low-Cost). A physical box trainer constructed from cost-effective acrylic plating with integrated optical magnifying lenses (10× magnification). This modality simulates depth perception and visual fields without digital camera assistance or electronic instrumentation. Instruments and training tasks are performed inside the acrylic box, with magnification provided by fixed optical lenses positioned at fixed viewing angles. This modality requires no electrical power and operates entirely on mechanical principles. (Fig. 2. A)

Modality B: Standard 3D Laparoscopic Camera model. A rigid laparoscopic tower setup featuring a high-definition optical camera system (full-high definition, 1080p resolution) projecting the operative field onto an external 3D monitor display in real-time. The system provides binocular viewing with electronic depth perception rendering and represents the gold-standard visualization approach used in laparoscopic operating rooms and training. (Fig. 2. B)

Modality C: Wearable Visual Display-Glasses modal (Emerging Technology). A compact simulation environment interfaced directly with a wearable head-mounted visual display device, which projects the operative field directly onto the trainee's retinae. This modality provides an egocentric perspective aligned with the trainee's natural line of sight, eliminating the spatial offset between instrument movement and visual feedback present in tower-based systems. (Fig. 2. C)

Training Curriculum.

Participants completed a 4-week structured training curriculum consisting of synchronized sessions across all cohorts. The curriculum progressed through three validated laparoscopic tasks of increasing complexity FLS by SAGES (18): Task 1: Peg Transfer; Task 2: Circle Cutting; Task 3: Intracorporeal

Suturing. Each participant completed exactly four sequential attempts (T_1 , T_2 , T_3 , T_4) of each task across the 4-week period. Sessions were conducted at standardized intervals.

Objective Performance Assessment.

Task Completion Times. Task completion times were recorded in seconds for each of the four attempts on each task. Timing commenced upon initial instrument contact with the task apparatus and concluded upon task completion as defined by standardized criteria specific to each task (pegs successfully transferred and seated for Peg Transfer; circular incision completed for Circle Cutting; suture knot secured with defined loop configuration for Intracorporeal Suturing).

Global Objective Assessment of Laparoscopic Skills (GOALS). Technical quality was assessed using the validated GOALS metric, an objective scoring matrix evaluating five fundamental psychomotor domains on a Likert scale ranging from 1 to 5 for each domain (total possible score: 5–25 points): 1. Depth Perception; 2. Bimanual Dexterity; 3. Efficiency of Movement; 4. Tissue Handling; 5. Autonomy/Flow of Operation. All training attempts were video-recorded in standardized format. Video recordings were subsequently evaluated by one independent expert surgical reviewer (attending surgeon with ≥ 10 years of laparoscopy surgery experience) who was blinded to participant cohort assignment, training attempt order, and all identifying participant information. All video recordings were evaluated using the GOALS framework.

Outcome Measures

Primary and secondary outcome measures were:

1. Task completion time (in seconds).
2. Total GOALS scores for each task at all four timepoints.
3. Learning curve progression for each cohort.
4. Baseline equivalence of Covariates.

Statistical Analysis.

All statistical analyses were performed using IBM SPSS Statistics (Version 26.0; IBM Corp., Armonk, NY, USA). Data normality and variance homogeneity were verified using Shapiro-Wilk and Levene's tests, respectively. Baseline demographic comparability across cohorts was assessed using One-Way ANOVA, Kruskal-Wallis H tests, or Fisher-Freeman-Halton exact tests, as appropriate. Task completion times was analyzed utilizing a Two-Way Mixed-Design Repeated Measures ANOVA (RM-ANOVA) with Visualization Modality as the between-subjects factor and Training Attempt (T_1 , T_2 , T_3 , T_4) as the within-subjects factor. Sphericity was evaluated via Mauchly's test, with Greenhouse-Geisser corrections applied where violated. Significant effects were decomposed using Tukey's HSD and Bonferroni-adjusted simple main effects. Effect sizes were reported as partial eta-squared (η^2p). For GOALS intra-cohort progression was evaluated using Friedman's Two-Way ANOVA and post-hoc Wilcoxon signed-rank tests. Inter-cohort

differences were analyzed via the Kruskal-Wallis H test, followed by Mann-Whitney U tests utilizing a Bonferroni-corrected alpha ($\alpha = 0.0028$ for 18 comparisons). An Analysis of Covariance (ANCOVA) was conducted on final performance metrics (T_4 completion times and T_4 GOALS scores), controlling for baseline video gaming frequency, musical training, and handedness, following confirmation of regression slope homogeneity. All analyses $p < 0.05$ were considered statistically significant. Continuous variables are reported as mean $\pm$ standard deviation (SD) or median with interquartile range (IQR). Categorical data are presented as absolute frequencies and percentages.

Results

Thirty-six medical students were enrolled and allocated across three visualization cohorts: Laparoscope ($n = 11$), Display Glasses ($n = 11$), and Magnifying Box ($n = 14$). Baseline demographic and experiential characteristics are summarized in Table 1. Sex distribution did not differ across groups ($p = 0.20$). Within the Laparoscope and Display Glasses cohorts, females comprised the majority (63.6% each), whereas the Magnifying Box cohort was predominantly male (71.4%). Video gaming frequency ($p = 0.10$), musical instrument background ($p = 0.80$), and handedness ($p = 1.00$) were likewise comparable across groups, with right-handedness near-universal across all cohorts (92.9–100%). A significant difference in year of study was identified $p < 0.00$. The Laparoscope cohort consisted exclusively of Year 6 medical students (100%), while the Display Glasses cohort comprised primarily Year 5 students (72.7%), and the Magnifying Box cohort included a mixed distribution spanning Years 4, 5, and 6 plus other academic standings (21.4%, 28.6%, and 50.0%, respectively).

Table 1
Baseline Characteristics

Variable	Laparoscope (N = 11)	Display Glasses (N = 11)	Magnifying Box (n = 14)	P-value
Sex, n (%)				
Female	7 (63.6%)	7 (63.6%)	3 (21.4%)	0.20
Male	4 (36.4%)	4 (36.4%)	10 (71.4%)	
Prefer not to say	0 (0%)	0 (0%)	1 (7.1%)	
Year of Study, n (%)				
Year 4	0 (0%)	0 (0%)	3 (21.4%)	< 0.05*
Year 5	0 (0%)	8 (72.7%)	4 (28.6%)	
Year 6	11 (100%)	0 (0%)	0 (0%)	
Other	0 (0%)	3 (27.3%)	7 (50.0%)	
Video Gaming Frequency, n (%)				
Never	2 (18.2%)	0 (0%)	4 (28.6%)	0.10
Occasionally	4 (36.4%)	7 (63.6%)	3 (21.4%)	
Regularly	5 (45.5%)	4 (36.4%)	7 (50.0%)	
Musical Instrument Background, n (%)				
Never played	5 (45.5%)	5 (45.5%)	5 (35.7%)	0.80
Played in past	3 (27.3%)	5 (45.5%)	6 (42.9%)	
Currently plays	3 (27.3%)	1 (9.1%)	3 (21.4%)	
Handedness, n (%)				
Right-handed	11 (100%)	11 (100%)	13 (92.9%)	1.0
Left-handed	0 (0%)	0 (0%)	1 (7.1%)	

Fisher-Freeman-Halton exact test applied (> 77% of cells had expected counts < 5). * p < 0.05.

Task Completion Times

Task completion times are presented in Table 2, 3. All three cohorts demonstrated significant improvement across the four training attempts, with large effect sizes. No significant Group × Time interactions were detected for any task (Peg Transfer: $F(3.79, 125.8) = 0.85$, $p = 0.49$; Circle Cutting: $F(5.14, 169.6) = 0.47$, $p = 0.81$; Intracorporeal Suturing: $F(4.29, 141.7) = 0.80$, $p = 0.54$), indicating that all

three visualization modalities produced parallel learning trajectories with equivalent rates of skill acquisition across the four training attempts. Summarized in Fig. 3.

Peg Transfer.

All three cohorts demonstrated significant reduction in completion time across the four training trials. With sphericity violated ($W = 0.58$, $p = 0.001$); Greenhouse-Geisser applied ($\epsilon = 0.72$). Therefore, (Greenhouse-Geisser: $F(1.89, 62.61) = 78.74$, $p < 0.001$, $\eta^2p = 0.71$), confirming progressive skill acquisition throughout the training period. The Group $\times$ Time interaction was non-significant ($F(3.80, 62.61) = 0.85$, $p = 0.49$, $\eta^2p = 0.05$), confirming that all cohorts improved at comparable rates. Figure 3. A

A significant main effect of visualization cohort was identified ($F(2, 33) = 15.34$, $p < 0.0$, $\eta^2p = 0.48$). Tukey's HSD post-hoc revealed that the Magnifying Box cohort (mean: 153.21 s) completed Peg Transfer tasks significantly faster than both the Laparoscope (222.75 s; $p = 0.01$) and Display Glasses cohorts (272.36 s; $p < 0.001$), while these latter two groups did not differ significantly from one another ($p = 0.10$). Within-cohort completion times improved from T1 to T4 as follows: Laparoscope (234.73 ± 70.56 s to 208.73 ± 66.97 s), Display Glasses (288.36 ± 58.21 s to 259.91 ± 44.80 s), and Magnifying Box (170.21 ± 44.58 s to 139.79 ± 41.19 s). Figure 3. A.

Circle Cutting.

All cohorts demonstrated significant improvement in circle cutting times over the four training trials. Mauchly's Sphericity test was satisfied ($W = 0.40$, $p = 0.13$). and retained ($F(3, 99) = 121.340$, $p < 0.001$, $\eta^2p = 0.79$), with the Group $\times$ Time interaction non-significant ($F(6, 99) = 0.47$, $p = 0.83$, $\eta^2p = 0.03$). A significant between-group main effect was detected ($F(2, 33) = 3.456$, $p = 0.04$, $\eta^2p = 0.17$); however, Tukey's HSD post-hoc analysis did not identify statistically significant pairwise differences between any individual cohort pairing (all $p \geq 0.05$). Figure 3. B. Completion times across the cohorts were 269.59 s (Laparoscope), 287.41 s (Display Glasses), and 217.41 s (Magnifying Box). All cohorts demonstrated progressive improvement from T1 to T4 (Laparoscope: 282.55 ± 74.57 s to 257.09 ± 76.10 s; Display Glasses: 302.36 ± 91.74 s to 274.91 ± 92.28 s; Magnifying Box: 230.50 ± 40.51 s to 203.50 ± 40.61 s).

Table 3

Intracorporeal Suturing.

All cohorts demonstrated significant improvement in suturing completion time over the four training trials (Greenhouse-Geisser: $F(2.14, 70.87) = 99.19$, $p < 0.001$, $\eta^2p = 0.75$), with the Group $\times$ Time interaction again non-significant ($F(4.30, 70.87) = 0.80$, $p = 0.54$, $\eta^2p = 0.05$). The between-group main effect for suturing represented the largest observed across all three tasks ($F(2, 33) = 21.25$, $p < 0.001$, $\eta^2p = 0.56$). Figure 3. C. The Magnifying Box cohort demonstrated lower averaged completion times (267.48 s) compared to the Laparoscope (419.48 s) and Display Glasses (461.39 s) cohorts, and post-hoc analysis confirmed significant superiority of the Magnifying Box group relative to both comparators (Tukey's HSD, both $p < 0.05$). Table 2&3. Figure 3. C.

Table 2
Pairwise Comparisons (Mean Differences, Time (seconds))

Task	Comparison	Mean DIFF	P-value
Peg Transfer	Laparoscope vs Magnifying Box	69.54	0.01**
	Display Glasses vs Magnifying Box	119.15	0.001***
	Laparoscope vs Display Glasses	49.61	0.10
Circle Cutting	All cohorts	52–70	≥ 0.05
Intracorporeal Suturing	Magnifying Box vs Laparoscope	152.00	0.001***
	Magnifying Box vs Display Glasses	193.91	0.001***
	Laparoscope vs Display Glasses	41.91	0.41
** p < 0.01; *** p < 0.001;			

The Laparoscope and Display Glasses cohorts did not differ significantly from one another (p = 0.41). Variance homogeneity was confirmed across all four suturing timepoints (Levene's p = 0.09–0.38). Completion times from T1 to T4 as follows: Laparoscope (437.64 ± 86.48 s to 400.55 ± 83.06 s), Display Glasses (485.18 ± 110.20 s to 440.64 ± 89.80 s), and Magnifying Box (288.64 ± 57.91 s to 250.36 ± 60.38 s) Table 3.

Table 3
Task Completion Times Across Training Attempts (Mean ± SD, seconds)

Peg Transfer				
Group	T1	T2	T3	T4
Laparoscope (n = 11)	234.7 ± 70.6	227.2 ± 69.9	220.4 ± 67.8	208.7 ± 67.0
Display Glasses (n = 11)	288.4 ± 58.2	273.4 ± 47.0	267.8 ± 51.5	259.9 ± 44.8
Magnifying Box (n = 14)	170.2 ± 44.6	155.7 ± 45.1	147.1 ± 44.7	139.8 ± 41.2

Circle Cutting				
Group	T1	T2	T3	T4
Laparoscope (n = 11)	282.6 ± 74.6	272.8 ± 74.0	265.9 ± 79.6	257.1 ± 76.1
Display Glasses (n = 11)	302.4 ± 91.7	289.7 ± 88.4	282.6 ± 89.3	274.9 ± 92.3
Magnifying Box (n = 14)	230.5 ± 40.5	220.1 ± 41.9	215.5 ± 41.5	203.5 ± 40.6

Intracorporeal Suturing				
Group	T1	T2	T3	T4
Laparoscope (n = 11)	437.6 ± 86.5	426.0 ± 85.4	413.7 ± 85.9	400.6 ± 83.1
Display Glasses (n = 11)	485.2 ± 110.2	463.0 ± 87.3	456.7 ± 90.7	440.6 ± 89.8
Magnifying Box (n = 14)	288.6 ± 57.9	272.0 ± 57.8	258.9 ± 61.8	250.4 ± 60.4

GOALS Scores.

GOALS total scores across all three tasks are presented in Table 4 and Fig. 4. All three visualization cohorts demonstrated significant improvements in psychomotor quality from (T₁) through final assessment (T₄) across all tasks confirming that all visualization modalities supported skill development. Wilcoxon signed-rank analysis confirmed significant improvement from T₁ to T₄ within every cohort across all three tasks (all $p \leq 0.05$). Friedman's tests confirmed significant within-group progression for Peg Transfer (Laparoscope: $\chi^2 = 32.73$, $p < 0.001$; Display Glasses: $\chi^2 = 32.73$, $p < 0.001$; Magnifying Box: $\chi^2 = 41.28$, $p < 0.001$), Circle Cutting (Laparoscope: $\chi^2 = 32.73$, $p < 0.001$; Display Glasses: $\chi^2 = 31.80$, $p < 0.001$; Magnifying Box: $\chi^2 = 38.79$, $p < 0.001$), and Intracorporeal Suturing (Laparoscope: $\chi^2 = 32.73$, $p < 0.001$; Display Glasses: $\chi^2 = 32.42$, $p < 0.001$; Magnifying Box: $\chi^2 = 41.48$, $p < 0.001$).

Between-group analysis using Kruskal-Wallis H testing revealed significant differences in GOALS scores across all cohorts at both baseline and endpoint for all tasks. Peg Transfer scores differed at T₁ ($H(2) = 13.02$, $p = 0.001$) and T₄ ($H(2) = 6.03$, $p = 0.05$). Circle Cutting demonstrated between-group differences at T₁ ($H(2) = 16.33$, $p < 0.001$) and T₄ ($H(2) = 10.32$, $p = 0.01$). Suturing showed the largest between-group effect at T₁ ($H(2) = 9.32$, $p = 0.01$) and T₄ ($H(2) = 12.07$, $p = 0.002$).

Post-hoc Mann-Whitney U testing with Bonferroni correction (corrected $\alpha = 0.0028$ for 18 comparisons) revealed a consistent pattern across all tasks and timepoints: the Laparoscope and Display Glasses cohorts did not significantly differ at any measurement point (all pairwise comparisons $p > 0.40$). In contrast, the Magnifying Box cohort demonstrated significantly higher GOALS scores compared to both the Laparoscope group and the Display Glasses group across most comparisons.

Specifically, at Peg Transfer T₁, Magnifying Box scores significantly exceeded both Laparoscope ($U = 16.0$, $p = 0.001$) and Display Glasses ($U = 30.0$, $p = 0.01$); After correction the the difference at T₄, of the Magnifying Box to Display Glasses was ($U = 39.0$, $p = 0.03$) and Laparoscope ($U = 42.5$, $p = 0.05$).

Circle Cutting demonstrated the Magnifying Box cohort had significantly higher GOALS scores than the Laparoscope cohort at both T₁ ($U = 11.0$, $p < 0.001$) and T₄ ($U = 39.5$, $p = 0.03$), and significantly higher than the Display Glasses cohort at both T₁ ($U = 22.0$, $p = 0.002$) and T₄ ($U = 22.0$, $p = 0.002$). The Laparoscope versus Display Glasses comparison did not reach significance at either timepoint (T₁: $U = 50.0$, $p = 0.480$; T₄: $U = 48.0$, $p = 0.403$).

Suturing showed significant Magnifying Box advantages over Laparoscope at both T₁ (U = 18.5, p = 0.001) and T₄ (U = 25.5, p = 0.004), and Display Glasses at T₄ (U = 23.5, p = 0.003), at T₁ (U = 45.5, p = 0.08).

Overall, the Magnifying Box visualization system supported superior technical quality compared to both laparoscope based and -display glasses modalities. Mean Total GOALS scores at T1 and T4 per cohort are detailed in Table 4. Across all tasks and timepoints, the Magnifying Box cohort demonstrated both superior baseline proficiency and greater absolute scores at training completion, though the within-group progression and the partial narrowing of between-group differences by T4 indicate that all visualization modalities supported skill acquisition.

Table 4
GOALS Total Scores by Task, Cohort, and T1 and T4

Group	T1 (Mean ± SD)	T4 (Mean ± SD)	Δ (T4 – T1)
Peg transfer Total GOALS			
Laparoscope (n = 11)	14.09 ± 1.51	22.36 ± 1.86	+ 8.27
Display Glasses (n = 11)	14.73 ± 2.41	22.00 ± 2.53	+ 7.27
Magnifying Box (n = 14)	17.43 ± 1.99	23.79 ± 1.58	+ 6.36
Circle cutting Total GOALS			
Laparoscope (n = 11)	15.00 ± 1.18	23.09 ± 1.51	+ 8.09
Display Glasses (n = 11)	15.55 ± 1.75	22.27 ± 2.01	+ 6.73
Magnifying Box (n = 14)	18.57 ± 2.17	24.36 ± 0.93	+ 5.79
Intracorporeal suturing Total GOALS			
Laparoscope (n = 11)	13.09 ± 1.87	20.64 ± 1.50	+ 7.55
Display Glasses (n = 11)	13.45 ± 2.34	20.18 ± 2.04	+ 6.73
Magnifying Box (n = 14)	15.36 ± 1.08	22.93 ± 1.77	+ 7.57

GOALS scores range from 5 (minimum) to 25 (maximum). Δ = change score (T₄ – T₁). T, training attempt; SD, standard deviation).

ANCOVA (Covariate Analysis)

None of the three covariates predicted performance outcomes across any task or GOALS scores (Gaming: all p > 0.05; Music instrument playing: all p > 0.05; Handedness: all p > 0.05), indicating that pre-existing individual differences in visuospatial abilities were not statistically significant determinants of endpoint performance. Table 5.

Table 5
Covariate significance

Covariate	P-value range	Finding
Video Gaming	0.48 to 0.94	Gaming frequency does NOT predict performance
Musical Training	0.07 to 0.98	Musical background does NOT predict performance ($p = 0.07$)
Handedness	0.21 to 0.74	Handedness does NOT predict performance

Time-Based Outcomes After Covariate Control.

Peg Transfer times differed by visualization modality ($F(2, 30) = 14.48$, $p < 0.001$, $\eta^2p = 0.49$); adjusted pairwise comparisons revealed Magnifying Box was significantly faster than both Laparoscope (mean difference = 66.10 s, $p = 0.01$) and Display Glasses (mean difference = 114.71 s, $p < 0.001$), while Laparoscope and Display Glasses did not differ significantly ($p = 0.11$). Intracorporeal Suturing completion times showed the largest effect ($F(2, 30) = 18.08$, $p < 0.001$, $\eta^2p = 0.55$); Magnifying Box was substantially faster than Laparoscope (mean difference = 145.36 s, $p < 0.001$) and Display Glasses (mean difference = 186.71 s, $p < 0.001$), with no difference between laparoscope and wearable display glass ($p = 0.70$). Circle Cutting times did not reach statistical significance after adjustment ($F(2, 30) = 2.67$, $p = 0.09$, $\eta^2p = 0.15$). Figure 3. Left panel A - C

GOALS Quality Outcomes After Covariate Control.

Peg Transfer GOALS scores did not differ across visualization cohorts ($F(2, 30) = 1.93$, $p = 0.16$, $\eta^2p = 0.11$). Circle Cutting GOALS scores differed significantly ($F(2, 30) = 4.69$, $p = 0.02$, $\eta^2p = 0.24$), with Magnifying Box (adjusted mean = 24.25) significantly superior to Display Glasses (adjusted mean = 22.40, $p = 0.02$), but not significantly different from Laparoscope (adjusted mean = 23.10, $p = 0.20$). Intracorporeal Suturing GOALS scores demonstrated significant group differences ($F(2, 30) = 7.02$, $p = 0.003$, $\eta^2p = 0.32$), with Magnifying Box (adjusted mean = 22.84) significantly higher than both Laparoscope (adjusted mean = 20.69, $p = 0.02$) and Display Glasses (adjusted mean = 20.24, $p = 0.005$). Figure 4. Left panel A - C. Overall, covariate adjustment did not change conclusions regarding visualization system effects. The persistence of significant Group effects after controlling for gaming experience and musical background provides evidence that these outcomes are driven by the visualization intervention rather than pre-existing individual differences in visuospatial abilities or motor skill conditioning.

Discussion

Standardized curricula for laparoscopic training outside the operating room are still being established; with an outright universal curriculum still not decided (29). This study demonstrated that a simple, low-cost optical system outperformed expensive technological alternatives. The Magnifying Box cohort achieved significantly superior task completion times across all three tasks: completing Peg Transfer

69–119 seconds faster than both Laparoscope and Display Glasses cohorts, Circle Cutting 52–70 seconds faster, and Intracorporeal Suturing 152–194 seconds faster. Beyond operational efficiency, technical quality assessed by GOALS scores was also consistently higher in the Magnifying Box cohort at endpoint across all tasks. Although the phrase "you get what you pay for" often applies, it does not necessarily hold true in this simulation. Aligning with previous studies on low-cost models that have demonstrated improved ability without negatively affecting training quality compared to high-cost models (30).

The superiority of the magnifying box suggests that for fundamental laparoscopic skills the magnifying box eliminates the spatial transformations like the fulcrum effect and spatial offset inherent in monitor-based systems, reducing extraneous cognitive demands and allowing learners to focus on intrinsic task features (31). The progressive skill automation in our cohorts reflected in decreasing completion times likely represents this cognitive load reduction. The system provides direct, unmediated visualization without the layered spatial mappings required when viewing an external monitor, potentially optimizing attention allocation to critical surgical movements, corroborating studies by Pagano et. al. (11, 32). The magnifying box, validated in principle by prior work on low-cost models (27), represents an evolution in accessibility, providing necessary instructional fidelity while optimizing the learner's attention allocation toward intrinsic task features rather than overcoming the spatial mapping required by external monitors.

Despite the endpoint performance differences, all three visualization modalities produced parallel learning trajectories with no significant Group $\times$ Time interactions (Peg Transfer $p = 0.49$, Circle Cutting $p = 0.81$, Intracorporeal Suturing $p = 0.54$). This finding is noteworthy because it demonstrates that the rate of skill acquisition improvement from T_1 to T_4 was equivalent across all cohorts. All three groups showed significant within-group improvement over the four training attempts ($p < 0.001$ for all comparisons), indicating that the fundamental mechanism of learning operates independently of visualization modality. This suggests that practice structure and feedback consistency, rather than technological complexity, are the primary drivers of skill improvement (26).

Notably, the Laparoscope and Display Glasses cohorts did not significantly differ from each other on any outcome measure (all pairwise comparisons $p > 0.40$), despite their fundamental differences in visualization approach. The traditional tower-based system and wearable display system achieved equivalent endpoint performance in both task completion times and technical quality. The wearable display system, despite theoretical advantages of first-person perspective and elimination of spatial offset, did not outperform the traditional laparoscopic tower. We hypothesized this may be due to the novelty of wearable display technology requiring extended adaptation periods before performance advantages emerge, or limitations in current display resolution and field-of-view for fine motor tasks. As Lee K. et.al. reported significant user challenges, including visual fatigue, dizziness, and altered color contrast when evaluating wearable displays in endoscopy (25). Alternatively, the uniform absence of haptic feedback across all three modalities may disproportionately disadvantage the wearable display system, as standardized training guidelines emphasize that force control and sensory feedback are essential components to minimize complications and foster technical precision (16). The equivalence of

these two expensive systems suggests that for early-stage surgical training, the specific technological approach (external monitor vs. wearable display) is less important than the fundamental visualization principles it provides.

The Magnifying Box cohort demonstrated significantly higher baseline GOALS scores at T_1 across all three tasks, suggesting superior entry-level proficiency or enhanced initial advantage conferred by the magnifying system's visualization characteristics. This baseline advantage persisted at T_4 , with adjusted mean differences remaining statistically significant after covariate control. Importantly, this baseline advantage was not attributable to pre-existing visuospatial abilities, as video gaming frequency, musical training background, and handedness did not significantly predict endpoint performance across any cohort (all $p > 0.21$). This finding indicates that the observed performance differences are attributable to visualization modality itself rather than confounded by individual baseline characteristics. The non-significance of gaming experience and musical training is particularly notable, as prior research has suggested these factors may enhance visuospatial and motor skills though recent evidence indicates that learners with non-spatial cognitive profiles can achieve equivalent proficiency when provided with structured, feedback-rich training environments (16). That we did not detect these effects across outcome measures suggests that visualization modality exerts a sufficiently strong influence to overcome potential advantages from baseline individual differences. Corroborated by Lee K. et. al. who reported prior familiarity with smart devices did not translate to improved adaptation or performance with wearable clinical displays in their study (25).

From a global health perspective, our findings have substantial implications for global surgical education and training equity. Surgical training in resource-limited settings is constrained by equipment cost, infrastructure requirements (electrical power, maintenance, technical support), and physical accessibility (30). This is especially pertinent in the Chinese context, where resource disparities across regions necessitate accessible training solutions (11, 33). As well as in sub-Saharan nations like Kenya and Mali, where surgical skills acquisition is frequently hindered by high equipment burdens and a heavy reliance on international donations (34). In these environments, trainees often lack access to commercial simulators. A magnifying box system costing \$100–500 USD, requiring no electricity, and occupying minimal space could substantially expand training access compared to laparoscopic towers costing \$50,000–100,000 USD. The portability of the magnifying box enables distributed training models, including remote surgical education in rural and underserved areas where expensive simulation equipment is inaccessible (35, 36). Furthermore, If low-cost alternatives produce equivalent or superior skill acquisition on validated assessment scales (GOALS, FLS completion criteria), then the justification for high-cost institutional simulators becomes questionable, potentially redirecting resources toward more comprehensive training programs or broader trainee access in settings with constrained budgets. Studies evaluating basic laparoscopic curricula have demonstrated that simple, task-based environments can discriminate between experience levels and facilitate progressive skill acquisition, even when constructed from inexpensive materials (36–40).

However, several limitations must be acknowledged. The single-institution design with convenience sampling of surgical novices limits generalizability to other training environments, experience levels, or geographic regions. The study population comprised surgical novices (medical students and non-surgical junior interns), which may limit generalizability to resident training, and the heterogeneous academic standing within the Magnifying Box cohort represents a potential confounding variable that was not statistically controlled. The 4-week training period may be insufficient to detect long-term effects or to allow learning curves to fully plateau; extended training might reveal whether initial advantages persist, narrow, or reverse. The study examined only three specific FLS tasks; findings may not generalize to other laparoscopic procedures with different spatial, temporal, or tactile demands. Additionally, all our assessment, while rigorous, was conducted in a simulated setting and did not measure performance under the real-world pressures of the operating room. Finally, the study did not assess skill transfer to operative room settings or long-term skill retention, limiting conclusions about clinical applicability.

The findings from this study point toward clear future directions. Broader adoption of cost-effective, high fidelity training models is warranted. Our curriculum design follows the philosophy of deliberate repetition and progressive task complexity, a framework established as effective for long-term skill retention in surgical education reported by Rodrigo et.al. (26). Future research should address several critical questions. Extended training studies (8–12 weeks or longer) would determine whether performance advantages persist or converge over time and whether learning curves ultimately plateau at equivalent levels. Assessment of transfer to operative room settings is essential for establishing whether simulation gains translate to superior intraoperative performance. Research examining more complex procedures with varying cognitive and motor demands could clarify whether findings generalize beyond the three FLS tasks. Integration of haptic feedback into the magnifying box or wearable display systems could potentially enhance performance and may be particularly important for tissue handling and dissection tasks. Finally, formal health economic analyses comparing cost per competency achieved would inform institutional decision-making and help justify investment in low-cost alternatives over expensive institutional simulators.

Conclusion

This study demonstrates that low-cost, mechanically simple laparoscopic visualization systems can achieve superior or equivalent skill acquisition compared to substantially more expensive, technologically complex alternatives. The magnifying box system produced both superior endpoint performance and lower total costs, suggesting that expensive technology does not necessarily translate to superior surgical education outcomes. These findings have important implications for making surgical training more accessible globally, particularly in resource-limited settings. The equivalent learning rates across modalities underscore that practice structure and feedback not visualization technology are the primary drivers of skill acquisition in early surgical training.

Declarations

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Author Contributions

Study conception and design: ZW, KD, JM; Acquisition of data: KD, OWZ; Analysis and interpretation of data: SMA, KD; Drafting of manuscript: KD,QM,QC ; Critical revision: ZW, JM, KYB; Statistical expertise: SMA, KD, JJB; Visualization and graphics: BFT, RN; Obtaining funding: JM, ZW; Supervision: ZW, KD, JM.

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Consent to Publish declaration

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Disclosures

Ketrine Desdery,Sidney Moses Amadi, Osama Wali Zada, Chen Qinmo , Qiutong Man ,Kyei Yaw Baffour,Jenifa Jacob Bunyese, Barnieh Frank Tachie, Zhifei Wang, Jinlei Mao declare no conflict of interest, and have no relevant financial or non-financial interests to disclose.

Informed Consent: Signed informed consent was provided for each participant prior to the begin of the study.

Ethical approval: The study was reviewed and approved by the Ethics Committee of Zhejiang Provincial People's Hospital IRB number: KT2026113, in accordance with the Helsinki Declaration.

Availability of data and materials

The data supporting the conclusions of this article are available from the corresponding author on request.

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Figures

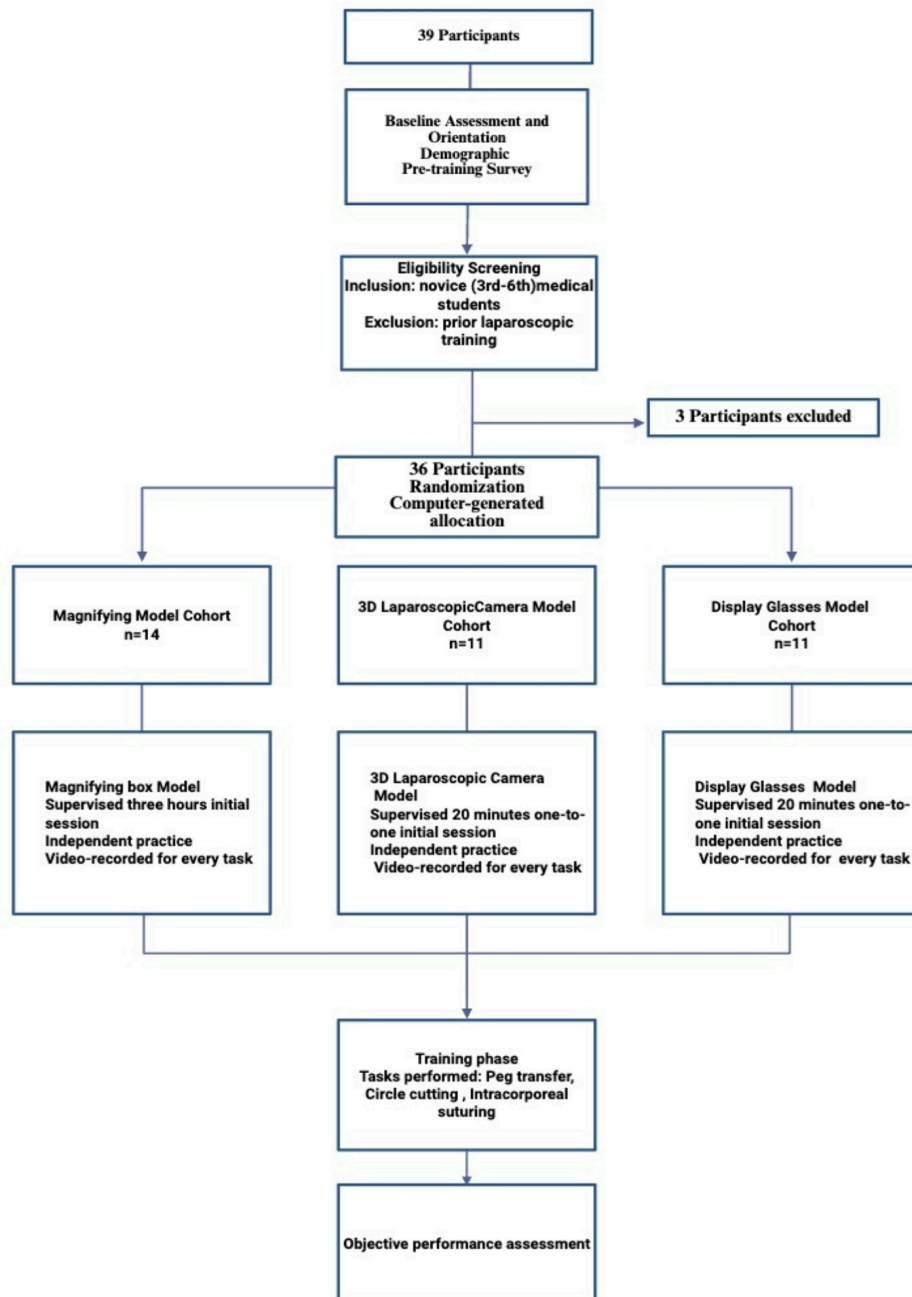


Figure 1

Study flowchart

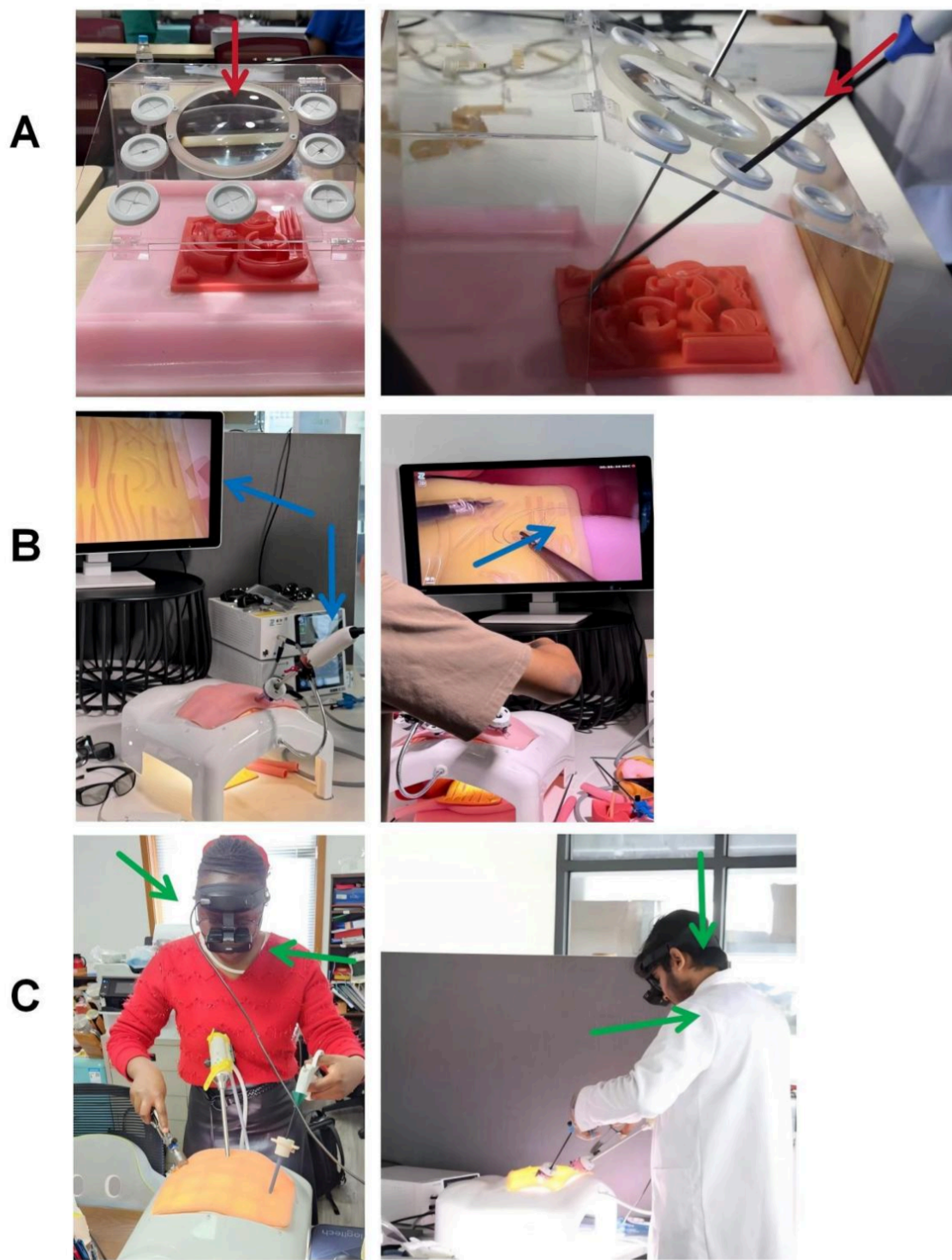


Figure 2

A. Magnifying Box platform with arrows indicating the display view. **B.** Standard Laparoscope model with arrows indicating the video display on screen. **C.** Visual Display-Glasses modal with arrows indicating the first-person-view glasses.

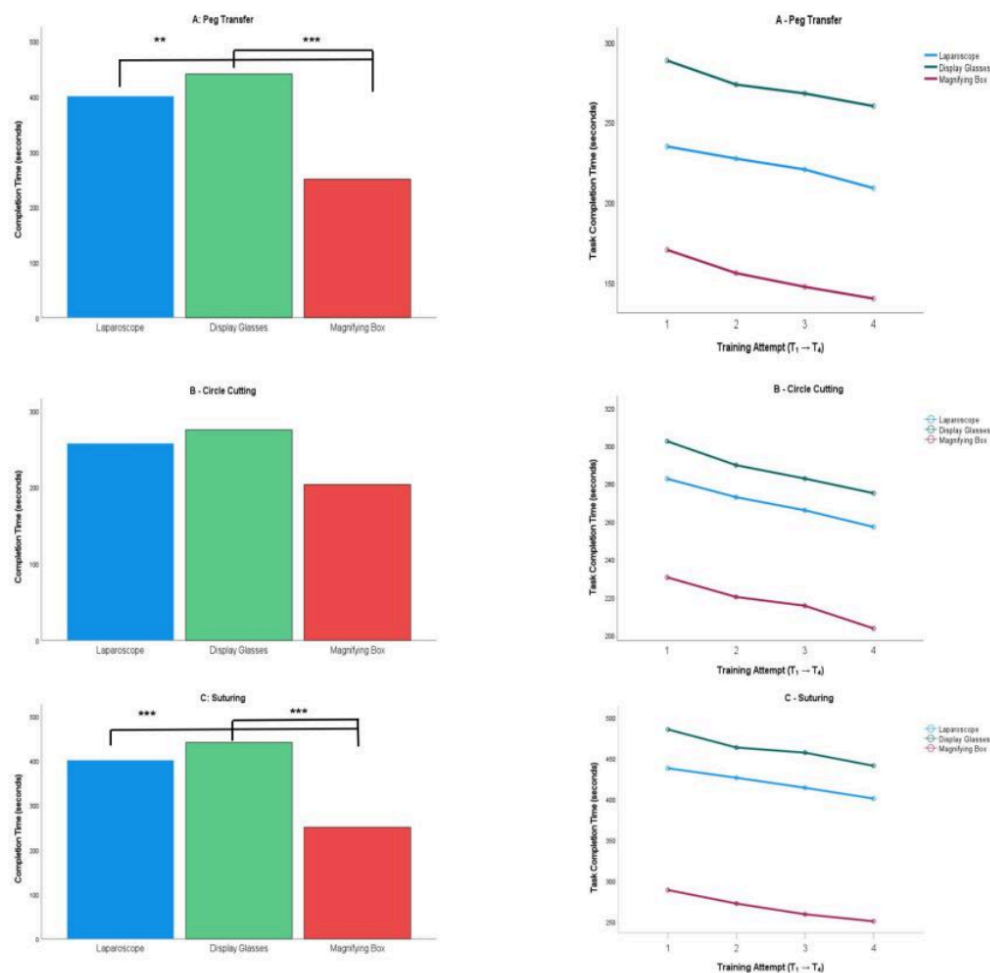


Figure 3

Task completion times across visualization cohorts during laparoscopic training simulation. Left panels display mean task completion time at the final training attempt (T4) after covariate adjustment. Right panels display mean ($\pm$ SE) task completion time across all training attempts (T1–T4). **A.** Peg Transfer; **B.** Circle Cutting; **C.** Intracorporeal Suturing. Brackets denote statistically significant pairwise comparisons between cohorts at T4. $p < 0.05$; * $p < 0.01$; ** $p < 0.001$; ***. SE, standard error of the mean.

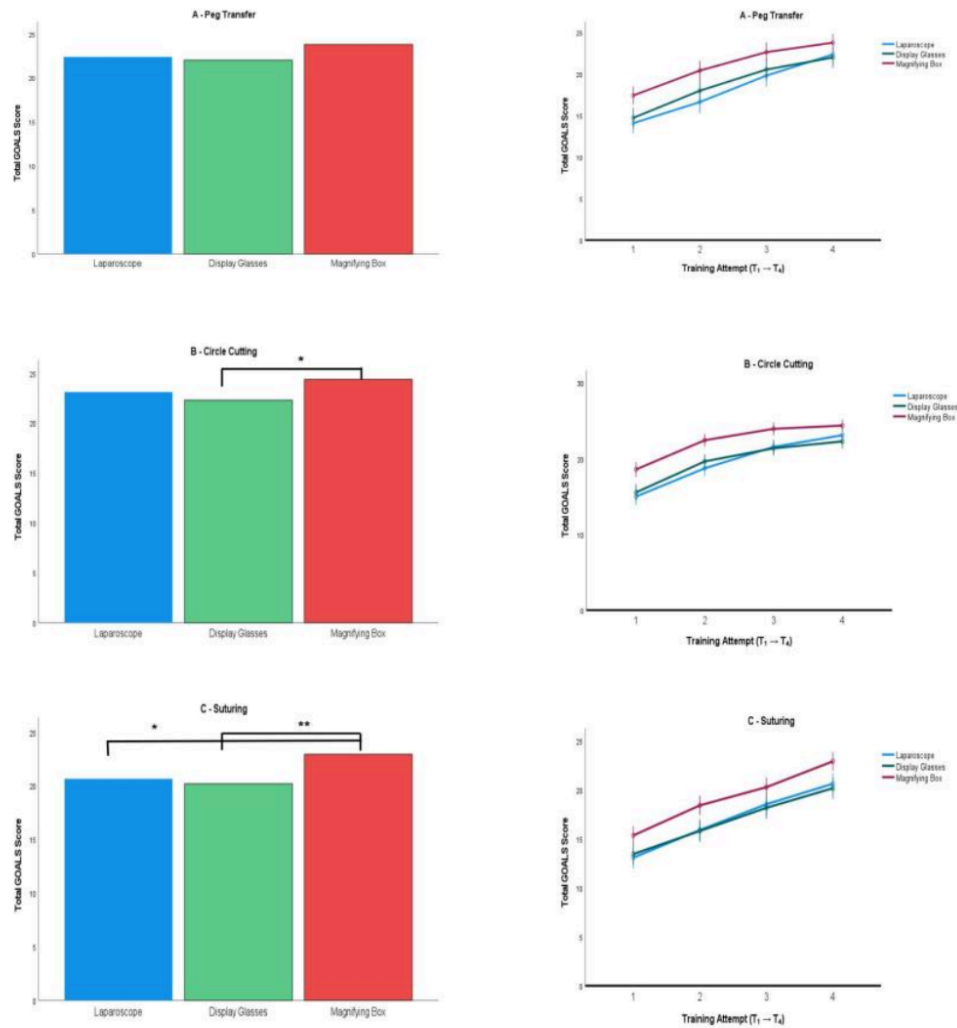


Figure 4

Total GOALS scores across cohorts during training simulation. Left panels display mean GOALS score at the final attempt (T4); maximum score = 25 points. Right panels display mean ($\pm$ SE) Total GOALS scores across all training attempts (T1–T4) after covariate adjustment. **A.** Peg Transfer; **B.** Circle Cutting; **C.** Intracorporeal Suturing. Brackets denote pairwise comparisons. * $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$. SE, standard error of the mean.

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