2026 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)

2026 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) | 979-8-3195-0529-3/26/$31.00 ©2026 IEEE | DOI: 10.1109/VRW70859.2026.00173

Simulating End-to-End Hand-Sewn and Stapled Anastomosis in a Virtual Colorectal Surgical Trainer

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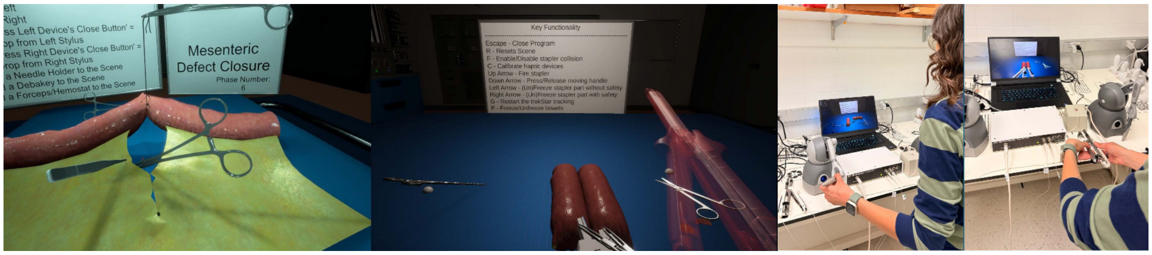

Figure 1: VCoST simulates both end-to-end hand-sewn and linear stapled colorectal anastomosis in an immersive physics-based VR environment. Left: completed hand-sewn anastomosis with circumferential suturing. Center: tracked physical linear stapler aligned with deformable bowel during firing. Right: user performing the procedure inside the VCoST system.

ABSTRACT

Open colorectal anastomosis remains difficult to support in virtual reality due to the need for unconstrained bimanual interaction and realistic soft-tissue behavior. We present the Virtual Colorectal Surgical Trainer (VCoST), a unified physics-based VR framework supporting both end-to-end hand-sewn anastomosis (VCoST-ETEHSA) and linear stapled anastomosis (VCoST-LSA). The system integrates deformable bowel models, phase-based procedural control, tracked instruments, and continuous performance logging. We evaluated VCoST-LSA with 24 participants (12 experts, 12 novices). Total rubric scores did not differ significantly between groups, though experts received higher scores, completed the task faster, and showed improved early bowel stabilization. Workload ratings indicated generally low-to-moderate perceived workload across subscales. While univariate kinematic metrics were not significant, multivariate analysis suggested dominant variability related to motion smoothness. Taken together, these findings suggest that VCoST-LSA captures complementary process-level kinematic signals that complement aggregate rubric scores; however, this initial study does not establish construct validity and motivates larger, confirmatory evaluations.

Index Terms: Virtual Reality, Surgical Simulator, Colorectal surgery.

1 INTRODUCTION

Colorectal cancer is the third most common cancer type in the world [11, 6]. It is the second leading cause of cancer-related death worldwide [18, 17]. In 2020, approximately 1.9 million new cases and 935,000 deaths were reported globally, accounting for nearly 10% of all cancer incidence and about 9–10% of cancer-related mortality [32, 24]. Surgical resection of the affected bowel, followed by the restoration of intestinal continuity through colorectal anastomosis remains the cornerstone of curative treatment for patients with localized colorectal cancer [10, 17]. Anastomotic integrity is critical, as failure at the anastomotic site can lead to serious complications, including anastomotic leak, increased morbidity, and prolonged hospital stays [23, 20]. Reported clinical leak rates range from approximately 3% to 19%, with associated mortality estimates between 6% and 22% [2]. Beyond early morbidity and mortality, anastomotic leakage has been linked to inferior long-term oncologic outcomes and significantly reduced postoperative quality of life [12, 8]. Consequently, ensuring a secure, well-perfused, and tension-free anastomosis is essential for optimizing both short- and long-term patient outcomes [15].

Two of the primary techniques used to construct colorectal anastomoses are traditional hand-sewn suturing and linear stapling. Extensive evidence indicates that, when performed appropriately, both techniques can achieve comparable leak rates and similar overall clinical outcomes [14, 31]. In routine practice, surgeons select between hand-sewn and stapled anastomoses based on intraoperative findings, anatomic constraints, and surgeon experience. Stapling devices are widely used because they provide efficiency and technical consistency, particularly in deep pelvic operations. However, mastery of hand-sewn anastomosis remains an essential compe-

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DOI 10.1109/VRW70859.2026.00173

tency for colorectal surgeons [33]. Situations such as narrow pelvic anatomy, unusual defect geometry, severe contamination, or stapler malfunction may preclude stapler use, requiring the surgeon to rely on suturing technique [15]. For this reason, colorectal training curricula must cultivate proficiency in both hand-sewn and stapled anastomosis to ensure that surgeons can safely adapt to a wide range of operative scenarios.

Beyond performing an anastomosis safely, surgeons must also demonstrate measurable technical competence. Documenting the importance of objectively assessing technical skill in colorectal surgery, the American Board of Colon and Rectal Surgery introduced the Colorectal Objective Structured Assessment of Technical Skill (COSATS) examination [3, 4]. COSATS is a multi-station, hands-on practical examination in which surgeons perform simulated colorectal procedures, including bowel anastomoses, under evaluation by expert examiners. COSATS-based analysis show that both hand-sewn and stapled anastomoses require proficiency across multiple domains, including tissue handling, needle or stapler control, procedural flow, and avoidance of technical errors [16, 28, 25]. These findings show the need for targeted, procedure-specific training environments that allow repeated practice and objective feedback.

Traditional surgical training for colorectal anastomosis relies heavily on operating room exposure, animal models, cadaver tissue, and physical box trainers. While these approaches remain valuable, they are limited by cost, availability, ethical considerations, and variability in training opportunities. As a result, simulation-based training has emerged as an essential component of modern surgical education, addressing limitations in access, cost, and consistency inherent to traditional training models [29, 9]. Physical simulators have demonstrated effectiveness for foundational technical skills, and virtual reality (VR)–based simulators have further extended these capabilities by enabling immersive interaction and automated performance tracking [21, 5, 30]. However, translating COSATS tasks to VR remains challenging because colorectal anastomosis is primarily an open surgical procedure. It requires unrestricted bimanual interaction and realistic soft-tissue handling that are difficult to capture in existing VR simulators.

To address these challenges and support the objectives of structured technical skill assessment frameworks such as COSATS, increasing attention has been directed toward simulation-based training and assessment using VR platforms. Simulation-based training has been shown to improve technical performance and accelerate skill acquisition across surgical disciplines [1]. In particular, VR simulators allow for repeatable task execution, automated data collection, and objective performance metrics that align closely with COSATS requirements. Recent work has demonstrated the construct validity of VR-based colorectal anastomosis simulators with complementary studies focusing on objective metrics for stapled anastomosis. Sankaranarayanan et al. [25] developed and validated step-specific performance metrics for a linear stapler-based small bowel anastomosis, showing discrimination between expert and novice surgeons in simulated settings. Similar metric-driven approaches have also been explored for hand-sewn anastomosis tasks [26].

Despite these advances, existing simulation platforms have largely addressed individual techniques or isolated subtasks, rather than the full spectrum of anastomotic skills required of colorectal surgeons. Many commercial simulators emphasize laparoscopic or endoscopic procedures, while open colorectal anastomosis techniques remain underrepresented [19]. Until recently, there was no virtual simulator capable of modeling the complex process of intestinal anastomosis, which requires realistic cutting, suturing or stapling, and deformation of soft tissue. Only in the past few years have physics-based approaches begun to emerge. Qi et al. [22] introduced a VR framework for simulating a side-to-side stapled intestinal anastomosis, representing the first physics-based virtual anastomosis model reported in the literature. Garces-Palacios et al. reported construct validity for a VR ileal pouch–anal anastomosis simulator [7]. In another study, Westergaard et al. [34] presented a high-fidelity virtual reality simulator for straight coloanal anastomosis that integrates VR, haptic feedback, and objective performance metrics derived from hierarchical task analysis and expert consensus. Their validation study with 16 participants, showed that expert surgeons (n = 7) outperformed novices (n = 9) by approximately 8.5% on total performance scores (93.65% vs. 85.18%, p = 0.0041) and demonstrated smoother hand motions, with about 3.6% lower jerk and 5.2% lower acceleration. Collectively, these developments show the promise of simulation-based anastomosis training and the absence of comprehensive platforms for open colorectal anastomosis.

The contributions of this work are threefold. First, we introduce two novel immersive simulators: Virtual Colorectal Surgical Trainer (VCoST) end-to-end hand-sewn anastomosis (VCoST-ETEHSA) and linear stapled anastomosis (VCoST-LSA) simulators within a unified training framework. Then, we present results from a user study evaluating VCoST-LSA. While a formal user study for VCoST-ETEHSA is beyond the scope, its inclusion demonstrates the extensibility of the proposed framework (see Fig. 1) and establishes a foundation for future validation and skill assessment studies.

2 METHODS

2.1 Framework

VCoST is an immersive framework designed to simulate colorectal anastomosis procedures. The framework (see Fig. 2) has three prominent components: i) Interface Devices, ii) Simulation Framework Stack, and iii) Objective Assessment. The framework follows a modular architecture that separates procedural logic, deformable tissue simulation, instrument interaction, and assessment. This allows for multiple anastomosis techniques to be supported within a unified environment.

At the core of the framework is a real-time simulation engine responsible for synchronizing user input from the input devices, physics updates, and rendering. Deformable colon tissue is represented using a physics-based soft-tissue model that supports grasping, traction, cutting, suturing, and stapling while maintaining interactive frame rates. For the colon and suture thread representations, we used eXtended Position Based Dynamics (XPBD) [13] due to XPBD providing stable, real-time simulation of deformable soft tissue with explicit constraint control with consistent stiffness behavior independent of time step size [35]. Tool–tissue interactions are handled through collision detection and constraint-based coupling between instrument geometries and tissue elements, allowing

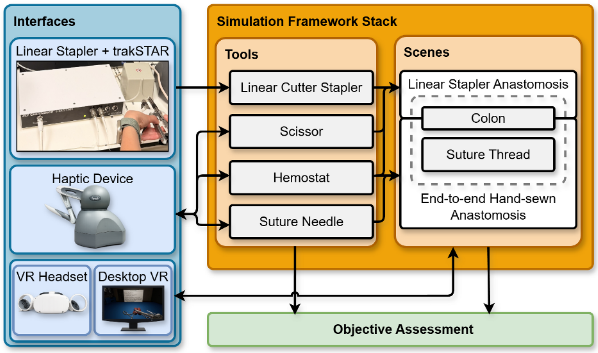

Figure 2: Overall architecture of VCoST, showing interface devices, objective assessment module, and the simulation framework stack comprising shared surgical tools and two procedural training modules (VCoST-ETEHSA and VCoST-LSA).

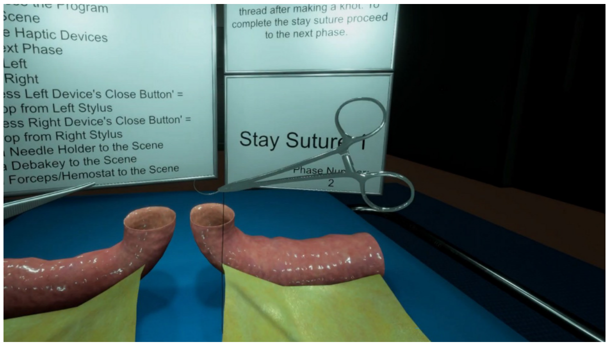

Figure 3: Initial setup of two transected bowel ends positioned for an end-to-end hand-sewn anastomosis in VCoST-ETEHSA.

localized deformation and controlled manipulation.

Procedural execution is structured using a phase-based workflow derived from hierarchical task analysis for ETEHSA [26] and LSA [25]. Each module progresses through predefined phases that reflect clinically correct steps of the procedure. Phase information is used to control tool availability, constrain invalid actions, and segment interaction data. This structure aligns with prior VR surgical simulation frameworks that emphasize task decomposition and state-based control for reproducibility and assessment [34, 27].

User interaction is achieved through a head-mounted display providing stereoscopic visualization and six-degrees-of-freedom tracking, combined with tracked hand-held devices for bimanual instrument control. For VCoST-ETEHSA, two 3D Systems Touch haptic devices (3D Systems, Rock Hill, SC) are used to provide six-degree-of-freedom input with three-degree-of-freedom force feedback during needle driving and tissue manipulation. For VCoST-LSA, alongside the two haptic devices, a tracked physical linear stapler is used, providing explicit control over jaw opening, closure, and firing. Only for VCoST-LSA, due to using two separate interfaces, we have opted to use a desktop VR rather than an immersive head mounted display (HMD) VR. Instrument pose tracking is performed using a 3D Guidance trakSTAR electromagnetic tracking system (NDI, Ontario, Canada) with a mid-range transmitter, providing accurate and low-latency six-degree-of-freedom tracking of the linear stapler pose for real-time mapping into the virtual simulation. Throughout each session, the framework records time-stamped interaction data, including instrument trajectories, tissue contact events, procedural transitions, and task completion times, and provides objective analysis of performance.

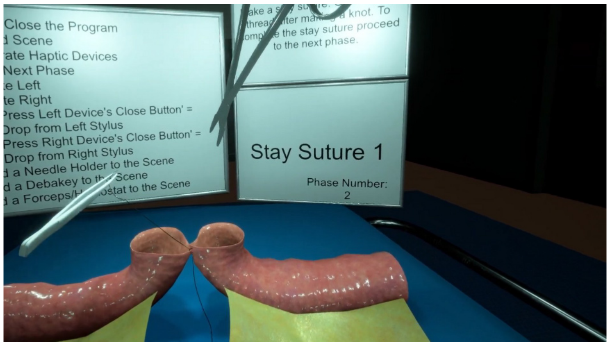

Figure 4: Placement of the first stay suture to align the bowel ends and establish lumen-to-lumen correspondence.

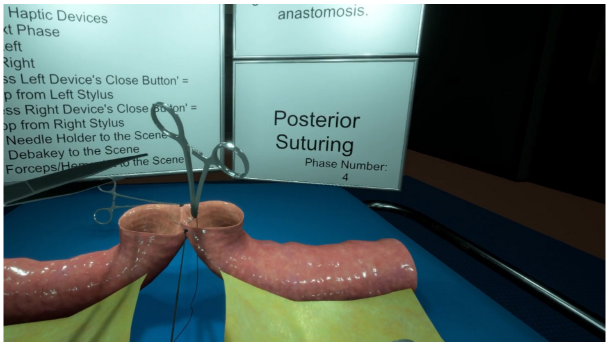

Figure 5: Posterior wall suturing phase showing needle driving and progressive approximation of the bowel edges.

2.2 End-To-End Hand-sewn Anastomosis

VCoST-ETEHSA simulates an end-to-end hand-sewn anastomosis (ETEHSA) as an open colorectal procedure, consistent with COSATS task definitions and implemented within the VCoST environment. The simulation begins with two transected bowel ends positioned for anastomosis and stabilized to maintain exposure and orientation. Tissue stabilization reflects the use of hemostatic control to limit excessive motion during suturing. The initial configuration of the transected bowel segments is shown in Fig. 3.

The procedure follows the sequence implemented in the simulator. Initial stay sutures are placed to align the bowel ends and establish lumen-to-lumen correspondence (see Fig. 4). These sutures serve both as alignment aids and as anchoring points for subsequent circumferential closure. The user then performs suturing along the posterior wall of the anastomosis, driving the needle through both bowel ends, advancing the suture material, and tightening each stitch to approximate tissue (see Fig. 5). After completion of the posterior wall, suturing proceeds along the anterior wall to close the remaining opening and complete the anastomotic ring.

Needle insertion and exit points are detected in real time, and sutures are instantiated dynamically based on these interactions. Thread advancement and tightening apply tension that incrementally brings the bowel ends together. Knot tying is represented as a locking operation that constrains the suture once sufficient tension has been applied, preventing unphysical relaxation. Throughout the procedure, the user must coordinate tissue handling and needle driving using bimanual control, consistent with the open hand-sewn technique implemented in the simulator. The completed hand-sewn anastomosis and final leak inspection are shown in Fig. 6.

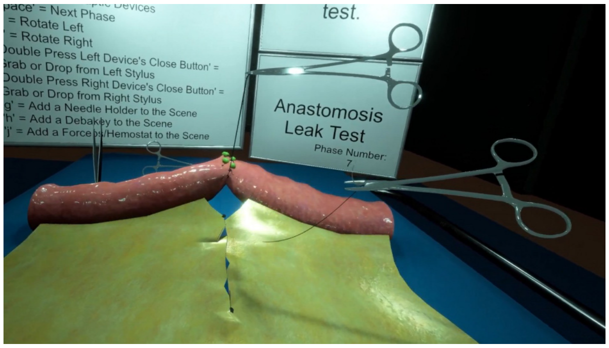

Figure 6: Final inspection and leak testing of the completed end-to-end hand-sewn anastomosis.

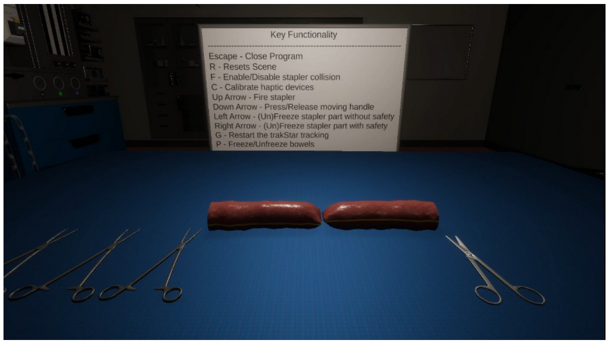

Figure 7: VCoST-LSA initial setup.

2.3 Linear Stapler Anastomosis

VCoST-LSA simulates linear stapler anastomosis (LSA) using a virtual linear stapling device, following the procedural sequence implemented in the simulator. Bowel segments are positioned to allow formation of the anastomosis, and the user manipulates the stapler and auxiliary instruments to align tissue and insert the stapler jaws. The initial setup of the bowel segments for stapled anastomosis is shown in Fig. 7.

The procedure begins with positioning and stabilization of the bowel to permit stapler access (see Fig. 8). The user introduces the stapler jaws into the bowel opening and aligns the tissue along the intended staple line. Jaw closure captures tissue between the stapler arms, and the simulator enforces alignment constraints to prevent firing under invalid configurations (see Fig. 9). Upon firing, the simulator generates a staple line and cut by modifying tissue connectivity within the deformable bowel model, representing creation of the anastomosis (see Fig. 10).

Following firing, the user inspects the stapled region and proceeds to close the common opening as implemented in the simulator workflow. Instrument control includes explicit state transitions for jaw opening, closing, and firing, as well as tracking calibration steps required to maintain spatial accuracy of the stapler. Tissue motion may be temporarily constrained during critical steps to ensure reproducible interaction and consistent task execution across users.

2.4 Case Study: VCoST-LSA

We carried out an Institutional Review Board (IRB) approved user study (IRB# STU-2021–0202) for VCoST-LSA at the University of Texas Southwestern Medical Center. General surgery residents from all postgraduate years (PGY) and expert colorectal surgeons were recruited to perform an LSA using the VCoST simulator as seen in Fig. 11.

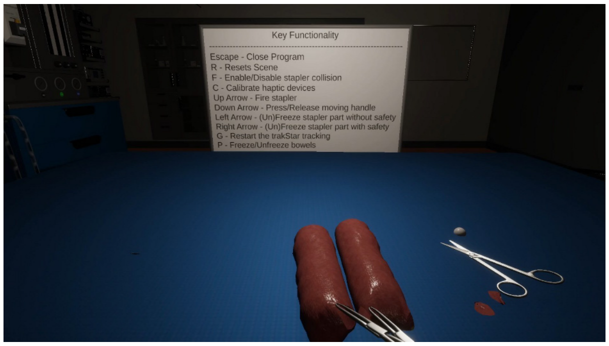

Figure 8: Bowel segments after enterotomy creation, showing the prepared openings for stapler insertion.

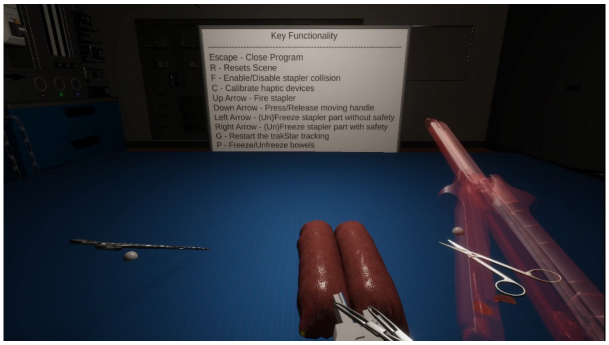

Figure 9: Stapler insertion and alignment prior to firing (translucent overlay indicates tracked stapler pose).

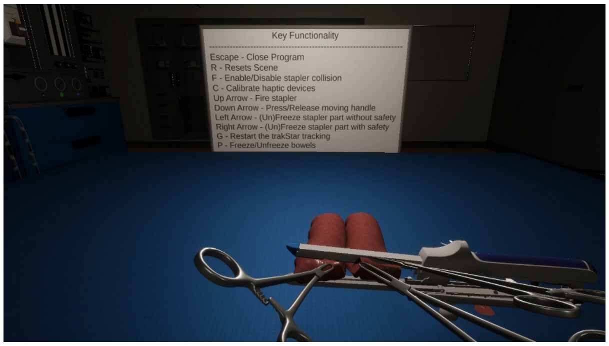

Figure 10: Stapler closure and firing step creating the staple line and dividing the tissue to form the anastomosis.

Participants recruited for the study completed a pre-questionnaire that assessed their experience in the task and exposure to simulation. They then proceeded to complete the task after which they filled in a post-questionnaire that assessed their perception of the simulator that included perceived realism of the anatomy, quality of the model and textures, interface design, and the usefulness of force feedback and the task, and the NASA-TLX questionnaire that assessed their task load.

The simulator automatically records the performance based on ten metric items (as seen in Table 1) and a total score. Each rubric item represents a procedural milestone derived from the task sequence implemented in the simulator. Each performance metric is automatically calculated. Successful completion of the corresponding procedural step is assigned a fixed score of 5, competent completion receives a score of 3, and failure to complete the step results in a score of 0. As a result, total rubric scores primarily reflect procedural success across milestones rather than fine-grained differences in technical execution. Additionally, task completion time and the path length of the left and right haptic devices was also recorded for analysis.

For this study, the participants were divided into novice group (PGY 1–2) and expert group (PGY 3–5, Fellows and attendings). Difference in group performance were assessed using Mann-Whitney U test and effect sizes are reported using Cliff's delta (δ).

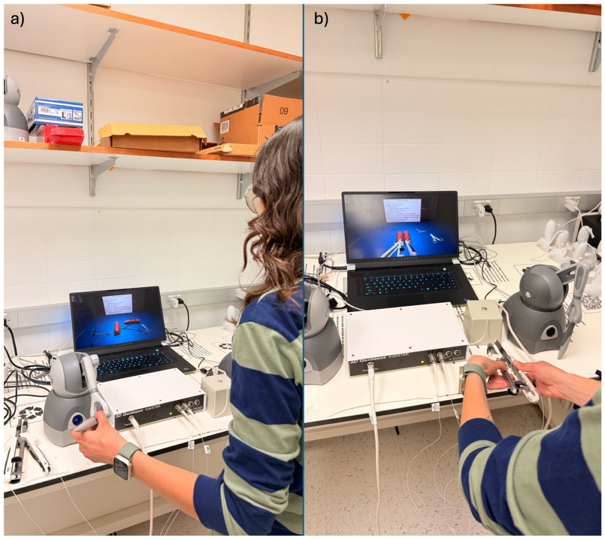

Figure 11: Surgery resident performing tasks during the VCoST-LSA user study: a) enterotomy creation using a haptic interface and b) stapler insertion using the integrated tracked physical linear stapler.

Table 1: Rubric metric items used to score performance in the VCoST-LSA task.

Metric	Description
Metric 1	Secure Enterotomy Point
Metric 2	Open Enterotomy Point
Metric 3	Grasp Enterotomy Point on Intestine
Metric 4	Insert Stapler into Enterotomies
Metric 5	Alignment of Antimesenteric Sides
Metric 6	Open and Remove Stapler
Metric 7	Clamp Transverse Opening
Metric 8	Stapler Across Transverse Opening
Metric 9	Cut Zone
Metric 10	Close Stapler

3 RESULTS

3.1 Rubric-based Performance Outcomes

A total of 29 participants consented to participate and completed the LSA on the simulator. Data from five participants were excluded due to data corruption resulting from logging failures during simulator execution. These exclusions were identified prior to analysis and were unrelated to participant expertise level or task performance. This resulted in a final cohort of 24 participants divided equally between the two groups ($n = 12$). Expert surgeons achieved a higher median total performance score than novices (median 28 vs. 25) and demonstrated superior performance in early procedural steps, particularly stabilization of the bowel prior to enterotomy creation (Metric #1: median 3 vs. 0) but the differences were not statistically significant between groups ($p = 0.483$ and $\delta = 0.18$). The total score distribution among the expert and novice surgeons can be seen in Fig. 12 and per-metric results can be seen in Table 2. Expert participants also completed the procedure more efficiently, with a mean task completion time approximately 42 seconds shorter than that of novice participants (median 745.653 vs. 633.447 seconds) and the differences were not statistically significant between groups again with ($p = 0.58$ and $\delta = -0.14$). Because the rubric encodes discrete procedural completion rather than graded execution quality, total score differences primarily reflect milestone attainment rather than fine-grained variations in technical performance.

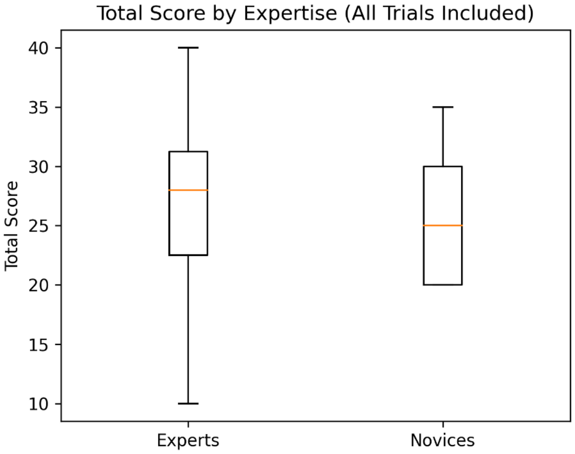

Figure 12: Total score distribution by expertise level for the VCoST-LSA study ($n = 12$ per group). Boxes indicate interquartile range with median; whiskers indicate range.

Table 2: Rubric item scores (median) by expertise group ($n = 12$ per group). Two-sided Mann–Whitney U tests and effect size reported as Cliff's δ (expert vs. novice).

Metric #	Expert	Novice	p	δ
Metric 1	3.0	0.0	0.189	0.33
Metric 2	1.0	1.0	0.483	0.19
Metric 3	0.0	0.0	0.942	0.02
Metric 4	0.0	0.0	0.775	0.07
Metric 5	2.0	1.0	0.433	0.21
Metric 6	3.0	2.0	0.631	0.11
Metric 7	2.0	1.0	0.278	0.27
Metric 8	2.0	2.0	0.884	0.03
Metric 9	3.0	3.0	0.166	0.34
Metric 10	2.0	2.0	0.466	0.19

3.2 Workload and Perceived Realism

Across both novice and expert groups, the median scores for all NASA–TLX subdomains were below moderate workload levels (≤ 5). Novice participants reported slightly higher mental demand (median $= 5$) compared with expert participants (median $= 4$), as well as higher temporal demand (median $= 4$ vs. 3). In contrast, expert participants reported a higher effort demand (median $= 5$) compared with novices (median $= 4.5$). Overall NASA–TLX scores remained low for both groups, with novices reporting a lower median total workload (median $= 18$) than expert participants (median $= 29$). Both novice and expert participants rated the anatomical realism as moderately realistic (median $= 3$). Novice participants also rated the interface realism and overall task realism relative to the real-world task as moderately realistic (median $= 3$), whereas expert participants assigned lower ratings for these domains (median $= 2$). With respect to force feedback, both groups reported moderate usefulness (median $= 3$).

3.3 Kinematic Analysis

In addition to rubric-based outcomes, we analyzed instrument kinematics recorded by the simulator for the left and right haptic devices, including path length, mean velocity, mean acceleration, and jerk (all computed per second).

Overall, univariate comparisons of kinematic metrics did not reach statistical significance ($p > 0.05$). However, novices exhibited a consistent trend toward less smooth motion on the left hand, with higher median jerk (expert: 2.68 vs. novices: 3.00; $p = 0.112$, $\delta = -0.39$) and higher median acceleration (expert: 1.55 vs. novices: 1.76; $p = 0.175$, $\delta = -0.33$). Median left-hand velocity was also higher for novices (1.04 vs. 1.16; $p = 0.312$, $\delta = -0.25$). Path-length measures were similar between groups, with comparable aggregate path length (expert: 1302.8 vs. novices: 1238.5; $p = 0.977$, $\delta = 0.01$).

To characterize the variability in execution, we performed principal component analysis (PCA) on a 12-dimensional feature vector consisting of left/right and aggregate kinematic measures (path, velocity, acceleration, and jerk) as seen in Fig. 13. The first principal component explained 64.2% of the variance and was dominated by motion smoothness and control-related terms (absolute PCA loading magnitude $|\ell| \approx 0.35$ for aggregate jerk/acceleration/velocity), whereas the third component (14.2% of variance) primarily reflected path-length variation (aggregate path loading ≈ 0.58). Together, these results suggest that variability in execution is driven more by smoothness-related control characteristics than by gross distance traveled, motivating kinematic features as complementary measures to outcome-based rubric scores. The complete kinematic summary is shown in Table 3.

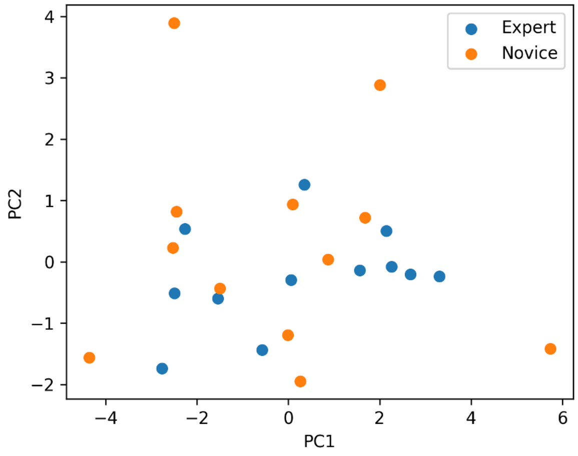

Figure 13: PCA projection of control-focused kinematic features for expert and novice participants ($n = 12$ per group). Each point corresponds to one participant in the first two principal components (PC1, PC2).

4 DISCUSSION

This study evaluated whether VCoST, a unified physics-based VR platform for colorectal anastomosis, can capture measurable differences between experience levels during a LSA procedure. Due to switching between haptics and tracked linear stapler, we carried out the study without the VR headset; rather the users used the screen. With an evenly balanced cohort ($n = 12$ expert, $n = 12$ novices), the outcome-based rubric measures showed limited group separation. The total score difference was not statistically significant (Mann–Whitney U, $p = 0.483$, $\delta = 0.18$), and none of the individual metric items differed significantly (all $p > 0.05$; Table 2). Although experts showed higher median performance on stabilization prior to enterotomy creation (Metric #1: median=3 vs. 0), the effect did not reach significance ($p = 0.189$, $\delta = 0.33$). Collectively, these results reflect the intentionally coarse resolution of the rubric, which verifies completion of procedural milestones rather than capturing graded execution quality. As such, rubric-based outcomes are not designed to resolve finer distinctions in technical skill expression once basic procedural success is achieved.

Table 3: Kinematic summary (median) for expert vs. novice participants ($n = 12$ per group). Two-sided Mann–Whitney U tests and effect size is Cliff's delta (δ).

Metric	Expert	Novice	p	δ
Left jerk (1/s)	2.68	3.00	0.112	-0.39
Left accel. (1/s)	1.55	1.76	0.175	-0.33
Left velocity (1/s)	1.04	1.16	0.312	-0.25
Right path	1344.0	1088.3	0.840	0.06
Aggregate path	1302.8	1238.5	0.977	0.01
Aggregate jerk (1/s)	2.72	2.96	0.544	-0.15

In contrast to rubric outcomes, kinematic analysis indicated more consistent, skill-aligned trends in execution quality. Kinematic measures were analyzed as exploratory process-level descriptors intended to complement milestone-based rubric outcomes rather than replace them. While none of the univariate kinematic comparisons achieved statistical significance (all $p > 0.05$), novices exhibited a tendency toward less smooth left-hand motion, with higher jerk (expert: 2.68 vs. novices: 3.00; $p = 0.112$, $\delta = -0.39$), higher acceleration (1.55 vs. 1.76; $p = 0.175$, $\delta = -0.33$), and higher velocity (1.04 vs. 1.16; $p = 0.312$, $\delta = -0.25$) (Table 3). By contrast, gross distance-based measures were largely comparable between groups, exemplified by near-zero effect for aggregate path length (1302.8 vs. 1238.5; $p = 0.977$, $\delta = 0.01$). This pattern is consistent with the interpretation that expertise is expressed more through controlled, stable interaction with tissue than through differences in distance traveled. From a training perspective, smoothness and stability metrics may reflect the development of fine motor control strategies and anticipatory handling that are not captured by milestone-based rubric scoring alone.

We further examined multivariate structure in the kinematic feature space using PCA. The first principal component explained 64.2% of the variance and was dominated by smoothness and control-related terms, with an absolute loading magnitude of approximately $|\ell| \approx 0.35$ for aggregate jerk/acceleration/velocity. In contrast, the third component accounted for 14.2% of the variance and primarily reflected path-length variation, with aggregate path loading ≈ 0.58. These findings reinforce that the largest source of between-participant variation lies in motion smoothness and control rather than travel distance. This supports the use of smoothness-derived kinematics as complementary signals for objective assessment, especially in settings where rubric totals show limited sensitivity.

Subjective responses suggest that VCoST-LSA provides an acceptable and usable simulation experience with generally low to moderate perceived workload. Across NASA–TLX subdomains, median ratings were at or below 5 for both groups. Novices reported slightly higher mental demand (median=5 vs. 4) and temporal demand (median=4 vs. 3), while expert participants reported higher effort (median=5 vs. 4.5). Both groups rated anatomical realism as moderately realistic (median=3) and rated force feedback as moderately useful (median=3). Expert participants rated interface and overall task realism lower (median=2) than novices (median=3), which is plausible given that expert surgeons may reflect stricter benchmarks informed by greater real-world experience. These findings point to interface and task realism as important targets for future refinement, particularly to improve acceptance among more experienced users and to support high-stakes assessment use cases. The moderate realism ratings reported, particularly by expert participants may reflect tradeoffs inherent in the desktop VR configuration used in this study, which prioritized interaction fidelity and detailed data capture over immersive visual embodiment. In this context, the absence of HMD–based embodiment may contribute to a perceptual disconnect between users' real and virtual hands, potentially influencing perceived realism.

This study is limited by modest sample size ($n = 12$ per group), which constrains statistical power and requires that the reported kinematic differences be interpreted as trends pending confirmation. In addition, the user study was conducted on a desktop VR configuration (rather than an HMD-based setup) due to switching between haptics and the tracked stapler, which prioritizes interaction fidelity and data capture over visual immersion. Finally, only the VCoST-LSA module was evaluated. A formal user study for VCoST-ETEHSA, along with reliability and longitudinal learning analysis, is needed before making stronger claims about assessment validity. Accordingly, the scope of this paper is to introduce the unified VCoST framework and provide initial empirical evidence that process-level kinematic signals may complement rubric scores in this setting.

Despite these limitations, the results support the broader conclusion that VCoST-LSA captures aspects of technical performance not reflected in rubric totals. The total score did not significantly differentiate groups ($p = 0.483$, $\delta = 0.18$), but smoothness-related kinematic measures showed consistent directionality with moderate effect sizes (jerk $\delta = -0.39$) and dominated the primary axis of kinematic variability (PC1: 64.2%). Moving forward, we will conduct a formal user study for VCoST-ETEHSA including expert–novice comparison and reliability analyses. These steps will strengthen evidence that a unified VR platform can support structured training and objective assessment for COSATS-aligned colorectal anastomosis skills.

5 CONCLUSION

We presented VCoST, a physics-based VR training framework that supports both linear stapled and end-to-end hand-sewn colorectal anastomosis within a unified simulation and assessment pipeline. In an expert–novice study of the VCoST-LSA module ($n = 24$), total rubric scores showed limited separation (27.08 vs. 25.91; $p = 0.483$, $\delta = 0.18$), but expert participants demonstrated stronger early tissue stabilization (Metric #1 median 3 vs. 0; $p = 0.189$, $\delta = 0.33$) and faster completion by approximately 42 seconds. Workload ratings were low to moderate (NASA–TLX subscales with medians ≤ 5 5), supporting usability and feasibility of the simulator for procedural practice. Although univariate kinematic comparisons were not statistically significant, novices exhibited consistent trends toward reduced motion smoothness (e.g., left-hand jerk 2.68 vs. 3.00; $p = 0.112$, $\delta = -0.39$), and PCA indicated that execution variability was dominated by smoothness-related control characteristics (PC1: 64.2% variance) rather than distance traveled. These findings motivate combining outcome-based rubric items with complementary kinematic measures to better capture control quality in open anastomosis simulation.

ACKNOWLEDGMENTS

This project was supported by grants from the National Institutes of Health (NIH)/NIBIB R01EB025241, R01EB033674, R01EB032820, and R01EB005807

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