Adding Safety Rules to Surgeon-Authored VR Training

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Abstract.
Introduction The Toolkit for Illustration of Procedures in Surgery (TIPS) is an open source virtual reality (VR) laparoscopic simulation-based training environment with force feedback. TIPS-author, is a content creation interface that allows a surgeon-educator (SE) to assemble new laparoscopic training modules. New technology enables safety rules to be specified by the SE, automatically tracks specified safety errors, and summarizes and communicates achievements and errors to the surgical trainee.
Methods TIPS-author combines and initializes building blocks of anatomy with their physical properties, as selected by the SE from a database. The SE can add any safety rule that can be tested in terms of location, proximity, separation, clip count, and force. Errors are then automatically monitored during simulation and recorded as visual snapshots for feedback to the trainee. TIPS was field-tested at two surgical conferences, one before and one after adding the error snapshot feature.
Results 64 respondents at two surgical conferences assessed the utility of TIPS on a Likert scale. While other ratings remained unchanged for an overall score of 5.24 out of 7 (7 = very useful), the rating of the statement “The TIPS interface helps learners understand the force necessary to explore the anatomy” improved from 5.04 to 5.35 out of 7 after the snapshot mechanism was added.
Conclusions The ratings indicate the viability of the TIPS open source SE-authored surgical training units with safety rules. Presenting SE-determined procedural missteps via the snapshot mechanism at the end of the training increases perceived utility.

Keywords: laparoscopy; virtual reality; computer simulation; patient-specific modeling; patient safety; education, medical; internship and residency

INTRODUCTION

Teaching laparoscopic surgery under one-on-one supervision in the operating room (OR) is costly ranging, a decade ago, from \$50–\$135 per minute[1] . Less supervision is risky: cauterizing too close to a sensitive organ or nicking a central vein are difficult to repair and may cause the patient unnecessary suffering. Therefore alternative training methods are ethically and fiscally prudent. Mentored self-study curricula, such as Fundamentals of Laparoscopic Surgery (FLS), offer dexterity training and certification on peg-board transfer, cutting and suturing of physical props as a foundation before working on real patients[2] . However, FLS box training can not prepare for the high variability of anatomy and soft tissue response that actual cases present. Moreover, FLS provides no automatic checking of safety criteria, an area of critical importance in surgical education[3,4] .

This report addresses the challenge of interpreting a gamut of surgical safety criteria that can be selected by a surgeon educator (SE). Selection triggers automatic monitoring of the criteria within the Toolkit for Illustration of Procedures in Surgery (TIPS), and feedback to the trainee. TIPS is an open source virtual simulation-based laparoscopic training environment supporting force feedback. The surgical safety criteria are expressed in TIPS-author, the VR content creation interface of TIPS. After introducing the new TIPS-author technology, this report presents the outcomes of a study whose aim is to assess the user-perceived utility of TIPS for laparoscopic training; and, in particular, of automatic surgical error monitoring and feedback to the trainee via snapshots.

We briefly review soft tissue simulation and VR trainers. TIPS and the details of the challenge of dynamically introducing safety criteria are reviewed in the Methods section.

Soft tissue simulation and VR trainers

Virtual reality simulators allow trainees to practice decision-making and execution prior to entering the OR[5,6] . The last decade has witnessed progress in soft tissue simulation for a range of surgical scenarios such as laparoscopic surgery, heart surgery, neurosurgery, orthopedic and arthroscopic surgery[7,8] . Early multilayered tissue models for orthopedic trauma surgery were based on 3D mass-spring systems accelerated with graphics hardware[9] . Using finite elements, real time simulation of cardiac electrophysiology, pre-operative planning of cryosurgery and per-operative guidance for laparoscopy has been based on the open source SOFA soft tissue simulation platform[10–13] . A real-time neurosurgery simulation of skull drilling and surgical interaction with the brain[14] has been reported and Cecil et al.[15] describe a virtual surgical environment for training residents in less invasive stabilization system surgery used to address fractures of the femur. Mitchell et al.[16] presented a framework for interactive outlining of regions for simulation of reconstructive plastic surgery. Drilling and cutting of the bone[17] have been based on the open source iMSTK framework. Recently, a standardized simulation platform for training and testing algorithms to control surgical robotic systems, and suturing in particular, has been announced.[18]

Several commercial VR training environments aim to reduce time spent teaching in the OR by offering training modules with virtual anatomy that can be probed using force feedback devices. However, commercial training environments neither aim to capture the broad spectrum of physical variations encountered in laparoscopic practice, nor prepare learners for less common interventions[19] . A number of products have sunset during the past 20 years (e.g. SimSurgery), or were merged or bought up by larger companies (e.g. SurgicalScience, Simbionics, Mimic).

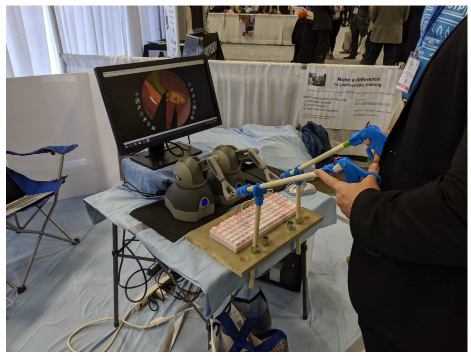


Fig. 1: TIPS: physical setup at surgeon's conference. The two haptic devices are manipulated via 3D printed hand pieces.

METHODS

The Toolkit for Illustration of Procedures in Surgery (TIPS)

TIPS addresses the need for fast prototyping of missing variants of anatomy and less common laparoscopic procedures. Fig. 1 shows the physical setup: force is transmitted to 3D printed hand pieces by small robotic devices. The TIPS open source environment consists of TIPS-simulator, an interactive soft-tissue laparoscopic simulation with force feedback; TIPS-trainee, a web-based component providing instruction and examples to a novice surgeon; and TIPS-author that allows the surgeon-educator to specify steps of a minimally invasive procedure in a fixed format: action, anatomy, tool, safety, comment, see Fig. 2. The 3-tuple "action, anatomy, tool" is used to initialize the geometry and physical properties of the virtual anatomy from a rich database of simlets. A simlet is a piece of anatomy with its physical properties, created by content artists. Simlets combine in a Lego-like fashion[20–22] . See for example cholecystectomy ensemble in Fig. 3: a gall bladder, cystic duct, cystic artery and the fatty tissue covering them (each with their unique Young's modulus etc.) combine via constraints to form a cholecystectomy simlet that is selected via TIPS-author. In our implementation, the web-based TIPS-author interface auto-completes typed items, once they are recognized to be in the database, and thereby steers the author towards existing individual or compound simlets[23] . Both the listing of steps and

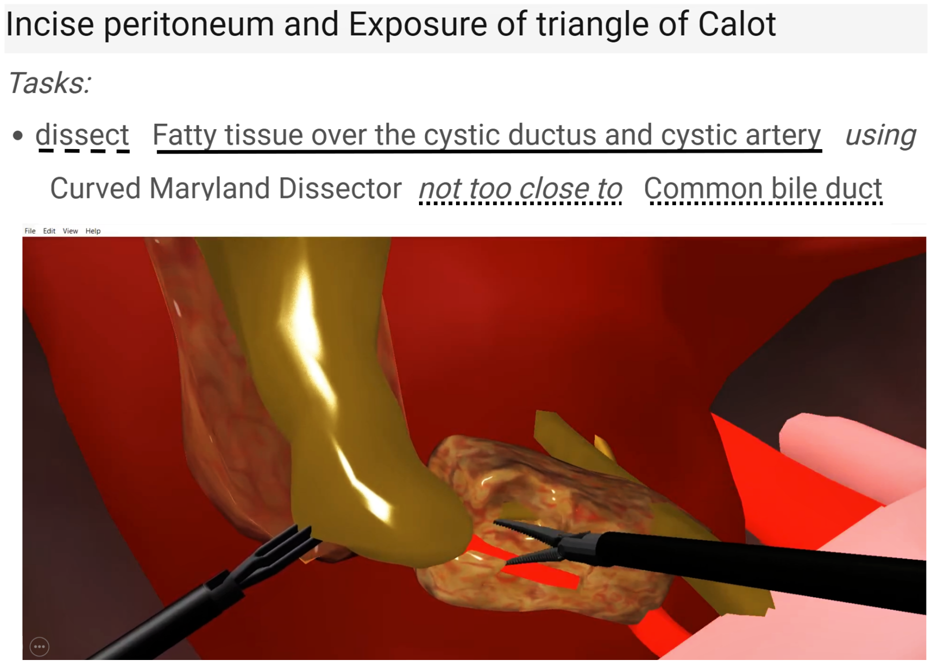


Fig. 2: TIPS-trainee interface, combining instructions (text, top) and video (bottom). auto-generated from the TIPS-author entries (underlined): action (dashed underline), anatomy (solid), tool(none), safety(dotted).

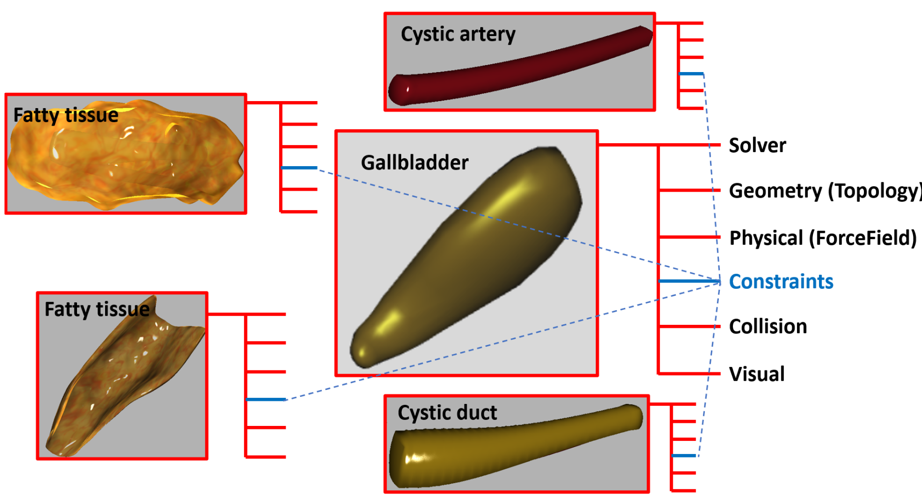


Fig. 3: Each simlet has its independent property field (solver, geometry, physical, constraints, collision, visual). Simlets are connected via constraints (blue prong of the fork-like property listing). See Fig. 2 for the ensemble.

the resulting simulation is peer-reviewed for completeness and relevance before roll-out to the trainees.

An initial study of 34 medical students[24] assessed whether the interactive learning within the prototype TIPS environment has advantages over passive learning from professional instructional videos[25] . The study showed that the inter-active TIPS platform instilled greater confidence in the ability to reproduce the steps of the procedure (p=0.001) and was preferred by the participants as a learning tool (p=0.011). Of course confidence is not always positively correlated with proficiency[26] .

The missing component and contribution: automatic initialization and monitoring of safety criteria

The missing component in earlier work is the lack of automatic interpretation of a "safety" entry in the specification of a surgical task. The entry should trigger deployment of monitors for a palette of surgical safety criteria set by surgeon educators. Examples are: do not cauterize near sensitive organs, limit the force when separating vessels from fatty tissue, etc. The challenge addressed in this report is to provide a *generic mechanism* for meaningful author-controlled yet automatic, unsupervised surgical safety feedback to the trainee, and so accommodate current and future, not yet specified laparoscopic training scenarios.

The challenge is to ensure that a large class of surgical safety criteria can be automatically translated into measurable events during VR simulation to generate both immediate feedback to the trainee and a meaningful final report for trainee and instructor. The next two subsections detail the new contributions:

1. surgeon-educator specified surgical safety criteria;
2. automatic safety-criteria monitoring within TIPS-simulator;
3. immediate feedback to the trainee;
4. safe visual summary feedback to the trainee and a summary message to the instructor via a series of snapshots.

Repeatedly empty error reports and full task-completion reports indicate proficiency with respect to the training unit. This can be used to trigger the final assessment by the instructor and complete a feedback loop to improve the teaching unit by setting additional safety criteria or better specifying steps of the procedure.

TIPS-author: a surgical simulation creation environment

TIPS-author enables a surgeon-educator (SE) to improve the specialization, variety and relevance of laparoscopic VR-training by creating and customizing hands-on, interactive force-feedback laparoscopy training units. As summarized in Fig. 4, TIPS-author extracts a set of compatible, computationally efficient simlets from a database based on the SE's listing. TIPS also generates step-by-step instructions for the web-based TIPS-trainee interface, quizzes. And TIPS

Fig. 4: TIPS-author defines the interactive VR training simulation: (1) The author specifies procedural steps and safety concerns in a fixed format. (2) Instruction pages are generated from the author's description. (3) Simlets (pieces of anatomy and their physical properties) are combined to initialize the scenario in TIPS-simulator. (4) Trainee achievements and safety violations are screen-captured in TIPS-simulator for post-review. This is the focus and contribution of the paper. (5) Completion and errors are reported to the trainee as snapshots of missteps.

initializes the monitoring of surgical errors. The database of simlets is generated by a scenario design cycle[21] that separates the roles of author, developer and artist and leveraging the open source projects *Blender*[27] for geometry and *SOFA*[28,29] for soft tissue simulation.

Adding safety monitoring and feedback to TIPS

Assessment, evaluation and feedback are critical components in the training of novice surgeons and obeying safety rules is paramount when executing complex sequences of maneuvers. Physician training is an experiential process. That is, learners acquire skill by engaging in supervised patient care. All US physicians-in-training, including surgical trainees, must demonstrate competency across a range of knowledge, skills and attitudes prior to graduation[30,31] . Assessing, evaluating and providing critical feedback and instruction in the workplace is time intensive and stressful and requires an experienced surgeon's active participation for expert judgment, to provide safe and effective patient care, and a quality learning experience. To ensure that the assessment and evaluation of surgical trainees is reliable and valid, many training programs employ peer-reviewed evaluative tools such as the objective structured assessment of technical skills (OSATS) for workplace-based assessment[32] .

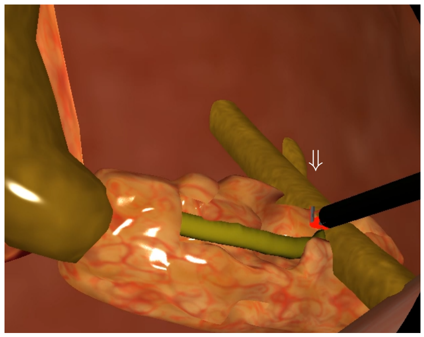
Assessment is also central, but arguably less stressful, in popular computer games where simple counters monitor progress. Psychometric games claim to measure mental agility, attention, cognitive speed, spatial aptitude and numerical processing ability. Increasingly, educational video games incorporate stealth assessment, ubiquitous, unobtrusive, and real-time assessments that intersect play, learning, and assessment. Stealth assessments measure knowledge and skill, then provide learning supports, feedback, instructions, or adapt challenges in the learning environment (e.g., difficulty) to students' proficiency levels, maximizing their learning[33] .

Existing VR surgery simulators typically report time to completion, task-specific data such as the number of staples used, and other general counters. By contrast, TIPS uses SE-established safety criteria that can be more relevant for the specific procedure and trainee group. The SE-authored approach implies that the *criteria cannot be hard-coded in the simulator ahead of time.* Consultation with the clinical experts identified general classes of training errors (i)–(vi):

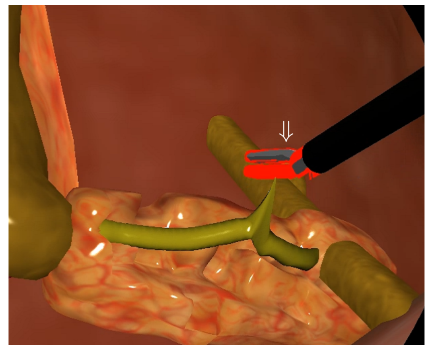
- i Incising or cauterizing at the wrong location.
- ii Injuring a nerve by applying too much force (pressure or over-stretching).
- iii Leaving foreign objects in the patient's body (clips, tools).
- iv Applying surgical clips incorrectly.
- v Removing the wrong (part of an) organ.
- vi Suturing at the wrong location.

These surgical errors can be abstracted as: distance to anatomy, force exerted, location and number of surgical safety clips, and incomplete execution. Initialized by the "safety" entry in TIPS-author, our solution is to have TIPS-author parse these safety criteria and append the corresponding safety tags to these simlets upon export to TIPS-simulator. TIPS-simulator monitors these data streams and reports violations both directly and as a sequence of screen-shot images labeled by error types. Fig. 5 shows screen-shots of four common surgical errors, corresponding to types (i) - (iv) during laparoscopic cholecystectomy.

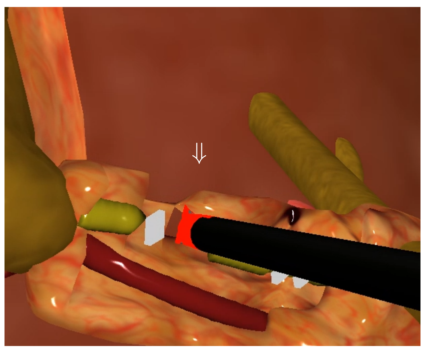
In more detail, error class (i) is monitored by TIPS-simulator as a collision event with an offset distance between the tool listed in the TIPS-author 3-tuple, augmented to a 5-tuple by an error type and the monitored anatomy that form the safety entry. For example, for cholecystectomy, for the step "Explore the triangle of Calot" (see Fig. 5a) the task 5-tuple reads: dissect Fatty tissue over the cystic ductus and cystic artery using Curved Maryland Dissector not too close to Common bile duct. Here "dissect" is the action, "Fatty tissue over the cystic ductus and cystic artery" is the anatomy (specifying a simlet), "Curved Maryland Dissector" specifies the laparoscopic tool, "not too close" indicates an error of type (i) and "Common bile duct" is an entry in the anatomy database that requires monitoring. TIPS-simulator then monitors distance between the cauterizing tool and the common bile duct. Distance below the offset triggers and registers the error.



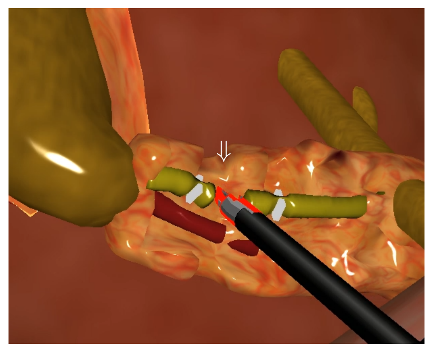
(a) Wrong incision on common bile duct.



(b) Overstretching the cystic duct.



(c) Clip drops to abdominal wall due to bile duct cut at the wrong location.



(d) Bile leak due to the lack of vascular clips on the left side.

Fig. 5: Four types of common surgical errors in laparoscopic cholecystectomy reported by TIPS-simulator. For immediate feedback, the tool tip becomes red (see $\Downarrow$) and the scene briefly freezes.[23]

Type (ii) errors are monitored in terms of force feedback returned to the haptic devices. This safety threshold is customized for veins or arteries with different physical properties Fig. 6. Type (iii) and (iv) errors are detected by tracking the deployed clips on each clip-able object. This monitors the number and placement of clips. For example, to prevent bleeding or leaking, two clips should be applied on the part of the duct or vein that remains inside the body. Type (v) errors are indirectly caught since they terminate the simulation without generating an "achievement" entry in the final visual report. Type (vi) errors are detected by initializing suturable regions on the object, say the fundus of the gaster during Nissen fundoplication.

Errors (i) – (iv) alert the trainee by a red-flashing instrument tip, see Fig. 5. A corresponding screen-shot is saved for later, named by time, error type, and error values.

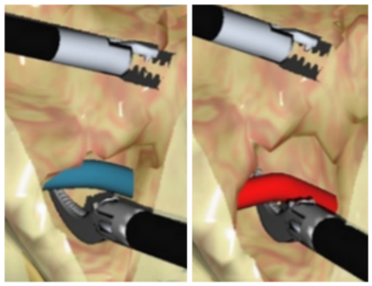
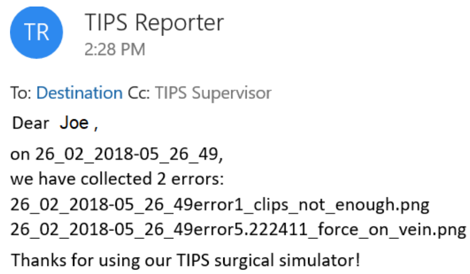


Fig. 6: Excessive force indicated by change of vessel color to red.



TR TIPS Reporter
2:28 PM

To: Destination Cc: TIPS Supervisor

Dear Joe ,

on 26_02_2018-05_26_49,
we have collected 2 errors:
26_02_2018-05_26_49error1_clips_not_enough.png
26_02_2018-05_26_49error5.222411_force_on_vein.png

Thanks for using our TIPS surgical simulator!

Fig. 7: Email reports to trainee (and the instructor) upon completion.

Summary feedback as a series of snapshots

Once the procedure completes, typically when the cancerous organ is retrieved via the surgical pouch, all screen-shots of errors (and small ones for task completions) are displayed to the trainee as a feedback report. This serves as a starting point for a discussion with the instructor. Proficiency with respect to the training module is equivalent to repeated performance without errors and a complete list of achievements. The final achievement is generically checked by asserting that the cancerous body is free from the remaining organs and tissues. Similarly, clip placement requires freeing the vessel and testing that two clips remain within the body while a third clip ensures integrity of the tissue to be removed. Such authored criteria can provide valuable feedback beyond time taken or number of clips deployed.

Additionally, the unique directory of screen-shots and the informative filenames are reported to the trainee by e-mail. Optionally the email is also sent to an account set up for the instructor (see Fig. 7) to document training progress and decide whether the pattern and number of errors requires intervention and what errors should be discussed.

In summary, faced with the complexity of supporting procedure-specific proficiency assessment, we categorized laparoscopic safety violations into several generic classes. This enables a simple but effective, implemented and tested strategy: to use TIPS-author safety entries to initialize, monitor and report error events, and to create a record of progress towards proficiency.

Studies

All training and studies were conducted under IRB201801343 at the University of Florida, with title “Toolkit for Illustrating Procedures in Surgery (TIPS) module assessment”. Participants were invited to volunteer when visiting the TIPS demo booth at the surgical conferences ACS 2019 and ASC 2020. Data were collected by SurveyMonkey (encrypted). Before the session each participant was reminded that they were free to refuse to answer any questions that they do not feel comfortable answering.

RESULTS

The design adds dynamic, customizable or entirely new safety rules via the instantaneous authoring process rather than via standard hard-coded rules. An accompanying video[23] demonstrates that and how the implementation achieves this objective.

Evaluation of TIPS training and feedback

TIPS was demonstrated and experienced by a broad range of medical professionals at the American College of Surgeons Clinical Congress 2019 (ACS) and the Academic Surgical Congress 2020 (ASC). Besides stress-testing the technology "in the wild", the venues allowed the team to conduct a formal survey of the utility of TIPS. A performance-based assessment of TIPS via pre-and post quizzes of 32 residents was reported in[34] .

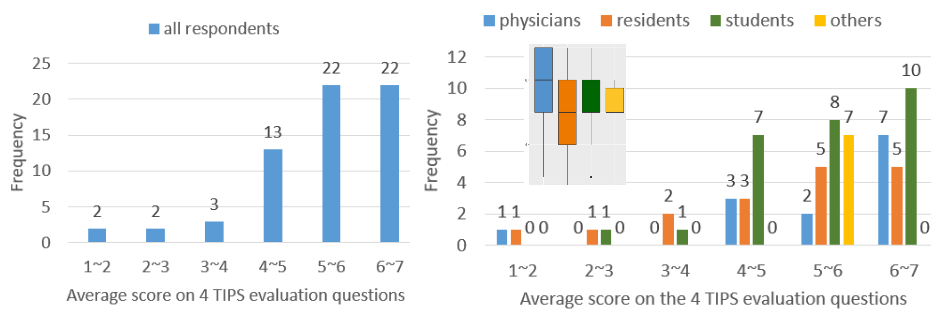
Prior to field-testing, face, construct and content validity of SE-authored TIPS modules had been established by laparoscopic surgeons and residents at the Universities of Florida and Buffalo[34] . The ACS and ASC field tests engaged 64 respondents: 13 board certified surgeons, 17 medical residents, 27 medical students and 7 other medical professionals. Each respondent completed a simulated cholecystectomy module, i.e., a complex sequence of surgical steps where only the goal, complete mobilization of the organ and safe preparation of the remainder, were prescribed. That is, individual motions were not prescribed or measured, allowing for multiple correct choices of tools and sequence, e.g., of applying clips to the cystic duct and blood vessels; however, the number of clips on the part of the duct and vessel remaining in the body (and no clip lost) were tracked as a safety measure (see minute 1:10 to 1:20 of[35]) . After completing the simulated cholecystectomy training module, the 64 respondents rated TIPS across several usability items on a Likert scale from 1 to 7 (7 = strongly agree, see[36]). The scale resolution was selected by the statistical expert in consultation with the collaborating surgeons at the University of Florida, as a trade-off between scale complexity and expressiveness. Table 1 lists the outcome of the four central questions of usability and Fig. 8 breaks down the score on these four central questions. (Four other questions established medical seniority, familiarity with virtual trainers, and prior experience with laparoscopy). All questions were selected in consultation with SEs at the authors' institutions.

The effect of summative visual feedback via snapshots

When analyzing the data sets from the two conferences, we noticed agreement of averages between the 13 ACS respondents and the 51 ASC respondents. The agreement was within .2 on all rating categories except one. The only outlier was the statement "The TIPS interface helps learners understand the force necessary to explore the anatomy". Here the rating improved from 5.04 at ACS to 5.35 at ASC. The only change applied to the TIPS software after the ACS survey and

TIPS ...	mean rating	standard deviation
helps understand the force necessary to explore the anatomy	5.34	1.46
interface does not distract from the surgical task	5.02	1.52
enhances lap-competency attainment over current methods	5.19	1.5
is compatible with the current lap training curricula	5.39	1.43
overall score	5.24	1.33

Table 1: TIPS with safety rules rated on the four central questions.



(a) cumulative

(b) by group,inset: box plot

Fig. 8: Breakdown of the average score on the four central TIPS evaluation questions.

before the ASC survey was the addition of the visual summary of the achievements and procedural errors as a series of snapshots. The immediate feedback by changing the color of a vessel was present in both tests.

DISCUSSION

TIPS is a novel authoring environment that allows surgeon-educators to build customizable VR lap scenarios. The bulk of the survey questions was aimed at evaluating TIPS. Ratings collected from medical professionals at two conference exhibitions indicate the viability of such SE-authored surgical training. In particular, the high score for "enhances lap-competency attainment over current methods" speaks to perceived added value of customized TIPS simulations over available current methods as a basis for adoption and integration[37] . The evaluators' successful practice with TIPS in an informal environment with only a brief introduction indicated a level of trialability and low complexity, while their impressions provided evidence of relative advantage as well as compatibility. Importantly, evaluators provided evidence that haptic fidelity, a key consideration in laparoscopic training, was maintained, with the system enabling an understanding of the force necessary for anatomical exploration.

We did not set out to measure the impact of automatic visual summative feedback on errors presented as screen snapshots. In fact, the immediate feedback on SE-authored error measurements, a change of color, was present at both field tests. It is therefore noteworthy that presenting trainee errors in visual form at the end of the training increased acceptance noticeably. Indeed, additional informal feedback from surgeons and trainees to the question ''what feature of TIPS do you recall" endorsed visual feedback via screen shots as both meaningful and memorable.

Ultimately, we aim to collect large data set for analysis, e.g., to glean error patterns and remove confounding factors in the interpretation of simulator results. The Qualtrics site[38] allows readers to contribute, anonymous or with attribution, specific surgical errors to test for, or errors that are not covered by the general classes (i)–(vi).

In sum, TIPS represents a risk-free, highly reusable, customizable learning tool for surgeons in training. Because the TIPS authoring environment allows surgeon-educators to build customizable VR lap scenarios, there is the opportunity for the creation of a range of cost-effective VR-training units with greater variety, specialization and relevance, addressing the need for enhanced individualized deliberate practice[39, 40] . Virtual reality remains a nascent field in surgical education, yet, emergent research indicates that virtual reality-based surgical simulators reduce cognitive load and encourage flow-state, potentially translating to reductions in training time for skill acquisition[41] . We feel that the adaptability, trialability and affordances offered by TIPS provide significant opportunities for surgical educators and trainees.

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