Adding Safety Rules to Surgeon-Authored VR Training

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Abstract.

Introduction Safety criteria in surgical VR training are typically hard-coded and informally summarized. The Virtual Reality (VR) content creation interface, TIPS-author, for the Toolkit for Illustration of Procedures in Surgery (TIPS) allows surgeon-educators (SEs) to create laparoscopic VR-training modules with force feedback. TIPS-author initializes anatomy shape and physical properties selected by the SE accessing a cloud data base of physics-enabled pieces of anatomy.

Methods A new addition to TIPS-author are safety rules that are set by the SE and are automatically monitored during simulation. Errors are recorded as visual snapshots for feedback to the trainee. This paper reports on the implementation and opportunistic evaluation of the snapshot mechanism as a trainee feedback mechanism. TIPS was field tested at two surgical conferences, one before and one after adding the snapshot feature.

Results While other ratings of TIPS remained unchanged for an overall Likert scale score of 5.24 out of 7 (7 = very useful), the the rating of ‘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. Presenting SE-determined procedural missteps via the snapshot mechanism at the end of the training increases acceptance.

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

1 Introduction

Teaching laparoscopic surgery under one-on-one supervision in the operating room (OR) is costly ranging, already a decade ago, from $50–$135 per minute.
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. However, FLS box training can not prepare for the high variability of anatomy and soft tissue response that actual cases present and provides no automatic checking of safety criteria.

The additional technical challenge that this work addresses is that entry must interpret and trigger deployment of monitors for a palette of surgical safety criteria set by surgeon educators. To explain the challenge, we first review soft tissue simulation and VR trainers in general in Section 1.1, then a customizable training framework (TIPS, Section 1.2) and then, in Section 1.3 formulate the specific challenge and new contributions.

### 1.1 Soft tissue simulation and VR trainers

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. Early multilayered tissue models for orthopedic trauma surgery were based on 3D mass-spring systems accelerated with graphics hardware. More recently, simulation of cardiac electrophysiology simulation, pre-operative planning of cryosurgery and per-operative guidance for laparoscopy use finite elements in real time in the open source SOFA soft tissue simulation platform. A real-time neurosurgery simulator of skull drilling and surgical interaction with the brain was proposed in and report on simulation of drilling and cutting of the bone using the burr and the motorized oscillating saw based on the open source iMSTK framework described a virtual surgical environment for training residents in less invasive stabilization system surgery used to address fractures of the femur.

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. Manual laparoscopic techniques lend themselves particularly well to simulation that leverage force-feedback devices. Virtual reality simulators allow trainees to practice decision-making and execution prior to entering the OR. A number of commercial solutions have sunset during the past 20 years (e.g. Simsurgery), or were merged or bought up by larger companies (see e.g. SurgicalScience, Simbionics, Mimic). However, commercial training environments neither capture the broad spectrum of physical variations encountered in laparoscopic practice, nor prepare learners for less common interventions.

Building a robust virtual environment is a formidable challenge, leveraging scientific advances in collision detection, real-time differential equation solving, interactive visual and haptic feedback in a well-engineered interface. Creating
or updating VR scenarios is a second hurdle: due to the back-and-forth between engineers, computer scientists and medical experts, content creation is neither cheap nor fast and can take months or years; and the result is not easily adjustable to create variants, uncommon or specialized scenarios.

1.2 The Toolkit for Illustration of Procedures in Surgery (TIPS)

The open source Toolkit for Illustration of procedures in Surgery (TIPS) addresses the fast prototyping challenge of missing variants of anatomy and of less common laparoscopic procedures. Fig. 1 shows two physical setup to transmit force via small robotic arms. 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

Fig. 1: Physical setup of the TIPS environment: (a) left screen TIPS-simulator; right screen TIPS-trainee providing instructions and quizzes. Two six degrees-of-freedom haptic devices provide physical feedback. The haptic setup can be augmented by (b) laparoscopic tool handles for a training setup with fulcrum, similar to an FLS box trainer, but wiring is cumbersome and brittle.

Fig. 2: Screenshot of TIPS-trainee instructions directly generated from the TIPS-author entries with embedded (real and) simulation footage video clips.
(see Section 2.1) that allows the surgeon-educator to specify steps of a minimally invasive procedure in the fixed format:

The triple ‘action, anatomy, tool’ is used to initialize the geometry and physical properties of the virtual anatomy. This high-level initialization is possible thanks to 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. For example, the cystic duct, cystic artery and the fatty tissue covering them (each with their unique Young’s modulus etc.), form an anatomy simlet. 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 simlets (see Video, Supplemental Digital Content 1). Both the listing of steps and the resulting simulation is peer-reviewed for completeness and relevance before roll-out to trainees.

An initial study of 34 medical students assessed whether the interactive learning within the prototype TIPS environment has advantages over passive learning from professional instructional videos. The study showed that interactive 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.

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

The missing component in earlier work is a lack of automatic interpretation of a ‘safety’ entry in the specification of a surgical task. The technical challenge is that this entry must interpret and 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 paper 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.

While on one hand, haptic interactive simulation is no different from (a specialized) computer game, on the other hand the safety criteria cannot be hard-coded a priori as in a game environment – because the surgeon-author sets the criteria. The challenge then is to insure that (a large class) of surgical safety criteria can be (i) formulated, (ii) automatically translated into measurable events during VR simulation and (iii) generate both immediate feedback to the trainee and a meaningful final report to be shared with the instructor. Section 2 introduces TIPS. Section 3 reports on the new contributions that

1. allow the surgeon-educator to specify the surgical safety criteria;
2. are automatically monitored within TIPS-simulator;
3. provide immediate feedback to the trainee; and
4. Return, in a secure fashion, visual feedback to both the trainee and a summary message to the instructor as a series of snapshots.

The list of errors and task-completion in the message (4.) record progress: a repeatedly empty error report and completed task report 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.

Fig. 3: 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.

2 Methods

2.1 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. TIPS-author provides a surgeon-
educator (SE) with an open source environment to create and customize hands-on, interactive force-feedback laparoscopy training units. Based on the SE’s listing, TIPS-author extracts a set of compatible, computationally efficient simlets from a database, and generates step-by-step instructions for the web-based TIPS-trainee interface, quizzes and, as specified in Section 2.2, the monitoring of surgical errors. The database is generated by a scenario design cycle that separates the roles of author, developer and artist:

- at the developer level, numerical simulation routines are selected or adjusted and admissible parameter ranges are determined;
- at the artist level, geometric models with collision and physics parameters (simlets) are created; and
- at the surgeon-author level, simlets are combined and the workspace and view determined via an interactive WebGL interface.

Key to this approach is that it can leverage the vibrant professional open-source geometric modeling software Blender (http://blender.org) and a library of numerical, geometric and visual algorithms for soft-tissue simulation, SOFA (http://www.sofa-framework.org). Blender and SOFA are combined to generate hex-meshes on the fly for carvable fatty tissue and thick-shell models of the stomach. Anatomy and physics are customized via a menu added to Blender that annotates the .xml files sent to SOFA for simulation. Combination and customization are possible due to a small disciplined choice of representation primitives.

2.2 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. Assessing, evaluating and providing critical feedback and instruction in the workplace is time intensive and stressful. And it requires an experienced surgeon’s active participation and 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.

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 provides learning supports, feedback, instructions, or adapts challenges in the learning environment (e.g., difficulty) to students’ proficiency level, maximizing their learning.

Existing VR simulators typically report time to completion, task specific data such as the number of staples used, and other general counters. TIPS’s incorporation of SE-established safety criteria makes cases more relevant for the specific procedure – but this approach also 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. 4 shows screen-shots of four common surgical errors (corresponding to type 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-authors tuple of the task and an organ listed in the safety entry.

For example, for cholecystectomy, for the step ‘Explore the triangle of Calot’ (see Fig. 4a) the task tuple reads:

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dissect Fatty tissue over the cystic ductus and cystic artery
using Curved Maryland Dissector not too close to Common bile duct.
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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.

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. Type (iii)
(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. 4: Four types of common surgical errors in laparoscopic cholecystectomy reported by TIPS-simulator. For immediate feedback the tool tip becomes red (see ¶) and the scene briefly freezes (see Video, Supplemental Digital Content 1).

and (iv) errors are detected by a map tracking the vector of deployed clips on each clip-able object to monitor not only the number but also 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 and type (vi) errors are caught 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 (Fig. 4a) instrument tip. A corresponding screen-shot is saved for later named by time, error type, and error values.
2.3 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 provide more valuable feedback than time taken or number of clips deployed.

Additionally, the unique directory of screen-shots and the filenames are reported to the trainee by e-mail and, optionally, to an account set up for the instructor (see Fig. 6) 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.

3 Results

3.1 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 testing the technology ‘in the wild’, the venues allowed the team to conduct a survey of TIPS.

Prior to field testing, face, construct and content validity of SE-authored cholecystectomy and appendectomy TIPS modules had been established by laparoscopic surgeons and residents at the Universities of Florida and Buffalo. At the congress field tests, after training with the modules, 64 respondents (13 board certified surgeons, 17 medical residents, 27 medical students and 7 other medical professionals) rated TIPS across several usability items on a Likert scale from 1 to 7 (7 = strongly agree, see Table 1). The scale resolution was selected as a trade-off between scale complexity and expressiveness. Table 1 lists the outcome of the four central questions of usability and Fig. 7 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.

| 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 key questions.

Fig. 7: Breakdown of the average score on the 4 central TIPS evaluation questions.

3.2 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 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.
4 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 to evaluate TIPS as a whole. 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 the added value of customized TIPS simulations over available current methods.

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.

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