

CELOTS: A clinically-based Computer Enhanced Laparoscopic Training System

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1. Introduction

1.1 The gap between what we have and what we need

Both the American Board of Medical Specialties (ABMS) and the Accreditation Council on Graduate Medical Education (ACGME) have shown interest in computer simulation technologies in medical training. [1] The Institute of Medicine, in its landmark report, “To Err is Human,” recommended explicitly in Recommendation 8.1 that “hospitals and medical training facilities should adopt proven methods of training such as simulation” [2].

According to Dr. David Leach, the executive director of ACGME “What we measure we tend to improve” [3]. The implicit challenge in Dr. Leach’s comment is that we know what to measure and that our measurements are relevant to the actions which require improvement. In the field of surgical simulation, agreed standards have not been reached. To date, most measures involve quantification of time and path length in a particular task on a particular simulator. Yet to be widely accepted, learning measures should be standardized, using clinically relevant tasks that are judged by practicing physicians to be important measures of competence. We must not fall into the trap that because we can measure a parameter, it becomes, by acceptance, an educationally relevant marker.

Yet computer-assisted systems can quantify a variety of parameters such as instrument motion, applied forces, instrument orientation, and dexterity, which cannot be measured with non-computer-based training systems. With proper assessment and validation, such systems can provide both initial and ongoing assessment of operator skill throughout one’s career, while enhancing patient safety through reduced risk of intraoperative error [4]. Additionally, a computerized trainer can provide either terminal (post-task completion) or concurrent (real time) feedback during the training episodes, enhancing skills acquisition. During the past ten years, several computer-based surgical trainers (either academic prototypes or commercial products) have been developed. However, none of them has been widely accepted and officially integrated into a medical curriculum or any other sanctioned training course.

1.2 Barriers to acceptance by organized medicine

Among the impediments to simulator acceptance by organized medicine are the lack of realism and the lack of appropriate performance assessment methodologies.

1.2.1 The lack of realism

The requisite level of realism in medical simulators has not been determined. Surgeons generally believe that the perfect trainer is one that is capable of reproducing the actual operative conditions in order to immerse the trainee in a virtual world that is an accurate representation of the real world. Clearly, currently available technology cannot provide virtual reality systems with “real-world” authenticity. However, one can argue that such levels of realism are important only for procedural and team training. Indeed, it has been shown that practicing on simple abstract tasks can lead to skills acquisition [4]. The latter statement though, begs the question of what level of abstraction is sufficient for skills training. Surgeons have never used abstract tasks for their training and this may explain in part why the available computer-based skills trainers have not been accepted by the surgical community.

1.2.2 The lack of appropriate performance assessment methodologies

Until recently there was a tendency to view performance assessment and metrics in very simplistic terms. The first computer-based trainers and the non-computer-based laparoscopic skills trainers incorporated empirical outcome measures as an indirect way to evaluate performance and learning. The metrics used in these trainers lack clinical significance. An effective metric should not only provide information about performance but also identify the key success or failure factors during performance, and the size and the nature of any discrepancy between expert and novice performance. Thus, an effective metric should indicate remedial actions that can be taken in order to resolve these discrepancies.

Additionally, currently available training systems lack a standardized performance assessment methodology. Standardization is a key characteristic of all successful examinations and educational aids.

2. The concept of “Visual Haptics”

It is clear that without an objective, standardized and clinically meaningful feedback system, the simplistic and abstract tasks used in the majority of available training systems are not sufficient to learn the subtleties of delicate laparoscopic tasks and manipulation, such as suturing. But even if we accept that a specific level of abstraction is permitted for surgical skills training, there are other fundamental issues that cannot be ignored. The most important of these are force feedback and visual feedback. In a clinically relevant context, rather than an engineering context, the two cannot be separated.

Force feedback is important for many types of surgical manipulation. In open surgery for example, force feedback permits the surgeon to apply appropriate tension during delicate dissection and exposure and avoid damage to surrounding structures. While force feedback is diminished in laparoscopic manipulations, surgeons adapt to this inherent disadvantage by

developing clever psychological adaptation mechanisms and special perceptual and motor skills. Conscious-inhibition (gentleness) is considered one of the major adaptation mechanisms. Conscious-inhibition implies that surgeons learn to interpret visual information adequately and based upon these cues, they sense force, despite the lack of force feedback. We have called this adaptive transformation from the visual sense to touch “*visual haptics*”: using “visual haptics”, a surgeon or other physician is able to appropriately modify the amount of force mechanically applied to tissues from the predominant input of visual cues. The visual cues come from tissue deformations. For example, a surgeon may not be able to feel with his/her hands a structure that is stretched when retracted, but he/she may “feel” the retraction of the structure by watching subtle indicators such as color, contour, and adjacent tissue integrity on the monitor.

The introduction of force feedback in computer-based learning systems is difficult and requires the knowledge of two elements: instrument-tissue interaction (computation of forces that are applied during surgical manipulations); and human-instrument interaction (design and development of an interface). These are active research areas, where efficient and cost-effective solutions remain to be found. As a separate issue, the requirement for realistic visual feedback implies that the computerized representation of the real world is able to depict tissue deformations accurately. The creation of virtual deformable objects is a cumbersome process that requires the development of a mathematical model and the knowledge of the object behavior during the different types of manipulation.

3. The Computer-Enhanced Laparoscopic Training System (CELTS)

In light of the preceding discussion, and in an effort to present a practical application of our research, we have developed CELTS, a novel computer-based laparoscopic trainer, as a step toward a more clinically relevant and standardizable training system. The CELTS system consists of a mechanical interface, a set of tasks, a standardized performance assessment methodology and a software interface.

3.1 The mechanical interface

The system is capable of tracking the motion of two laparoscopic instruments, while the trainee performs a variety of surgical training tasks. We use a modified Virtual Laparoscopic Interface (VLI) (Immersion Corp., San Jose, CA), in order to use real laparoscopic instruments. The use of real laparoscopic instruments permits a simple solution to the human-instrument interactions encountered during laparoscopic operations. Different instruments are used depending on the training task to be performed. Visual feedback is provided through a moveable laparoscopic camera and a light source [Telecam SL NTSC/Xenon 175, Karl Storz Endoscopy-America, Inc., Culver City, CA] [Figure 1].

3.2 The tasks

The instructor or end user may choose to use a set of tasks from established training programs (such as the Yale Laparoscopic Skills and Suturing Program or the SAGES-Fundamentals of Laparoscopic Surgery training program) or may develop his/her own set of tasks. Because of

the system architecture, specific new metrics are not required for each new training task: the tasks and standardized performance metrics are independent of each other. This is a particular strength of the approach we have chosen.

For each training task, the system uses a railed locking and alignment mechanism to consistently secure a common task tray to the base [Figure 1]. Once locked in place, the training exercise proceeds without dislodging the task tray from the camera's field of view. Task trays can be easily and quickly changed without complicated setup procedures. This system offers task designers a set of physical constraints within which new tasks can be designed as well as providing a common scale amongst all tasks used to gather validation data.

In developing and testing CELTS, we have used various tasks and materials. We favor the use of synthetic models that provide accurate deformation and force feedback during manipulation [Figure 2], again simplifying the tissue-instrument force feedback problem. We are preparing a basic instructional guide (CD-ROM based tutorial) describing the initial tasks.



Figure 1. Front view of the CELTS system: the interface device, the railed locking and alignment mechanism, and two of the task trays are shown.

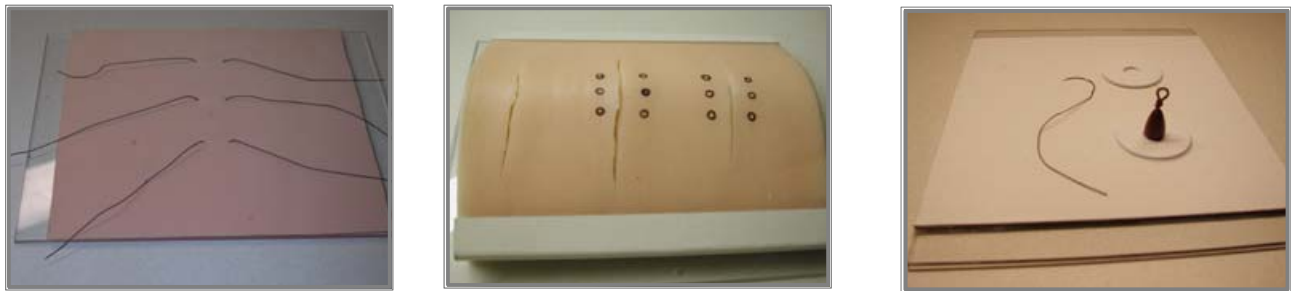


Figure 2. Three tasks that can be used to teach the subtleties of delicate laparoscopic suturing. Specifically, the tasks teach depth perception, needle handling, orientation-alignment, precision of motion and knot tying.

3.3 Standardized performance assessment

CELTS uses a unique performance assessment methodology: it is the first trainer that incorporates a *standardized and task independent scoring system* for performance assessment. We introduced this concept and described the scoring system in detail in a previous report [5]. Briefly, in order to define a quantitative performance metric which is useful across a large variety of tasks, we have looked at the way expert surgeons instruct and comment upon the performance of novices in the operating room. Expert surgeons are able to evaluate the

performance of a novice by observing the motion of the visible part of the instruments on the video monitor. Based on this information and the outcome of the surgical task, the expert surgeon can qualitatively characterize the overall performance of the novice on each of the key parameters that are required for efficient laparoscopic manipulations. We have identified the following components of a task that account for competence while relying only on instrument motion: compact spatial distribution of the tip of the instrument, smooth motion, good depth perception, response orientation, and ambidexterity. Time to perform the task as well as outcome of the task are two other aspects of the “success” of a task that are also included in the computation. Finally, in order to transform these parameters into quantitative metrics, we use kinematics analysis theory, which has been used previously to study psychomotor skills [6]. The five kinematic parameters we have defined for the proof of concept system are presented in Figure 3. They are calculated as cost functions, in which a lower value describes a better performance. A z-score is computed for each parameter as shown in Figure 3, and then the final z-score of a trainee is derived from the z-scores of the individual parameters. To account for the two laparoscopic instruments we compute a z-score for each instrument and then we average the two values. The instructor or the end user is allowed to vary the weights α_i of the parameters according to which parameters are more important or are more relevant in each task.

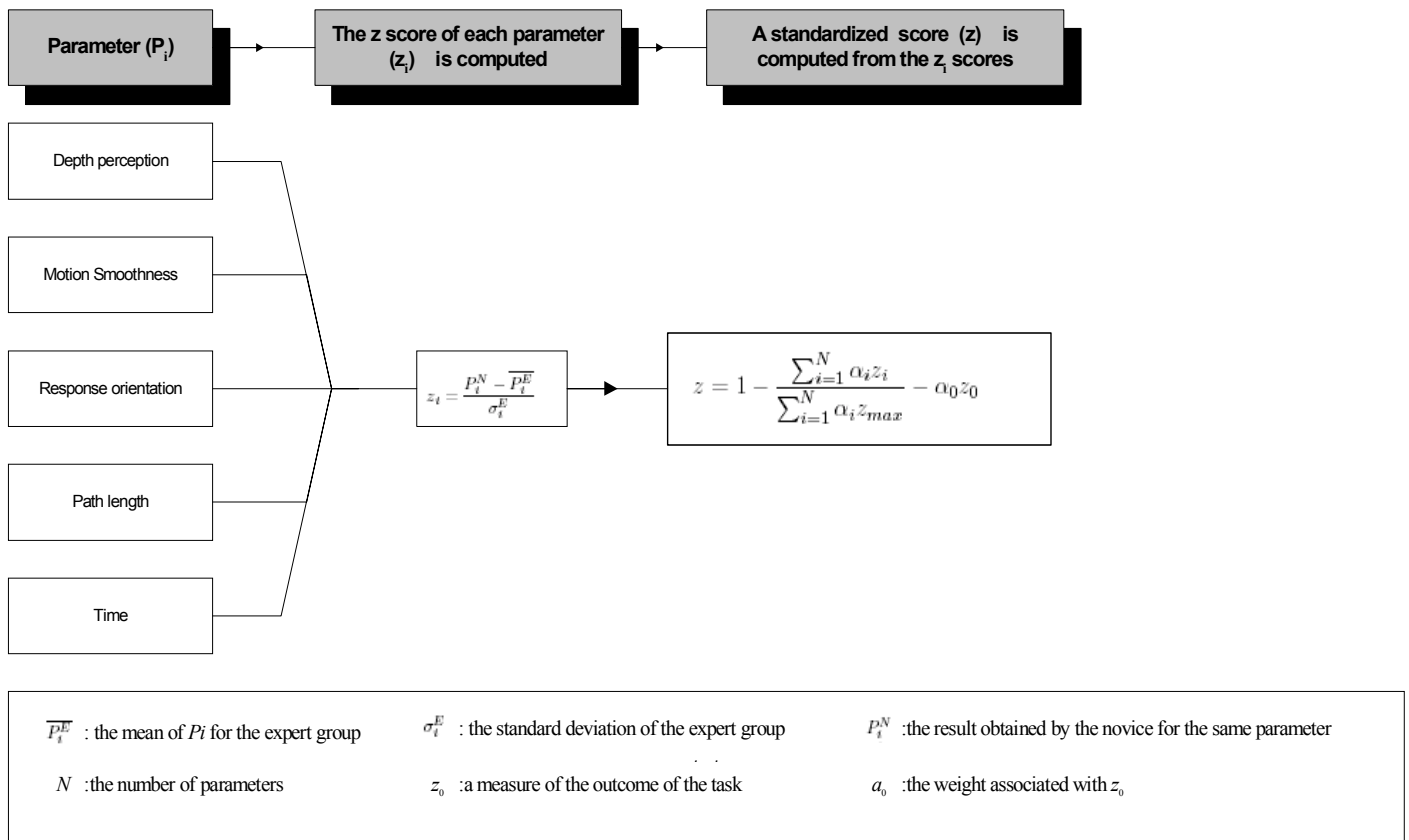


Figure 3. Metrics employed in the initial CELTS proof of concept and the computation of the final score

3.4 The software interface

A software interface was developed for data processing. Raw data consists of time-stamped values of the position and orientation of each of the two laparoscopic instruments. The raw

data is filtered and the performance metrics and the standardized score (described above) are computed. The user interface is implemented using C++, FLTK and OpenGL. It offers real-time and playback display of the tip of the laparoscopic instruments and its path. Kinematics analysis and performance assessment were calculated at the end of the task, providing immediate information to the user. The feedback also includes a visual comparison of the results of the experts group and the trainee [Figure 4]. This comparison informs the trainee about what skills need to be improved in order to improve surgical skill.

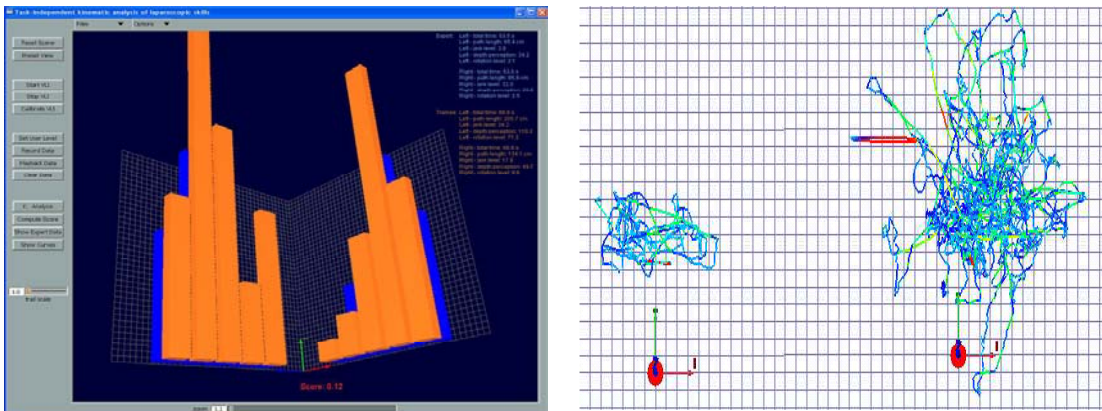


Figure 4. Screenshots of the user interface showing *left*, the values of the individual parameter, the total score, a visual comparison of the results of the expert group and the trainee: *right*, the path of the expert (left) and novice (right) after completion of a task. A compact path is characteristic of an expert’s performance

4. Survey of surgeons’ preferences

Our goal was to develop an advanced educationally and clinically relevant training system after consideration of our research goals and surgeon’s requirements for an “ideal” laparoscopic skills trainer. Before developing the current version of the system, we administered a survey to a panel of thirty expert surgeons attending the 8th annual meeting of the Society of American Gastrointestinal Endoscopic Surgeons (SAGES). The majority of the experts surveyed agrees on the importance of skills training and suggested that skills training should be officially integrated into residency programs and medical curricula. The results of the survey confirmed our assumption that surgeons are not satisfied with the currently available virtual reality simulators: they consider training boxes the best training aid for practicing surgical skills outside the operating room. The experts were also asked to rate the importance of various metrics in assessing performance. As shown in figure 5C, the metrics that are widely employed in the currently available systems (time and path length) received the lowest score among the surgeons in this survey. In contrast, the metrics used in the CELTS system were ranked most important in assessing task performance.

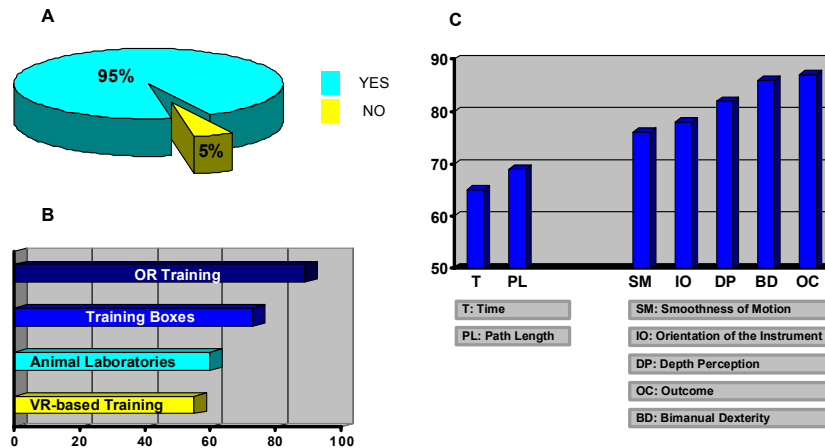


Figure 5. Three of the questions in our survey were: (A) Should skills training be officially integrated in residency programs and medical curricula? (B) Using a scale 0-100, rate the available training modalities. (C) Using a scale 0-100, rate the importance of the parameters shown in assessing task performance.

5. Conclusion

We have developed a clinically derived laparoscopic skills trainer which is currently based upon the SAGES Fundamentals of Laparoscopic Surgery tasks, and which uses real instruments, true full color video display, and software-based task independent metrics. We have shown that a set of appropriate performance metrics can be defined and a standardized scoring system can be designed. Our initial proof of concept evaluations have demonstrated the usefulness of our novel approach. However, further evaluation is required. We have initiated a two-phase study to evaluate the ability of the scoring system to track progress over time and to compare our system to other commercially available training systems.

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