Immersive Training and Mentoring for Laparoscopic Surgery

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ABSTRACT

We describe in this paper a training system for minimally invasive surgery (MIS) that creates an immersive training simulation by recording the pathways of the instruments from an expert surgeon while performing an actual training task. Instrument spatial pathway data is stored and later accessed at the training station in order to visualize the ergonomic experience of the expert surgeon and trainees.

Our system is based on tracking the spatial position and orientation of the instruments on the console for both the expert surgeon and the trainee. The technology is the result of recent developments in miniaturized position sensors that can be integrated seamlessly into the MIS instruments without compromising functionality. In order to continuously monitor the positions of laparoscopic tool tips, DC magnetic tracking sensors are used. A hardware-software interface transforms the coordinate data points into instrument pathways, while an intuitive graphic user interface displays the instruments spatial position and orientation for the mentor/trainee, and endoscopic video information. These data are recorded and saved in a database for subsequent immersive training and training performance analysis. We use two 6 DOF DC magnetic trackers with a sensor diameter of just 1.3 mm - small enough for insertion into 4 French catheters, embedded in the shaft of a endoscopic grasper and a needle driver. One sensor is located at the distal end of the shaft while the second sensor is located at the proximal end of the shaft. The placement of these sensors does not impede the functionally of the instrument. Since the sensors are located inside the shaft there are no sealing issues between the valve of the trocar and the instrument.

We devised a peg transfer training task in accordance to validated training procedures, and tested our system on its ability to differentiate between the expert surgeon and the novices, based on a set of performance metrics. These performance metrics: motion smoothness, total path length, and time to completion, are derived from the kinematics of the instrument. An affine combination of the above mentioned metrics is provided to give a general score for the training performance.

Clear differentiation between the expert surgeons and the novice trainees is visible in the test results. Strictly kinematics based performance metrics can be used to evaluate the training progress of MIS trainees in the context of UCLA - LTS.

Keywords: minimally invasive surgery (MIS), haptic feedback, telementoring, magnetic tracking sensors, laparoscopy, UCLA – LTS.

1. INTRODUCTION

Minimally invasive surgical (MIS) techniques, such as laparoscopic surgery, are used for many common operations such as gallbladder removal, appendectomy and hernia repair [1]. MIS technique provides many advantages over classical approaches such as shorter hospital stays, faster recovery times, and minimal scarring resulting in improved cosmetics [2]. While the advantages are obvious, the extended training time required to achieve proficiency are among its major disadvantages. Currently employed training methodologies rely on dry box simulators followed by actual surgical operations. Given the extensive growth of simulation software during the last couple of decades, for example training pilots on computer simulations, one would expect the medical profession to be at the forefront of these simulations systems. While there have been attempts at developing training platforms, a widely accepted system by the medical and surgical community for interventional training does not currently exist. Therefore, there is an immediate need to develop superior training systems that are cost effective to teach the next generation of laparoscopic surgeons.

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The general consensus of the community is that surgical training should be structured and skill level assessed at various levels. Rosser and collaborators [3, 4] addressed this aspect when they evaluated the suturing skills of trainees in a dry box environment. Similarly, in a study aiming to compare the reliability of various scoring systems, Martin et all [5], tested overall surgical skills following animal live tissue training compared to dry box models, and concluded that the acquired skill set was equivalent between the two methods. Traditional apprentice-model type training during actual surgical procedures is time consuming [6] and does not obviate the need for additional skills-acquisition training as found in a study by Chen [7]. Furthermore, training in the OR exposes the patients to risk and is further compounded by the recently mandated reduced working hours for surgical trainees [6]. Therefore, a need exists for virtual reality (VR) based trainers to at least master the basic skills and thereby reduce the length of the learning curve involved in acquiring the MIS skills [6], [8]. Additionally, the digital nature of these training systems allows automated and standardized scoring of performance, thus eliminating the confusion and bias of subjective performance interpretation.

There have been several attempts at creating virtual reality (VR) based trainers for laparoscopic surgery [7-9]. Some of these projects have produced commercially available products but none have gained wide acceptance in the medical community. For example the Virtual Laparoscopic Interface (VLI) tracks 2 instruments in spatial position and orientation (5dof) with near real time representation of hands movement on screen; the LSW offers the addition of touch sensitivity to visual cues. Both of these systems have been licensed to other developers: LapSim (Surgical Science), MIST-VR (Mentice). MIST-VR [9] and Procedicus MIST, are some of the systems that have been most extensively studied and validated, [10], [11], [12], [13], [14], [15], [16], [17]. In addition to these systems a number of other systems have been reported on such as the Procedicus [18], LapSim [19-22], Xitact [23-25], VEST [26], and CELTS [27].

This brief overview indicates that a variety of training systems with varying degrees of complexity or specialization are available for teaching laparoscopic skills [28, 29]. However their wide spread acceptance is limited primarily due to their limitation on transferring a general set of surgical skills, i.e. not just psychomotor skills, to enable clinical performance in an operation [29]. Furthermore, when addressing psychomotor skills these simulators have not proven to be superior to basic training techniques, such as videotape [30] or basic trainer boxes [28, 31]. Therefore, there still exists a need for a virtual trainer that teaches psychomotor skills as well as performance feedback to the laparoscopic novice surgeons. Some general shortcomings include the limited number tasks available for training, inability to educate anatomical variation in patients, and variation in the technical approach to a given situation. The purpose of this paper is to develop a more complete virtual simulator system to specifically meet these needs.

2. SYSTEM OVERVIEW

The computer based UCLA-LTS (Laparoscopic Training System) is based around the fundamental philosophy that surgical procedures must be taught on actual surgical devices rather than simulated systems. The UCLA LTS system thus uses two actual laparoscopic instruments containing position tracking sensors seamlessly integrated into the instruments. The sensing signals are visually produced on a screen in real time graphic form as well as recorded for later feedback. The sensing data is fed into a software package to assess the performance metrics of the surgeon as well as provide individual scores on specific metrics as well as a final compound score. In general terms the system consists of a mechanical interface with instruments and tracking sensors, a software interface that acquires the data relating to the motion of each instrument, and a cognitive and psychomotor skills evaluation software, based on analysis of the instruments kinematics. This system combines the advantages of computer simulation with the features and simplicity of the traditional training boxes, which allows it to be easily customized in situ for a wide array of training tasks.

The general configuration of the UCLA-LTS is illustrated in Fig 1. The laparoscopic training box has the porthole plate top covered with opaque material such that operators will see their instruments in action only on the monitor. A pegboard from a SAGES approved training set is fixed on the inside using Velcro tape. The active source electromagnet of the tracking system is rigidly attached to the far side of this box to provide a fixed reference system of coordinates. Visual feedback normally coming from an endoscopic camera is currently provided by a USB based webcam fixed to the front of the training box. Each laparoscopic instrument is inserted into a porthole through a trocar, which forms a friction joint with the rubber of the porthole simulating the friction normally encountered between trocar and abdominal wall tissue. The wiring from the electromagnetic tracking sensors is routed to the control box seen in the background plane; with the control box linked to the PC via a USB port. The computer monitor displays the video feed from the webcam as well as the performance monitoring graphics.

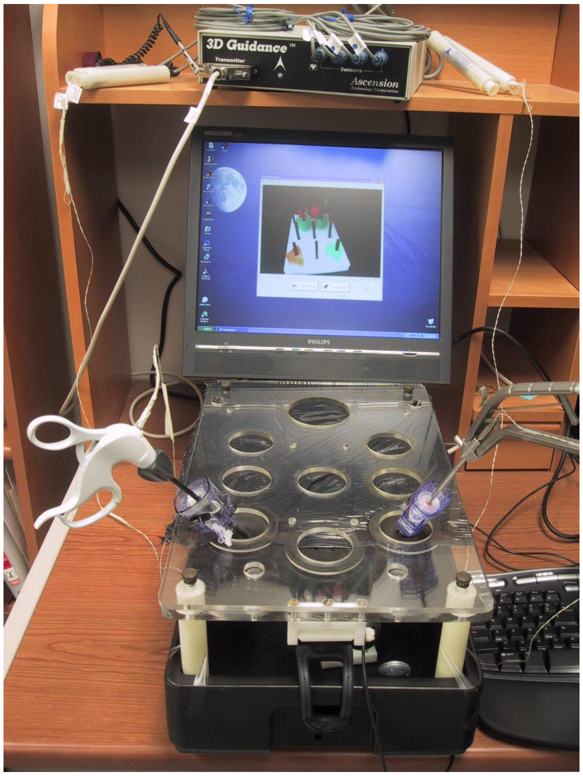


Fig. 1. Overall view of the UCLA-LTS with the laparoscopic instruments and the trocar inserted in the training box portholes visible in the fore plan; the webcam use dof r video feedback is also visible. In the back plan we can see the computer monitor and the control box for the magnetic tracking system. Not visible in this image is the active source magnet of the tracking system, being placed in a fixed position behind the training box and the PC.

Spatial and temporal tracking of the laparoscopic instruments is achieved through electromagnetic tracking. For the purpose of this paper we focused on two instruments most commonly used, i.e. a tissue grasper (Ethicon Endosurgery, Cincinnati, OH) and a needle driver (KARL STORZ GmbH & Co. KG, Tuttlingen, Germany). Each laparoscopic instrument contains two seamlessly integrated DC electromagnetic motion sensors (microBird, Ascension, Burlington, VT, USA). These three axis magnetic sensors (Fig 2a) contain three orthogonally oriented coils encased in an epoxy based coating forming a basic three-axis ring core fluxgate magnetometer. Each sensor is approximately 4 French or 1.3 mm in diameter and approximately 5 mm in length.

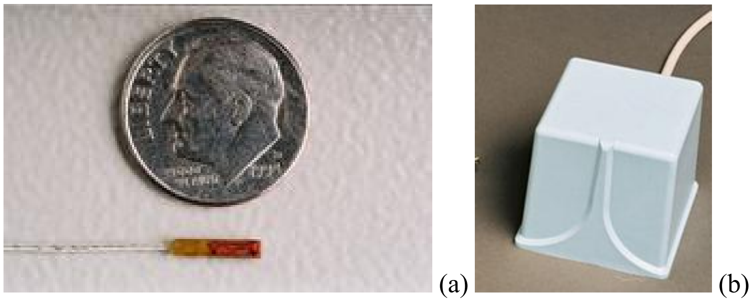

(a) (b)

Fig. 2. Ascension microBird sensor (a) and active source electromagnet (b)

The active source electromagnet unit (Fig 2b) consists of three orthogonally oriented coils excited by a multi-millisecond pulsed dc current applied to a single coil at a time. The active electromagnet unit is rigidly attached to the training box. The sensor can be detected within a 0.5m radius from the electromagnetic unit, within the confines of the dry box. According to the manufacturer data sheet, for a working distance of 0.305 m, the static resolution of the sensors is 0.5 mm for position and 0.1º RMS angular for orientation. The output from the control unit provides 90 measurements of position and orientation per second. A recent study by Hummel [32] looked at the potential application for these kind of sensors in endoscopes and guiding wires. Their experimental measurements, has largely confirmed these data and suggests many opportunity exists for spatial tracking during medical procedures. For the purpose of our training system we consider this level of accuracy and resolution to be sufficient. To compensate for the magnetic field distortions due to the presence of metallic objects we employ two of these sensors per instrument, one at the instrument tip (distal) and the other at the instrument handle (proximal).

2.1. Sensor Integration

The sensors were integrated into the shaft of each tool without affecting its functionality. Each instrument was disassembled and the sensors were subsequently embedded into the metal shaft. The distal sensor is placed at a distance of 25 mm from the instrument tip, inside the shrouded part of the shaft, while the proximal sensor is placed 50 mm from the opposite end of the instrument shaft. The placement at the tip and the handle of the instruments allows complete tracking in space and time. The sensor wires that energize the magnets are self contained in the shaft with slow cure epoxy as seen in Fig 3 for the Ethicon endoscopic grasper.

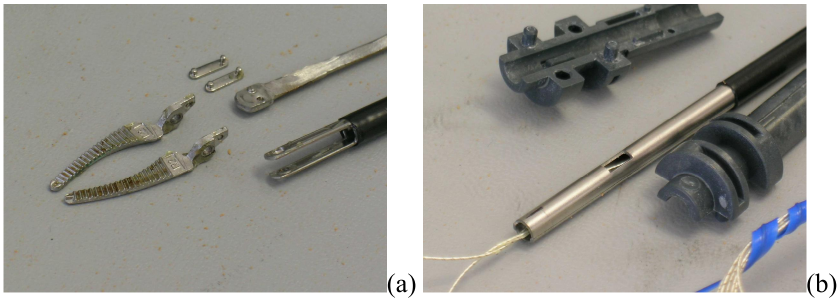


Fig. 3. Ethicon grasper disassembled (a) wiring sensors pulled through the metal shaft (b).

The sensor wire exists through electrocautery connector of the instrument handle, as seen in Fig 4a. The 2 m long and 0.9 mm diameter sensor wires hook up to the micro Bird control unit via customized connectors, as seen in Fig. 4b next to the instrument handle.

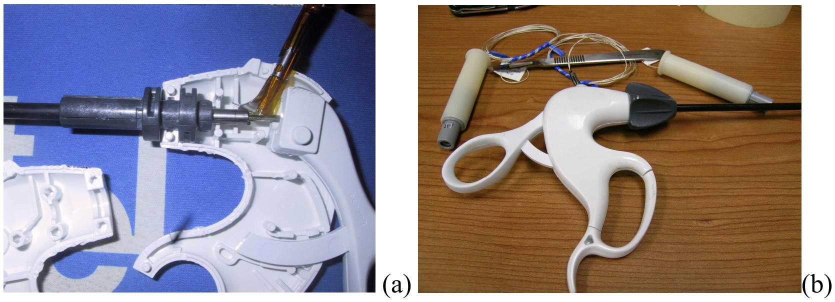


Fig. 4. Ethicon grasper with the handle disassembled to show the sensors wire routing (a) and the assembled grasper handle with the sensors wiring and their connectors (b).

Before each session the sensors are calibrated to a set of fixed points located inside the training box, due to the nature of the fluxgate magnetometers, and to get the price position of the instrument tip relative to the position of the sensors. The active source coil is attached to the training box in order to maintain a reference coordinate system.

2.2. The Hardware – Software Interface

Each of the four sensors integrated into the laparoscopic tools provides its position (in millimeters) and orientation (as a 3x3 matrix) to the host computer through the standard Universal Serial Bus (USB). Two sensors have been placed in each tool, one at the distal position (i.e., closer to the tool's end-effector), and one at the proximal end in the tool's handle. For each sampling, the real-world position (p_w) of the end-effector is computed from the distal (p_d) and proximal (p_p) sensor's positions as

$$p_w = k(p_d \cdot p_p) + p_d \tag{1}$$

where k is the known and fixed ratio of the distance between the distal sensor and the end-effector and the distance between the two sensors. Real world position p_w must also be transformed from the device coordinate system to world coordinates using the transform,

$$f\left(\begin{bmatrix} R_{00} & R_{10} & R_{20} & T_0 \\ R_{01} & R_{11} & R_{21} & T_1 \\ R_{02} & R_{12} & R_{22} & T_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}\right) = \begin{bmatrix} R_{11} & R_{21} & -R_{01} & -T_1 \\ R_{12} & R_{22} & -R_{02} & -T_2 \\ -R_{10} & -R_{20} & R_{00} & T_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

If two of the sensors are in close physical proximity, the disturbance of the magnetic field of one may affect the other's accuracy adversely. To eliminate the systematic errors in measurement due to interference, the system detects cases where the distal sensors are within 10mm of each other and, for these samples, calculates p_w based only on the proximal sensor position and orientation.

2.3. The User Interface

The software component of the system is comprised of separate interfaces for acquisition and analysis. Both interfaces make use of a common library for trace analysis written in C++. The acquisition program provides a simple interface, using the FLTK windowing library, to store new traces in the motion database. The analysis program uses the OpenSceneGraph library to allow real-time, three-dimensional playback and analysis of user traces from the motion database. To assist the user in self-assessment, several performance metrics are computed by the common library and reported via the interfaces.

3. TEST DESCRIPTION

The exercises in the training program are designed to train hand eye coordination using basic tasks as designed by the training supervisor. These tasks can be standardized or customized for the individual needs or requirements of a specific student or program.

Using the console, the mentor defines the appropriate basic skill pathways for the novice surgeon to manipulate his instruments, over a set of synthetic models. An immersive training simulation is being generated by recording an expert surgeon perform a real operation while using this system. Intra-operative data is stored and later accessed at one or multiple training stations that are designed to reproduce an operating surgeon's ergonomic experience.

Due to system design the specific tasks for a basic training session are independent of the performance metrics. The basic performance metrics are based strictly on the kinematic analysis of the instrument motion. This approach offers flexibility for in situ and impromptu designed training tasks as deemed appropriate by the mentor.

For complete surgeries or complex scenario training a different set of performance skills are to be designed that should take into consideration more complex factors that should take into account the transition from a skill based behavior to a rules and knowledge based behavior [33].

In this exercise we start with a short explanation of the difficulties encountered during laparoscopic surgery: fulcrum effect, use of long instruments, poor depth perception, and disorientation, with the goal of mentally preparing the trainee to the difficulty of the task ahead. Following this preparation, the user is then introduced to the training task as described in Fig 5 a-e.

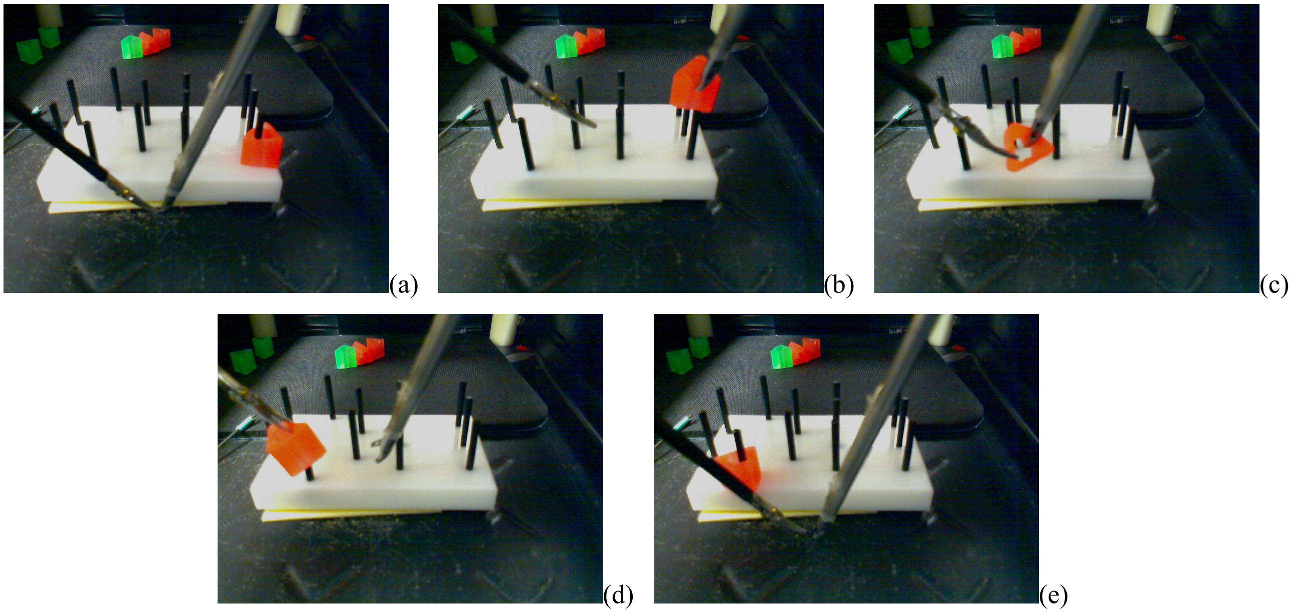


Fig. 5. (a) place the instruments in a central neutral position, (b) pick the rubber piece located on the right side peg the with the needle driver (in the right hand), and lift it out of the peg, (c) over the training board pass the rubber piece from the needle driver to the grasper (grasping with the left hand), (d) using the grasper now place the rubber piece over the peg located on the left hand side, (e) release the rubber piece and bring both instruments back to the central location.

To complete this training task, repeat the previous steps but in reverse order, thus transferring the rubber piece from the peg on the left hand side to the right hand side peg, and again end with both instruments in the central location. Repeat these tasks for 10 times and then analyze the kinematic performance parameters for the each participant in this study.

4. PERFORMANCE METRICS

To better develop an adequate training approach we propose specific objective metrics to assist in the evaluation of laparoscopic surgery skill. A variety of metrics have been previously suggested [34], with various degrees of success[10]. Although any metric that successfully distinguishes motions made by novice trainees from those made by expert surgeons is beneficial, the invention of new metrics is non-trivial, and their validation is expensive and time consuming. For these reasons we believe it is beneficial to use a principled approach to the development of new metrics. We believe that the tool tip motion of an expert surgeon using the UCLA – LTS strongly resembles normal human limb end effector (i.e. wrist) motion, as if the tool has become an extension of the surgeon's own limb, for the purpose of motion planning. This suggests that the neurophysiologic findings characterizing human arm motion should be a rich source of evaluative motion classifiers. Following this principle we propose performance metrics based on current neurophysiologic hypotheses.

3.1. Smoothness Metric

Early neurophysiologic work found that the speed profile of natural human arm motion is bell-shaped [26]. This finding has been generalized and extended to the general result that human arm motions naturally are as smooth as possible [35]. Our smoothness metric is derived directly from the "minimum-jerk" model developed by Flash and Hogan [25]. Maximally smooth motion is equivalent to motion that minimizes the total of the third derivative of the position ("jerk") over the course of the task. This metric has been previously suggested [23], and follows our general hypothesis that expert surgeons' tool-tip motion will resemble the motion of natural human limbs.

$$m_1 = \frac{\frac{1}{2}\int_{t_0}^{t_1}\left(\left(\frac{d^3 p_x}{dt^3}\right)^2 + \left(\frac{d^3 p_y}{dt^3}\right)^2 + \left(\frac{d^3 p_z}{dt^3}\right)^2\right)dt}{t_1 - t_0} \tag{3}$$

3.2. Total Path Length Metric

This heuristic metric is common among attempts to measure laparoscopic skill objectively. The assumption is that novice users will have poor economy of linear motion compared to expert users. This is been independently verified in previous studies [36]. The metric is the line integral along the path of motion:

$$m_2 = \int_{t=t_0}^{t_1}\sqrt{\left(\frac{dp_x}{dt}\right)^2 + \left(\frac{dp_y}{dt}\right)^2 + \left(\frac{dp_z}{dt}\right)^2}\,. \tag{4}$$

The path length implicitly captures common user errors, such as dropping the manipulated peg during the peg-transfer task, because such motions require additional tool-tip travel distance to correct, such as retrieving the dropped object.

3.3. Time to Completion metric

A common measure of the user's ability is the time required to complete the task,

$$m_3 = t_1 - t_o \tag{5}$$

Time-to-completion has been previously shown to be a good distinguisher of user skill [36], and is an intuitive measure. Nonetheless, over-emphasis on this metric encourages students to learn speed over precision. We suggest that the time-to-completion metric, as the easiest to measure and most common, has been over-emphasized in practice. To correct this, we adjust the relative weighting of the time-to-completion in the total score.

3.4. Scoring

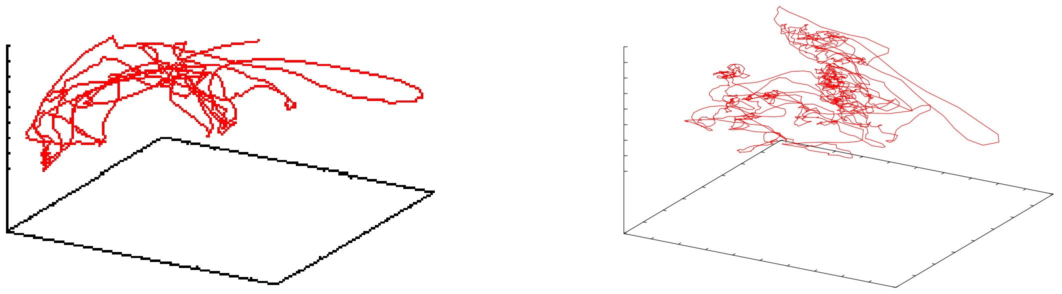
The total score, s, for a task is an affine sum of the relevant metrics, m_i, scaled by weighting constants, k_j, as

$$s = \sum_i k_j m_i \tag{6}$$

The weighting factors serve to both normalize the metrics to a common abstract unit and to provide a relative measure of importance. To compute the total score, each metric was multiplied by a constant, k. Each metric's k was the maximum expert measurement attained, times an affine weighting factor of 0.5 for path-length, 0.2 for Time-to-Completion, and 0.3 for smoothness.

5. TEST DATA

A small number of trials were performed using the described system to illustrate its utility at performance evaluation. Two traces of recorded motion, one from an expert (a) and a second from a novice (b), are shown in Fig 6.

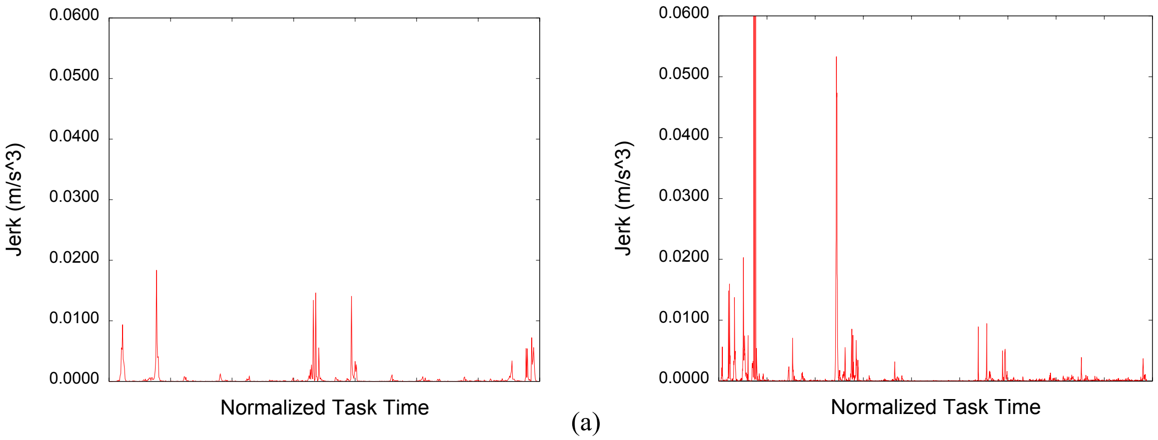


(a) (b)

Fig. 6. Two example motion traces for the peg-transfer task showing clear differences in the character of motion tracked between an (a) expert surgeon and a novice (b).

Although contained in about the same physical volume, the expert surgeon describes a smooth and efficient instrument tip pathway. The novice trainee on the other hand wanders around as it repeatedly attempts to grab the rubber piece, or to pick it up from the floor after it dropped from his instrument. A clear difference is qualitatively visible from this graphical representation alone.

The smoothness metric, as seen in Fig 7 directly compares the amount of "jerk" during a peg-transfer task, and provides a measure of the amount of change in acceleration at the tool-tip during the training task. .



(a) (b)

Fig. 7. these graphs show the instantaneous jerk (third derivative of motion) of an expert (a) and a novice (b) that provides the basis for the Smoothens Metric.

The novice user's motion is substantially less smooth than the expert performing the same peg-transfer task. Note that expert trace shows high "jerk" at the beginning, middle, and end of the training task. These times correspond to the rapid motion of the tool-tip from the neutral position to the object's position and back, and show the purpose driven motion of an expert. In contrast, the novice user shows a far less patterned motion though, with much larger changes in instrument acceleration (more than 3 times) as it attempts to grab the transfer object; the two anomalous spikes in the jerk are due to dropping the rubber piece on the floor of the training box.

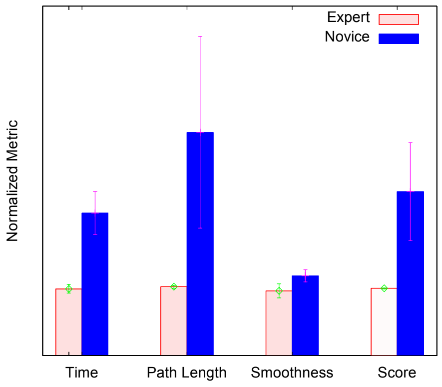


Fig. 8. the three baseline metrics and total score are shown for the expert and novice users. The error bars indicate the standard deviation for each metric (for experts, n=2; for novices, n=3)

Although a rigorous validation is out of the scope of this work, Fig 8 shows that even for the small number of investigators tested, each of the metrics individually is able to distinguish novice from expert motions. The Score bars show the affine sum of the metrics of novice and expert users, and demonstrate the potential for performance evaluation.

6. CONCLUSIONS

The UCLA – LTS is built around the idea of using actual laparoscopic instruments on a PC based training environment thus combining the simplicity of the training boxes currently approved by SAGES (Society of American Gastrointestinal and Endoscopic Surgeons) with the advances in PC based virtual reality trainers currently available on the marketplace. An important development is the integration of the motion tracking sensors into the shaft of actual laparoscopic instruments, and therefore the instrument functionality is preserved. As a consequence these instruments can be used for collecting kinematic data while performing actual surgeries not just the basic training session over a synthetic model. This presents the opportunity for high fidelity training on actual cases, and the exposure to large number cases from that same simulator/trainer and without unnecessary risk to the patient. An obvious advantage when compared to either the classical training boxes or the PC based virtual reality based trainer is the increased variety of training material. By having an expert surgeon design each and every task the training simulation is not limited to the prepackaged simulations. Training tasks can be retrieved from the database of standardized curricula or can be designed by the training expert specifically for the needs of a certain surgeon, or of a specific upcoming surgery. The ability to design any skill deemed necessary by the expert is unlimited, from basic skills to complex surgery without the need to buy the additional software simulation package.

Expertise from several sources and therefore different technical approaches can be accessed on this trainer. This enables not only more depth to trainee teaching, but equally important allows expert surgeons to exchange technical information for the betterment of surgical education. We envision a future where medical schools will have a data base of surgeries performed with this kind of instruments. These databases can become public knowledge to be exchanged for the good of the society, among the physician body, as a means of communicating and improving upon surgical knowledge and competency, just as other published research material.

The electromagnetic motion sensors have been used previously to track motion for assessment of surgical skills, either by tracing instruments [37], or surgeons hands [38]. Since the magnetic fields experience no attenuation in the human body, there is no "continuous line of sight" requirement as in other instrument tracking systems. The major drawback, magnetic field distortion due to metallic instruments nearby is addressed by Ascension through the use of specific pulsed DC signals in the active source [39]. After each source coil is activated with the DC current, the system waits for the eddy currents induced in the nearby metallic object to die out before taking the measurement. By using only a small volume to track the instruments and therefore the magnetic sensors we overcome the drawback of position and orientation resolution degrading as the fourth power of the separation distance [39]. This also minimizes the latency issue normally associated with the need to use filter the noise of the signal.

Given the large variety of training tasks that from the basis of the UCLA –LTS we couldn't rely on the performance metrics normally used on the PC based VR reality trainers. The other approach to asses the performance of training on SAGES approved laparoscopic training boxes needs the presence of an expert on site. We addressed the challenge of giving meaningful performance metrics for the impromptu designed training tasks through the use of kinematic analysis of instrument tip. Metrics such as motion smoothness, total path length graphical display and time to completion analysis, are complimented by an overall score defined as their affine sum. Within the limitations of this study, these performance metrics were able to reveal the differences of surgical skill among the participants, and therefore segregate novices from expert surgeons.

7. REFERENCES

1. *hand assisted laparoscopic procedures*.
2. Nippon Geka, G.Z., *Laparoscopic surgery for gastrointestinal malignancies.* 2000. **101**(8): p. 525-30.
3. Rosser, J.C., L.E. Rosser, and R.S. Savalgi, *Skill acquisition and assessment for laparoscopic surgery.* Arch Surg, 1997. **132**(2): p. 200-204.
4. Rosser, J.C., Jr, L.E. Rosser, and R.S. Savalgi, *Objective Evaluation of a Laparoscopic Surgical Skill Program for Residents and Senior Surgeons.* Arch Surg, 1998. **133**(6): p. 657-661.
5. J. A. Martin, G.R., R. Reznick, H. Macrae, J. Murnaghan, C. Hutchison, M. Brown,, *Objective structured assessment of technical skill (OSATS) for surgical residents.* British Journal of Surgery, 1997. **84**(2): p. 273-278.
6. Aggarwal, R., J. Hance, and A. Darzi, *Surgical education and training in the new millennium.* Surgical Endoscopy, 2004. **V18**(10): p. 1409-1410.
7. Chen, W., et al., *Operative time is a poor surrogate for the learning curve in laparoscopic colorectal surgery.* Surgical Endoscopy, 2007. **V21**(2): p. 238-243.
8. Aucar, J.A.G., Nicholas R; Troxel, Scott A; Eubanks, Steve W, *A Review of Surgical Simulation With Attention to Validation Methodology.* Surgical Laparoscopy, Endoscopy & Percutaneous Techniques, 2005. **15**(2): p. 82-89.
9. Kothari, S.N., et al., *Training in Laparoscopic Suturing Skills Using a New Computer-Based Virtual Reality Simulator (MIST-VR) Provides Results Comparable to Those with an Established Pelvic Trainer System doi:10.1089/10926420260188056.* Journal of Laparoendoscopic & Advanced Surgical Techniques, 2002. **12**(3): p. 167-173.
10. Maithel, S., et al., *Construct and face validity of MIST-VR, Endotower, and CELTS.* Surgical Endoscopy, 2006. **V20**(1): p. 104-112.
11. Gallagher, A.G., et al., *Discriminative validity of the Minimally Invasive Surgical Trainer in Virtual Reality (MIST-VR) using criteria levels based on expert performance.* Surgical Endoscopy, 2004. **V18**(4): p. 660-665.
12. Adamsen, S., et al., *A comparative study of skills in virtual laparoscopy and endoscopy.* Surgical Endoscopy, 2005. **V19**(2): p. 229-234.
13. Avgerinos, D.V., et al., *Comparison of the sensitivity of physical and virtual laparoscopic surgical training simulators to the user's level of experience.* Surgical Endoscopy, 2005. **V19**(9): p. 1211-1215.
14. McNatt, S.S. and C.D. Smith, *A computer-based laparoscopic skills assessment device differentiates experienced from novice laparoscopic surgeons.* Surgical Endoscopy, 2001. **V15**(10): p. 1085-1089.
15. Hackethal, A., M. Immenroth, and T. BÃ¼rger, *Evaluation of target scores and benchmarks for the traversal task scenario of the minimally invasive surgical trainer-virtual reality (MIST-VR) laparoscopy simulator.* Surgical Endoscopy, 2006. **V20**(4): p. 645-650.
16. Madan, A.K., C.T. Frantzides, and L.M. Sasso, *Laparoscopic Baseline Ability Assessment by Virtual Reality.* Journal of Laparoendoscopic & Advanced Surgical Techniques, 2005. **15**(1): p. 13-17.
17. Windsor, J.A. and F. Zoha, *The laparoscopic performance of novice surgical trainees.* Surgical Endoscopy, 2005. **V19**(8): p. 1058-1063.
18. *Procedicus MIST*. 2004, Mentice AB.
19. *LapSim System*. 2004, Surgical Science Ltd.
20. Duffy, A.J., et al., *Construct validity for the LAPSIM laparoscopic surgical simulator.* Surgical Endoscopy, 2005. **V19**(3): p. 401-405.
21. Langelotz, C., et al., *LapSim virtual reality laparoscopic simulator reflects clinical experience in German surgeons.* Langenbeck's Archives of Surgery, 2005. **V390**(6): p. 534-537.

22. Larsen, C.R., et al., *Objective assessment of gynecologic laparoscopic skills using the LapSimGyn virtual reality simulator.* Surgical Endoscopy, 2006. **V20**(9): p. 1460-1466.
23. Schijven, M. and J. Jakimowicz, *Construct validity.* Surgical Endoscopy, 2003. **V17**(5): p. 803-810.
24. Schijven, M. and J. Jakimowicz, *Face-, expert, and referent validity of the Xitact LS500 Laparoscopy Simulator.* Surgical Endoscopy, 2002. **V16**(12): p. 1764-1770.
25. Schijven, M.P. and J. Jakimowicz, *The learning curve on the Xitact LS 500 laparoscopy simulator: profiles of performance.* Surgical Endoscopy, 2004. **V18**(1): p. 121-127.
26. Feygin, F.T.M.H.D.M.S.S.L.W.P.M.C.C.M.K.C.S.M.D.D., et al., *VESTA*. 2004.
27. STYLOPOULOS., N., et al., *Computer-enhanced laparoscopic training system (CELTS): Bridging the gap.* Surgical endoscopy, 2004. **18**(5): p. 782-789.
28. Torkington, J., et al., *Skill transfer from virtual reality to a real laparoscopic task.* Surgical Endoscopy, 2001. **V15**(10): p. 1076-1079.
29. Kimura, T., et al., *Usefulness of a virtual reality simulator or training box for endoscopic surgery training.* Surgical Endoscopy, 2006. **V20**(4): p. 656-659.
30. Ahlberg, G., et al., *Does training in a virtual reality simulator improve surgical performance?* Surgical Endoscopy, 2002. **V16**(1): p. 126-129.
31. Munz, Y., et al., *Laparoscopic virtual reality and box trainers: is one superior to the other?* Surgical Endoscopy, 2004. **V18**(3): p. 485-494.
32. Hummel, J.B., et al., *Design and application of an assessment protocol for electromagnetic tracking systems.* Medical Physics, 2005. **32**(7): p. 2371-2379.
33. Wentink, M., et al., *Rasmussen's model of human behavior in laparoscopy training.* Surgical Endoscopy, 2003. **V17**(8): p. 1241-1246.
34. Cotin, S., et al., *Metrics for Laparoscopic Skills Trainers: The Weakest Link!* Medical Image Computing and Computer-Assisted Intervention - MICCAI 2002: 5th International Conference, Tokyo, Japan, September 25-28, 2002, Proceedings, Part I. 2002. 35-43.
35. Flash, T. and N. Hogan, *The Coordination of Arm Movements: An Experimentally Confirmed Mathematical Model.* Journal of Neuroscience, 5:1688--1703., 1985. **5**(7): p. 1688-1703.
36. Vassiliou, M., G. Ghitulescu, and L. Feldman, *The MISTELS program to measure technical skill in laparoscopic surgery : evidence for reliability.* Surgical endoscopy, 2006. **20**(5): p. 744-777.
37. Datta, V., et al., *The use of electromagnetic motion tracking analysis to objectively measure open surgical skill in the laboratory-based model.* Journal of the American College of Surgeons, 2001. **193**(5): p. 479-485.
38. Aggarwal, R., et al., *Motion tracking systems for assessment of surgical skill.* Surgical Endoscopy, 2007. **V21**(2): p. 339.
39. Foxlin, E., *Motion Tracking Requirements and Technologies*, in *Handbook of Virtual Environment Technology*, K. Stanney, Editor. 2002, Lawrence Erlbaum Associates. p. 163-210.