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Learning Kinematic Mappings in Laparoscopic Surgery

Felix C. Huang^{1,5}, Carla M. Pugh³, James L. Patton^{2,5}, and Ferdinando A. Mussa-Ivaldi^{4,5}[Member, IEEE]

¹Department of Biomedical Engineering, Northwestern University

²Department of Bioengineering, University of Illinois, Chicago

³Center for Advanced Surgical Education at Northwestern University

⁴Physical Medicine & Rehabilitation, Mechanical and Biomedical Engineering at Northwestern University

⁵Sensory Motor Performance Program, Rehabilitation Institute of Chicago

Abstract

We devised an interactive environment in which subjects could perform simulated laparoscopic maneuvers, using either unconstrained movements or standard mechanical contact typical of a box-trainer. During training the virtual tool responded to the absolute position in space (Position-Based) or the orientation (Orientation-Based) of a hand-held sensor. Volunteers were further assigned to different sequences of target distances (Near-Far-Near or Far-Near-Far). Orientation-Based control produced much lower error and task times during training, which suggests that the motor system more easily accommodates tool use with degrees of freedom that match joint angles. When evaluated in constrained (physical box-trainer) conditions, each group exhibited improved performance from training. However, Position-Based training enabled greater reductions in movement error relative to Orientation-Based (mean -13.7% , CI: $-27.1, -0.4$). Furthermore, the Near-Far-Near schedule allowed a greater decrease in task time relative to the Far-Near-Far sequence (mean -13.5% , CI: $-19.5, -7.5$). Training at shallow insertion in virtual laparoscopy might promote more efficient movement strategies by emphasizing the curvature of tool motion. In addition, our findings suggest that an understanding of absolute tool position is critical to coping with mechanical interactions between the tool and trochar.

I. Introduction

BE_{NCH-TOP} box trainers have been shown to provide meaningful training for the challenging and prevalent problem of learning surgical laparoscopic skills [1],[2],[3]. While lacking in realism, these training systems perhaps are successful by preserving features relevant to surgical conditions. If so, perhaps learning of surgical skill could be improved upon by focusing on key features of the task environment. Virtual reality interfaces have been proposed as a means to enhance training, by augmenting feedback [4–6], or presenting novel conditions. However, before identifying what features to emphasize in a surgical training environment, we need to determine what characteristics pose obstacles to learning.

Simulated laparoscopy environments offer opportunities not only for surgical training, but also as means to investigate the basis of manual dexterity in surgery. Researchers have provided some evidence that haptic feedback is essential for laparoscopic manipulation [7],

[8],[9]. Others have proposed that such information is masked by trochar friction [10], and is subject to perceptual limitations [11]. While the value of haptic cues could depend on the particular type of tissue or the active trochar resistance[10], the difficulties associated with perceiving and interpreting visual cues remains.

The underlying computational processes for spatial reasoning associated with laparoscopy, however, are not well understood. Keehner et al. [12] argued that while spatial reasoning ability was correlated with surgical performance, the importance of such predictors of performance was strongest with novices. Spatial ability might depend in part on learning a representation of tool operation in terms of its mechanical relationships. In a typical real-life situation, the laparoscope pivots about a fixed point. Therefore, the motion of the tip is opposite to the motion of the surgeon's hand. This reversal creates a sensory motor conflict. Additionally, the pivoting action of the tool produces curvature, which demands specific coordination to recover straight movements.

Researchers have suggested that the human nervous system employs specialized cerebellar processes for tools [13], adopts internal representations for objects with external degrees of freedom[14], and makes use of external coordinate systems appropriate for tool use. Beyond perception of space, the sliding and pivoting action of the tool within the trochar represents a kinematic constraint, which likely requires learning of specialized skills. Rather than simply test a candidate-training environment, we seek to understand the underlying learning processes inherent to surgical skills. To this end, virtual environments may allow an artificial decoupling of different features of control, such as sliding, pivoting, and the application of contact forces [15–16]. This enables independent analysis of each feature's influence on learning training roles of each element on the separate roles of each feature.

In this study we investigated the importance of learning the kinematic relationships associated with laparoscopy. We developed an experiment test-bed in which operators could control the movements of a virtual tool by manipulating a hand-held grip. Using this virtual environment, we examined how training in free space influences the ability to perform with true mechanical interaction between the tool and port (i.e. the virtual environment trochar). The interface was programmed to either respond to the absolute position or the orientation of hand motion, as measured from a sensor attached to the grip. While these control schemes were equivalent in task space, we hypothesized that their compatibilities with the motor system would differ. In addition, because we believed that learning could be influenced by workspace dependencies by the fulcrum effect, we also investigated the influence of practicing on near and far targets as well as target directions. We predicted that the fulcrum action of the tool would bias learning to either emphasize or hide certain features of the environment.

II. Methods

A. Human Subjects

In this study 28 healthy individuals volunteered and were randomly assigned to subject groups. All participants reported have normal or corrected to normal vision. Each subject provided informed consent in accordance with Northwestern University Institutional Review Board. Individuals were not paid for their participation.

B. Experimental Apparatus

Subjects performed a virtual laparoscopy task by controlling the movement of a custom-made plastic handle with finger grips. During the task, subjects were presented with real-time feedback from a video display system known as PARIS (Personal Augmented Reality Immersive System) described elsewhere [17]. The position and orientation of the handle was

tracked using a magnetic tracking system (Ascension Flock of Birds™). Using MATLAB and Simulink, we implemented a virtual surgical workspace, featuring a cubic environment (100 mm wide) with grid marking on the boundaries at 20 mm intervals. The port location was fixed at the top front edge of the workspace (See Fig. 2). Data was recorded at 66 Hz.

C. Development of Virtual Environment

We investigated motor learning of environments that featured the kinematic constraints involved in laparoscopic manipulation. A novel virtual environment, developed in our laboratory represented the pivoting and sliding motion of a laparoscopic instrument. This system was used to record real-time measurements of position and orientation of a handle. Real-time measurements position and/or orientation of a handle were used as inputs to drive the movements of a virtual laparoscopic tool.

We developed three different modes of operation, or mapping schemes: Direct Mapping, Position-Based, and Orientation-Based. Direct Mapping was employed in the control condition in which the tool was actually constrained by passing through a physical port. The motion of virtual tool in this mode simply mirrored that of the physical handle. Direct Mapping was employed in the control condition in which the tool was actually constrained by passing through a physical port. The motion of virtual tool simply mirrored that of the physical handle.

In the case of the physically constrained mode, the handle included a wooden dowel that was mechanically constrained to pivot and slide through a hole (10 mm diameter) in a stationary plastic brace. In the case of the virtually constrained mode of operation, the dowel and brace were omitted so that subjects operated the handle in free space. Instead of a mechanical constraint, the virtual environment presented simulated tool motion that maintained pivoting and sliding constraints without mechanical contact from the operator. The next two modes exploit the capabilities only possible in virtual environments that allow an artificial decoupling of kinematic relationships. These two modes each replaced the presence of the physical port with a virtual one, with each of these accurately preserving one kinematic aspect while ignoring (sacrificing) the influence of the other.

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For Position-Based mapping, the position of the handle of the virtual tool (x_h, y_h, z_h) coincided with that of the physical handle. With the position of the port (x_p, y_p, z_p) fixed, the orientation (θ_t, ϕ_t) of the virtual tool was completely determined:

$$\theta_t = \tan^{-1} \frac{y_p - y_h}{x_p - x_h}, \quad \phi_t = \tan^{-1} \frac{z_p - z_h}{\sqrt{(x_p - x_h)^2 + (y_p - y_h)^2}} \quad (1)$$

With the orientation of the virtual tool computed, the final constraint to be satisfied is the length of the virtual tool L to completely define the tool tip position (x_t, y_t, z_t). While this mapping scheme is simple and faithfully represents the position of the physical handle, it ignores the orientation information from user input.

For Orientation-Based mapping, the orientation of the virtual tool (θ_t, ϕ_t) corresponds to that of the physical handle (θ_h, ϕ_h). The linear translation of the tool, however, cannot follow that of the handle—otherwise the constraint to the port would not be maintained. Instead, the radial penetration of the virtual tool was calculated as the integrated motion of the handle projected along the tool axis. Given the linear velocity of the handle $\dot{\mathbf{r}}_h$ and the orientation (θ_h, ϕ_h) with respect to a global reference frame (i, j, k), the radial penetration of the virtual tool is:

$$\Delta r_t = \int \dot{\mathbf{r}}_h \cdot (\cos\phi_h \cos\theta_h \hat{i} + \cos\phi_h \sin\theta_h \hat{j} + \sin\phi_h \hat{k}) dt \quad (2)$$

The tool tip position (x_t, y_t, z_t) then maintains the length of the tool L while sliding by an amount equal to the computed change in radial penetration. Note that while Orientation-Based mapping faithfully represents the orientation of the physical handle, it ignores any translation orthogonal to the axis of the virtual tool.

D. Protocol

Subjects were asked to control the virtual tool so that the tip followed a target path as smoothly and accurately as possible. The display presented visualization of target paths as a white beaded line (40mm) between two target spheres (5 mm radius) at the endpoints. The trial ended when the tip was held within the final target for 1 second. To aid depth perception of the task, the target starting and ending points were visualized as spheres atop two poles fixed to the floor of the workspace. In addition, real time shadows of the target path and tool were presented during movement. Each group was presented with the same sequence of randomized target locations. The virtual tool length was 330 mm. See Table I for a summary of experiment conditions.

Our experiment design compared the influence of training from two forms of virtual laparoscopy. The two subject groups (14 in each) differed by their training mapping scheme (Position-Based or Orientation-Based). Both groups were evaluated in the Direct Mapping condition before and after training. Groups were also divided into subgroups presented with one of two target distance sequences: Near-Far-Near ($n=14$) or Far-Near-Far ($n=14$). Table I summarizes the schedule of the experiment trial blocks.

E. Data Analysis

We analyzed performance in terms of movement error and time, as means to measure accuracy and efficiency in movements. At each time step, the path error was computed as the distance along the line perpendicular to the target path to the tip position. As a final metric for path error, we considered the maximum perpendicular deviation from the direct path between targets. Movement time was simply calculated as the total duration of moving between targets. To examine the change in learning, performance for both metrics was calculated as the percentage change between the initial and final evaluation for each unique condition of target heading and movement direction.

In addition to evaluation blocks, we present an analysis of the changes in performance during training. To determine which conditions pose the greatest challenge to learning, we compared performance between mapping schemes and between training schedules. To determine how practice with near and far target distances (75 or 150 mm) transferred skill to each other during training, we analyzed how performance changed between the first 12 trials of each block (Far-Near-Far or Near-Far-Near transfer).

To analyze the change between evaluation blocks, we performed ANOVA considering both the between and within-subject experiment factors. The between subject factors includes control mapping (Position-Based or Orientation-Based) and target schedule (Near-Far-Near / Far-Near-Far), while the as well as within-subject factors included target heading (angle about the vertical: 67.5, 90, 112.5°), and path direction (left, right, up, down). Note that for the evaluation trials analysis, the between-subject factors pertain to conditions experienced during training, while within-subject factors pertain to evaluation conditions. Similarly, to assess performance during the training trials, we performed ANOVA considering the 5 between-subject factors: control mapping (Position-Based or Orientation-Based), target distance (near/far), target pitch (target angle about the horizontal: -33, 0°), target heading (angle about the vertical: 67.5, 90, 112.5°), and movement direction (left, right, up, down). We performed Tukey's post-hoc HSD (Honest Significant Difference) to determine how trends depended on specific experiment conditions. The threshold level of significance for both ANOVA and post-hoc tests was set at $\alpha=0.05$.

III. Results

A. Performance Evaluation with Physical Port

In the baseline evaluation block, subjects demonstrated systematic deviations in movement, which were consistent with a failure to compensate for tool rotation. Groups improved between evaluation blocks (path error: $F[1,24]=16.67$, $MSE=534.91$, $p=4.27e-04$; movement time: $F[1,24]=51.50$, $MSE=1406.36$, $p=2.04e-07$), indicating a training effect from practicing in the virtual surgery environment. Performance varied by movement direction (path error: $F[3,71]=27.60$, $MSE=420.28$, $p=5.43e-12$; movement time: $F[3,71]=17.17$, $MSE=203.98$, $p=1.64e-08$). Systematic curvature appeared most evident in the vertical directions of movement (See Fig. 3).

Our analysis of evaluation blocks revealed group differences, revealing separate trends for path error and movement time. Position-Based training reduced path error more than Orientation-Based training ($F[1,24]=4.53$, $MSE=0.36$, $p=4.36e-2$; mean -13.7%; CI: -27.1, -0.4). Subjects who trained in the Orientation-Based condition exhibited an average of $8.5\pm19.5\%$ decrease in error, while training with the Position-Based conditions resulted in a $22.3\pm13.2\%$ decrease (mean $\pm$ SD). The mapping scheme did not significantly influence changes in movement time. Subjects who trained with Near-Far-Near exhibited greater reductions in movement time compared to Far-Near-Far ($F[1,24]=4.36$, $MSE=3.07$, $p=4.76e-2$; mean -13.5%; CI: -19.5, -7.5). Subjects who trained with Far-Near-Far exhibited an average of $14.0\pm16.2\%$ decrease in movement time, while subjects training with Near-Far-Near exhibited a $25.8\pm13.0\%$ decrease (mean $\pm$ SD). The two block schedules did not differ in the change in path error.

Reductions in path error were greater for downward movements ($F[3,72]=11.00$, $MSE=3.66$, $p=4.98e-6$; compared to left, mean -30.8%; CI: -48.9, -12.7; $p=1.28e-4$; right, mean -31.4%; CI: -49.5, -13.3; $p=9.03e-5$, and upward movements, mean -24.0%; CI: -42.2, -6.0; $p=4.08e-3$, according to Tukey HSD). The training advantage exhibited from the Position-Based mapping was particularly evident for downward movements ($F[3,72]=5.87$, $MSE=1.96$, $p=1.21e-3$; mean -42.2; CI: -72.5, -11.8, $p=9.60e-4$, according to Tukey HSD). Differences between directions on the change in movement time were marginal ($F[3,72]=2.25$, $MSE=0.59$, $p=8.90e-2$).

B. Performance during Training

Training with the Position-Based mapping exhibited greater path error (mean: 3.04, CI: 1.89, 4.20, $p=2.83e-6$, t-test) and movement time (mean: 3.41, CI: 2.16, 4.66, $p=1.42e-6$, t-

test) compared to the Orientation-Based mapping. We observed performance variations particular to the Position-Based mapping from movement direction (path error: $F[3,63]=4.03$, $MSE=180.92$, $p=1.09e-2$) and heading angle (path error: $F[2,42]=5.48$, $MSE=146.54$, $p=7.70e-3$; movement time: $F[2,42]=8.53$, $MSE=182.54$, $p=7.75e-4$). Path error was greater in downward versus leftward (mean: 1.04, CI: 0.37, 1.72; $p=4.30e-4$) and rightward (mean: 0.94, CI: 0.26, 1.62; $p=2.02e-3$) directions. Movement time was greater in upward versus leftward directions (mean: 1.19; CI: 0.12, 2.25; $p=2.19e-2$). Path error was lower for 90° compared to 65° (mean: -1.42; CI: -1.95, -0.88; $p=2.54e-10$) and 112.5° (mean: -1.27; CI: -1.80, -0.74; $p=7.10e-8$). Movement time was lower for 90° compared to 67.5° (mean: -1.41; CI: -2.25, -0.57; $p=2.54e-4$) and 112.5° (mean: -1.07; CI: -1.91, -0.23; $p=8.29e-8$).

Focusing on the differences in performance between the first 12 trials of each training block, we confirmed successful skill transfer from near to far targets. We found that the Far-Near-Far exhibited better performance than Near-Far-Near only for the case of Position-Based mapping. The differences were significant for path error (mean difference: -0.15, CI: -0.30, 0.01, $p=4.36e-2$, T-test), but only marginally significant for of movement time (mean difference: -0.15, CI: -0.30, 0.01, $p=6.38e-2$, T-test). No differences were found between practice schedules for the case Orientation-Based mapping. These trends suggest that training with near targets results in successful skill transfer to far targets, specifically due to the lever amplification effect only present with the Position-Based mapping.

IV. Discussion

We devised an interactive virtual environment in which subjects could perform laparoscopic maneuvers with and without mechanical contact. Researchers have debated on whether tactile feedback [7],[8],[11] associated the interaction between the tool and the port is necessary for training. Even without mechanical contact, both mapping schemes contributed to improvements in performance between the evaluation blocks. Our primary finding was that training that faithfully represents the position of the tool grip as opposed to orientation of the tool resulted in greater reductions in path error during the evaluation conditions. Secondly, our analysis suggests that training that focuses in near targets results in a greater reduction in movement time. These results suggest that training in free space can contain useful information about the constrained tool operation. Beyond processing of haptic cues and general spatial reasoning [12], learning of laparoscopic maneuvers depends in part to understanding kinematic relationships.

The motor system has been shown to prefer a joint-based coordinate system for certain degrees of freedom of the arm [18], or for adaptation to novel environments [19]. However, external constraints, such as those occurring during laparoscopic tool use, simply pose a greater challenge to learning since the motor system cannot directly perceive external states or locations. To this end the Position-Based mapping may have presented a more realistic challenge since this condition preserved the features of absolute space. Note that the improved performance with the Position-Based mapping came at the cost of much larger error and longer task time during training. During training, movement exhibited errors which suggest incomplete compensation of tool rotation. These errors were most apparent for low pitch targets under the Position-Based mapping. The scale and curvature of tip movement depends on the effective mechanical advantage, which were features of both mapping schemes presented during training in this study. However, the use of a physical constraint requires positioning the hand in absolute space. Evidently, experiencing the large errors during Position-Based training provided learning relevant to the physical constraints of the evaluation task.

Beyond differences in orientation versus position mapping, we found that the training focused on near targets provided better training. Our findings show training of laparoscopic maneuvers featuring near targets (Near-Far-Near schedule) promoted greater reductions in task time in evaluation conditions. Because the trochar acts a fulcrum for the tool, there is a natural amplification / attenuation effect between the hand and tool tip movement. Jordan et al. [20] found that virtual laparoscopy training that featured more movement reversals prepared novice learners better for an incision skill transfer test. They argued that more exposure to the reversal actions due to fulcrum rotation allowed training more relevant to the target task. Previous studies have shown that error augmentation can enhance learning [21], presumably because amplified feedback accelerates appropriate changes to motor planning. It was plausible that practice with farther targets could have provided useful training. A lower mechanical advantage would have amplified movements of the tool tip relative to the hand, potentially providing heightened feedback about hand motion. However, because of the rotation of the tool, near targets would naturally promote greater curvature of tip motion—in effect providing more feedback about tool behavior. Training that was focused on near targets may have prepared subjects to employ a greater economy of movement for operation in the evaluation conditions.

The findings of this investigation provide a foundation for future investigations for how to improve training for laparoscopic skills. It remains to be seen whether absolute spatial relationships and the working insertion depth constitute the most critical learning challenges in practical surgical situations as they did in our simplified virtual environment. However, it is likely these fundamental mechanical behaviors underlie the more complex features of real-world laparoscopy. Our findings have shown that proper understanding of kinematic mappings alone, in the absence of haptic perception or visual transformation, contributes importantly to achieving improved performance in laparoscopy.

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Fig. 1.

Evaluation trials featured Direct Mapping (left), while training trials featured either Position-Based (center) or Orientation-Based (right) mappings. In Direct Mapping, the virtual tool motion (green) follows the full motion of the operator's input (orange) as constrained by a physical port. In Position-Based mapping, the virtual tool tip (x_t, y_t, z_t) is defined by a line of fixed length L , constrained through the port (x_p, y_p, z_p) and the hand positions (x_h, y_h, z_h). In the Orientation-Based mapping, the virtual tool mirrors the orientation (θ_t, ϕ_t) and radial motion (Δr) of the physical tool.

Fig. 2.

The visual display of the virtual surgery environment. Subjects attempted to control the tool (cyan) tip to move smoothly and accurately along a path (white beaded line). Starting targets varied in insertion depth R , heading angle θ , and pitch angle ϕ (not shown). The movement directions were left, right, up, or down.

Fig. 3.

Average trajectories for the four movement directions reveal systematic deviations from the ideal straight line paths in the initial evaluation trial block (far left). Errors typically reduce between initial baseline (top) and final evaluation for each training sub-group: two control mappings (Orientation-Based versus Position-Based, left/right) and two sequence of target distance (Far-Near-Far versus Near-Far-Nar, top/bottom). Coloring indicates progression in time (starting from red to and ending in blue), and cones indicate direction of motion.

Fig. 4.

Subjects who trained with Position-Based control and the Near-Far-Near target schedule exhibited the largest reduction in maximum error and task time. Training with the Far-Near-Far target schedule evidently promoted a tradeoff between the two metrics, while training with the Near-Far-near sequence promoted a similar advantage of Position-Based control for both metrics.

Fig. 5.

Average trajectories for vertical movements (shown w/95 percent CI) for training blocks at near (75 mm) and far (150 mm) targets reveal systematic error patterns for Position-Based control. These patterns suggest that subjects do not fully compensate for the intrinsic curvature due to kinematic constraints of sliding and pivoting tool action, especially at pitch angles away from center.

Fig. 6.

During training, Position-Based mapping exhibited greater overall path error compared to Orientation-Based mapping. Training with the Far-Near-Far target demonstrated a transfer effect from near to far targets but only for Position-Based mapping. The movement time metric (not shown) exhibited similar trends during training.

Table I**Experiment Conditions**

Virtual Tool Length:	330 mm
Starting Target Location:	
ϕ , pitch (Low, High)	-33, 0°
θ , heading	67.5, 90, 112.5°
R, distance (Near, Mid, Far)	75, 100, 150 mm
Path Direction:	Left, Right, Up, Down
Session 1:	
1. Baseline Evaluation (Physical Constraint)	
Direct Mapping, 24 Trials, 2 replicates	
Targets: R=100 mm, $\phi=-33^\circ$, all headings, all directions	
2. Training (Virtual Constraint)	
All Groups, 108 trials Per Session, 4 replicates	
Mapping: Orientation-Based or Position-Based	
Practice Schedule:	Near $\times$ 12, Far $\times$ 96 or Far $\times$ 12, Near $\times$ 96
Session 2:	
3. Training (Virtual Constraint)	
All Groups, 108 trials Per Session, 4 replicates	
Mapping: Orientation-Based or Position-Based	
Practice Schedule:	Near $\times$ 108 or Far $\times$ 108
4. Transfer Evaluation (Physical Constraint)	
(Same conditions as baseline Evaluation)	