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Laparoscopic Motor Learning and Workspace Exploration[☆]

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BACKGROUND: Laparoscopic surgery requires operators to learn novel complex movement patterns. However, our understanding of how best to train surgeons' motor skills is inadequate, and research is needed to determine optimal laparoscopic training regimes. This difficulty is confounded by variables inherent in surgical practice, for example, the increasing prevalence of morbidly obese patients presents additional challenges related to restriction of movement because of abdominal wall resistance and reduced intra-abdominal space. The aim of this study was to assess learning of a surgery-related task in constrained and unconstrained conditions using a novel system linking a commercially available robotic arm with specialised software creating the novel kinematic assessment tool (Omni-KAT).

METHODS: We created an experimental tool that records motor performance by linking a commercially available robotic arm with specialized software that presents visual stimuli and objectively measures movement outcome (kinematics). Participants were given the task of generating aiming movements along a horizontal plane to move a visual cursor on a vertical screen. One group received training that constrained movements to the correct plane, whereas the other group was unconstrained and could explore the entire "action space."

RESULTS: The tool successfully generated the requisite force fields and precisely recorded the aiming movements. Consistent with predictions from structural learning theory, the unconstrained group produced better performance after training as indexed by movement duration ($p < 0.05$).

CONCLUSION: The data showed improved performance for participants who explored the entire action space, highlighting the importance of learning the full dynamics of laparoscopic instruments. These findings, alongside the development of the Omni-KAT, open up exciting prospects for better understanding of the learning processes behind surgical training and investigate ways in which learning can be optimized. (J Surg Ed 73:992-998. © 2016 The Authors Published by Elsevier Inc. on behalf of the Association of Program Directors in Surgery. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).)

KEY WORDS: laparoscopy, surgery, motor control, kinematic, motor learning, structural learning

COMPETENCIES: Patient Care, Practice-Based Learning and Improvement, Professionalism

INTRODUCTION

Laparoscopic surgery has revolutionized medicine with greatly improved patient outcomes, yet it requires surgeons to learn complex and challenging movement patterns. In contrast to open surgery, laparoscopy can introduce a variety of constraints, such as restricted movement, degradation or loss of haptic feedback, reduced visual depth perception, as well as the fulcrum effect (where the hand needs to move in the opposite direction to that in which the tip of the instrument needs to move).[1] The difficulties associated with learning new motor skills when using laparoscopic instruments are exacerbated by the costs of clinical training and reduced training time, for example, the European working time directive has had a direct effect on training opportunities. Relatedly, the National Patient Safety Agency identified that surgeon factors are the most important elements in patient harm[2] and, commensurate with this, a recent survey of ASGBI members identified these issues as

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an area of concern for most surgeons.[3] Such pressures have contributed to the increased prevalence of virtual reality (VR) simulators that allow trainees to learn and practice surgical skills outside the operating theater.[4]A growing body of evidence suggests that VR training results in performance benefits in the operating room.[5-7]Training novice surgeons to automaticity leads to superior skill acquisition and transfer to the operating room. However, this requires an extensive amount of training, and the VR systems constitute a considerable expense.[8,9] Development of VR systems has suffered from the assumption that only high-fidelity simulators improve operating room performance, yet research clearly demonstrates the benefits of low-fidelity training.[10,11] In addition, disagreement over how best to integrate VR into training curriculums is widespread.[4] Thus, our understanding of the best way to train surgeons using VR is limited.

A major problem faced within laparoscopic skill acquisition is that movements must be generated through novel force fields that create unexpected forces perturbing planned movements.[12]For example, when controlling laparoscopic instruments, the interaction between the abdominal wall, laparoscopic port, and the instrument results in complex disruptive forces that vary across position and time. This is particularly noticeable in bariatric surgery where the restriction of movement because of abdominal wall resistance and reduced intra-abdominal space present additional challenges. The relative difficulty of learning to move in novel force fields suggests that this might be a particularly important aspect for consideration in laparoscopic training. In addition, laparoscopic training requires individuals to learn new perceptual-motor mappings while simultaneously learning how to move in a novel force field. It seems probable that these different challenges would interact, necessitating investigations into motor learning under these concurrent task constraints. However, despite the centrality of motor skill in surgical performance, there is a fundamental lack of research into the underlying factors that influence learning the complex visual-motor skills required by laparoscopic surgeons. It is clear that without such research, laparoscopic visual-motor training is unlikely to see significant advances in the near future.

Within the last 50 years, substantial progress has been made in our understanding of visual-motor control. A recent computational theory of motor skill acquisition—structural learning—suggests that specific training regimens can allow the central nervous system to learn general rules about how task parameters covary, improving later performance in novel environments (e.g., operating on a new patient).[13] The principles of structural learning have recently been shown to have implications for training surgeons on different port sites,[14] and thus predictions derived from the theory offer a potentially useful route toward understanding how to accelerate motor skill acquisition in this domain more generally. Although this approach is promising, the motion capture systems required to objectively record kinematics are often expensive and unsuitable for simulation of laparoscopic tasks, and VR trainers offer researchers poor experimental control.

In summary, there is evidence that training in VR simulators benefits laparoscopic skill acquisition.[8]However, it is equally clear that we do not know the best way of using these systems for optimum training outcomes. If we are to make progress in this area, a suitable research tool is needed—one that can parametrically vary the factors that make laparoscopic surgery difficult while providing detailed kinematic measures of performance. Critically, this should be achievable at a low cost to promote widespread use.

The kinematic assessment tool (KAT) presents an opportunity to address the problems identified: it is an experimentally validated, powerful and portable system capable of providing accurate and repeatable measures of kinematic performance.[15] KAT is a modular system that allows for easy integration with third-party controllers, circumventing the need for bespoke software solutions. An ideal controller for simulating laparoscopic style movements is the Phantom Omni: a force feedback haptic device, which allows movement across 6 degrees of freedom, with variable force along the X-, Y-, and Z-axes. The Phantom Omni has previously been successfully integrated with VR systems, demonstrating its suitability for investigating motor learning in surgery.[16] The combination of a precise kinematic assessment device with an ecologically valid controller (i.e., users interact with the Phantom Omni by holding an intuitive pen-like stylus) allows hypotheses regarding the learning of surgical tasks to be experimentally investigated. Here we create such a device and test its merits by exploring whether it can provide useful data to address a relevant question: is it easier to learn planar movements when training is constrained to a plane or when training takes place in unconstrained Cartesian space? Constrained conditions make the requisite perceptual-motor map explicit, whereas unconstrained movements allow full exploration of the relationship between movement of the device and the perceptual outcomes. This tests a key prediction from structural learning theory suggesting that full exploration of a task's workspace produces better learning.

MATERIALS AND METHODS

Description of Experimental Tool

We developed an experimental tool based on the KAT system.[15] The KAT system allows investigation of human motor control by recording end point movement data (kinematics) in response to visually presented stimuli. KAT has a modular software structure, developed using LabVIEW (National Instruments, version 2010), permitting the use of different input devices. The key development of the KAT software to make it suitable for exploring issues relating to laparoscopic surgery involved replacing the original input device (a stylus) with a commercially available 6 degrees of freedom haptic device (SensAble Technologies Inc., PHANTOM Omni). This provides 2 key features, (1) the manipulandum has a full 6 degrees of freedom that allows one to produce natural movements while manipulating objects displayed on a 2D screen—in the same way that a laparoscopic device allows one to move in Cartesian space and view this information on a remote monitor in the operating theater and (2) the haptic device can be controlled to provide a range of force fields during a task (up to a maximum of 3.3 N, with a 0.05-mm positional reporting resolution).

The Omni is a portable device that is compact and easy to use. It is controlled from a PC using an IEEE-1394a FireWire interface and the QuickHaptics software toolkit (SensAble Technologies Inc.) that provides device drivers and an application programming interface for interaction with third-party software. The KAT software was modified to integrate an interface to the QuickHaptics application programming interface, thus providing a mechanism for measurement and control of the Omni haptic device. This device has previously been used to examine a variety of manual control tasks, from handwriting to surgery.[17,18]

This development (combining KAT with the Phantom Omni) would be described as the Omni KAT (Omni-KAT) from hereon to distinguish it from the original systems.

Figure 1 illustrates the configuration of the Omni-KAT system. The Omni interface obtains the 3-dimensional Cartesian position of the Omni stylus, and 2 of the coordinates are selected to drive the task. This determines the plane in which the 2-dimensional motor tasks are orientated within the Omni workspace. In addition, the Omni interface simulates a spring element (using the haptic force capabilities of the device) that acts between the stylus tip and a center point. The spring stiffness and position of the center point in each axis can be configured per task to create a customizable force field where the force varies predictably with the spring extension.

Participants

Participants ($n = 21$; 17 males/4 females) were recruited via an opportunity sample from the University of Leeds. The ages ranged from 20 to 32 years (mean = 23.31 y, standard deviation = 3.45 y). The group consisted of 20 right-handed individuals and 1 left-handed individual. All participants reported a normal sense of touch and vision and had no history of neurological problems. Participants all gave informed consent, and ethical approval was granted by the University of Leeds in line with the declaration of Helsinki.

Task and Procedure

Participants sat on an adjustable seat in front of a table on which the Phantom Omni controller was placed. A Toshiba Tecra M7 (screen: 303 × 190 mm^2, 1600 × 1200 pixels, 16 bit color, 60 Hz refresh rate) was positioned to the right of the Omni. The screen was angled vertically (90° to the table). Participants were required to use the Omni stylus to guide a cursor on the Toshiba display. Movement across the X and Z plane resulted in corresponding movement of the displayed cursor. Movement along the Y-axis had no effect on the cursor. Green dots of 10-mm diameter appeared sequentially on the screen in a pentagram pattern. Participants were required to move the cursor to each dot as quickly and as accurately as possible (Fig. 2). When a dot was reached (defined as staying within its boundary for > 0.5 s), the next dot in the sequence was displayed. There were 60 dots in total within a block.

Participants were randomly assigned to 2 training groups. In the “constrained” group, no force was applied to the X and Z plane, whereas a force was applied in the Y-axis using a spring element (stiffness = 2 N/mm) with an origin 20-mm below the Y minimum position limit. This configuration pulled the stylus toward an explicit X-Z plane along which it moves. In the unconstrained group, no forces were applied in the X-, Z-, and Y-axes. Participants completed 2 blocks of training trials (trials 1 and 2). Subsequently, all participants immediately completed 2 test blocks (60 dots per block) in which movements were *unconstrained* in all axes (trials 3 and 4). The total movement time between dots was recorded for each block.

Outcome Measures

We recorded 2 specific measures of performance, (1) mean movement time (MT), the time taken by participants to

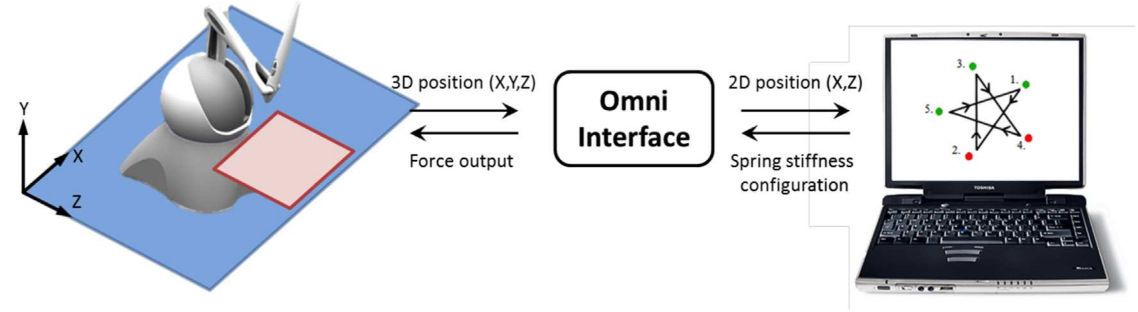

FIGURE 1. A schematic of the Omni-KAT system. The Omni interface is used to transfer data between the Omni and the Omni-KAT Software. Overlaid on the Omni device is the plane in which the task was orientated (red) and the Cartesian coordinate system (white). The Omni-KAT display shows the pentagram task used in this study.

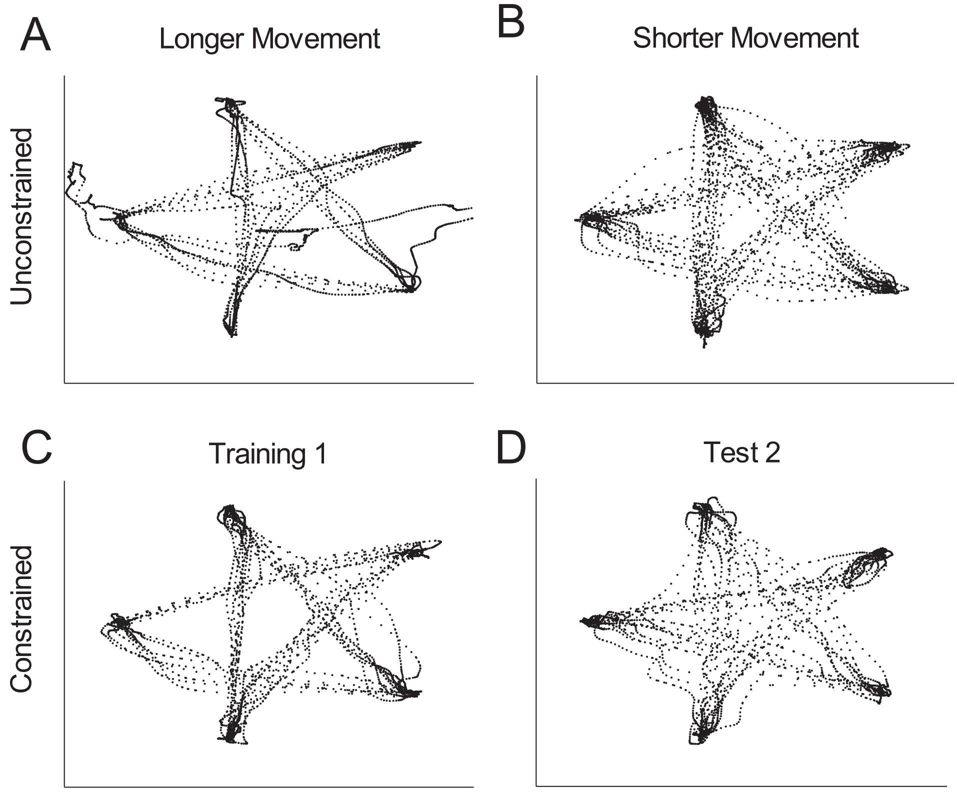

FIGURE 2. Tracing the 2-dimensional pentagon. Participants were required to use the Omni-KAT device to move from one dot to the next to follow the pentagon shape. Dots were repeated one at a time in sequence of 60 times within a single block, with each dot appearing sequentially after the required movement to the previous dot had been completed. The task consisted of 4 trials—2 training blocks (constrained or unconstrained) and 2 test blocks. Example traces of individual trials are shown for the Trial 1 (left hand panels; longer MT) and Trial 4 (right hand panels; shorter MT) for a participant in the unconstrained group (top panels) and a participant in the constrained group (bottom panels). Data points were sampled at 125 Hz.

move the Omni stylus from 1 dot to the next; (2) The normalized jerk (NJ) of movement. Jerk is the time derivative of acceleration, and this score was normalized with respect to time and distance such that trajectories of different durations and lengths could be compared giving a measure of "smoothness" of the movements. Skilled motor behavior is usually quick (low MTs) and smooth (low NJ), whereas poor motor skill can be slow and involve many corrective adjustments (which can cause jerkier movements).

Statistical Analysis

The MT and NJ data were input into separate, mixed 2×4 (training group × trial) analyses of variance (ANOVA). Greenhouse-Geisser estimates of sphericity (ε) are reported where degrees of freedom have been adjusted.

RESULTS

Mean Movement Time

The mean MT for the 2 training groups for each trial are shown in Figure 3A. Details of the ANOVA are shown in Table 1. Performance improved in both groups across the trials (MT decreased). There was no difference between the constrained and unconstrained groups during training (trials 1 and 2). Crucially, at test (trials 3 and 4, where movements were unconstrained for all participants) the participants that were unconstrained during training performed significantly better (shorter MTs) than participants who had been constrained.

Normalized Jerk

NJ for the 2 training groups for each trial are shown in Figure 3B. Details of the ANOVA are shown in Table 2. The overall pattern is similar to that seen in MT. Performance for both groups is better across the trials (jerk reduces reflecting smoother movements). The main difference is that the unconstrained group had significantly higher NJ values during training (trials 1 and 2), which presumably reflects the corrective movements required to find the correct plane of motion. When both groups performed the unconstrained test (trials 3 and 4), there was no longer a significant difference between the 2 groups suggesting that smoothness of performance transferred from training to test for both groups.

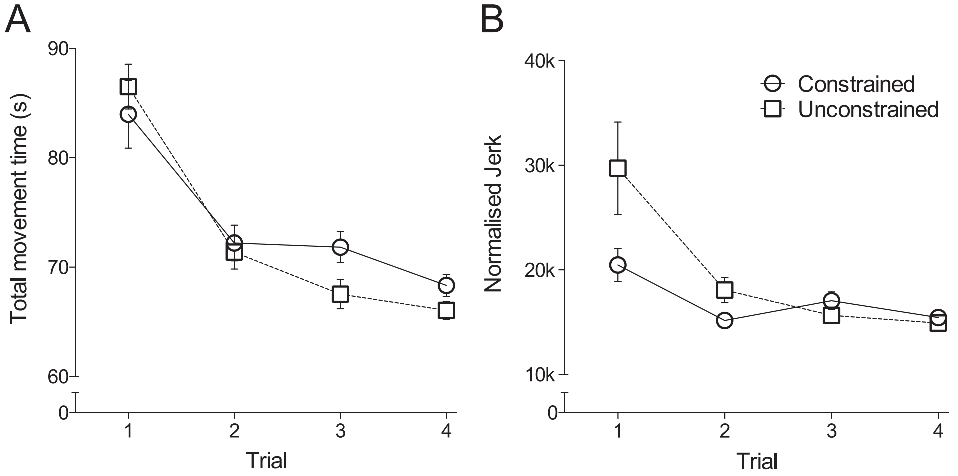

FIGURE 3. (A) Total movement time during trials for the constrained (circle symbol, solid line) and unconstrained (square symbol, dotted line) groups. A smaller value indicates faster movements. (B) Normalized jerk during trials for the constrained and unconstrained groups. A smaller value indicates smoother movements. Error bars represent SEM.

DISCUSSION

The Omni-KAT device was designed to replicate some of the fundamental demands of laparoscopic surgery, for example, the manipulation of tools in 3D using visual information provided on a remote (2D) monitor display. These data demonstrate that this system is able to provide a cost-effective (low cost, off-the-shelf equipment) yet powerful method to measure and investigate motor skill learning related to minimally invasive surgery (MIS). A large range of forces, spatial restrictions, and visual-motor mappings can be parametrically varied to manipulate and study the factors that make laparoscopic surgery difficult. This can be achieved easily through Omni-KAT that also automates data analysis to generate standardized kinematic performance metrics.

A recent motor learning theory suggests that general rules about a class of behaviors can be extracted to accelerate learning; a process termed “structural learning.”’[19] In our experiment, performance at test was significantly better for participants who trained in an unconstrained condition. These findings suggest that learning the device control dynamics was more beneficial than having the requisite plane for optimum movement made explicit. This result is consistent with the prediction of structural learning theory. The performance benefits conferred by exploring controller dynamics reflects the importance of error-based learning yet, to the best of our knowledge, no studies have examined previously whether constraining movement to the required perceptual-motor plane improves later performance.[13] Our findings are consistent with recent studies that have found exposure to random or gradually varying rotation angles of displacement speeds up subsequent adaption to a novel rotation.[20,21] Within the surgical literature, there is further evidence to support this suggestion; adaption to the “fulcrum” effect is facilitated by training under randomly alternating viewing conditions.[22] The practical implication of our findings is that the surgical trainees should not be subjected to constraints when learning new device dynamics and that training for a specific task (e.g., using the laparoscopic diathermy tool) can benefit performance in a similar task (such as the use of the clip applicator on the cystic duct and artery).

TABLE 1. The Effects of Training Group and Trial on Movement Times

	Movement Time (MT)				
	F	***df***	η_{p2}	ε	**p**
Training group (TG)	0.69	1,19			>0.05
Trial	72.16	3,57	0.79	0.55	<0.001
Trial × TG	3.79	3,57	0.17	0.55	<0.05

It is worth noting that there are some limitations to the present study. In contrast to laparoscopic surgery, Omni-KAT in its current configuration is unimanual—thus, it remains an open question whether these findings translate to the bimanual task demands of laparoscopic surgery.[23,24] Work is underway to integrate 2 robotic devices with Omni-KAT to better understand issues related to bimanual control and motor learning. Secondly, we only used participants with no previous knowledge of laparoscopy to ensure that experience was matched across training groups. Further research is required to examine the value of the methods described here in trained surgeons and the effect of the training methods described here on different stages of surgical training (e.g., it is reasonable to predict that the value of variation in training may vary with function of experience).

The present results suggest that learning planar movements (such as dissecting the gall bladder from the liver bed during a laparoscopic cholecystectomy) is hindered if training is constrained to a plane despite this allowing the surgeon to develop an appropriate perceptual-motor map.

TABLE 2. The Effects of Training Group and Trial on Smoothness (Normalized Jerk)

	Normalized Jerk (NJ)				
	F	***df***	η_{p2}	ε	**p**
Training group (TG)	16.56	1,19	0.47		<0.001
Trial	72.16	3,57	0.79	0.55	<0.001
Trial x TG	4.63	3,57	0.20	0.39	<0.05

In contrast, allowing the surgeon to move through unconstrained Cartesian workspace eventually leads to improved performance because of enhanced learning of the control dynamics of the surgical instrument. These findings demonstrate the usefulness of Omni-KAT in helping us understand how trainee surgeons can learn to move skilfully in the presence of complex disruptive force fields—and provide insights into optimal virtual training environments. The insights provided may lead to techniques that can improve the ability of surgeons to learn and adapt to the complex visual-motor challenges presented by laparoscopy. For example, structural learning is thought to improve both feed-forward learning and feedback control (greater speed and accuracy) in prism adaption and handwriting, and our current results indicate that structural learning is also relevant in MIS.[21,25]

To summarize, the present work demonstrates that a novel research tool (the Omni-KAT) allows one to examine motor skill learning in an environment that simulates some of the task demands of laparoscopic surgery. The degree of precise control and flexibility offered by the system means that there is substantial potential for this system to be used for the training and assessment of laparoscopic surgeons' motor skills. Finally, the experimental data reported here demonstrate the considerable potential value of using current approaches in understanding motor learning (e.g., structural learning) to accelerating skill acquisition in MIS-related tasks.

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