2007

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JOURNAL OF LAPAROENDOSCOPIC & ADVANCED SURGICAL TECHNIQUES
Volume 17, Number 1, 2007

DOI: 10.1089/lap.2006.05101

Technical Report

Objective Assessment of Proficiency with Bimanual Inanimate Tasks in Robotic Laparoscopy

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ABSTRACT

Purpose: Development of objective criteria and optimum training protocols are priorities for robotic laparoscopy. However, studies that have attempted to objectify learning have been limited due to lack of task complexity and absence of comparisons between experts and novices. Our aim was to address these limitations and assess proficiency in robotic laparoscopy using bimanual inanimate tasks.

Materials and Methods: Six experts and 18 novice users of the da Vinci surgical system (Innovative Surgical, Sunnyvale, CA) performed three bimanual surgical manipulations, two of them in opposite directions, for a total of five different test tasks. During each task, elapsed time and kinematics with respect to the instrument tips were measured and a bimanual coordination analysis was conducted to assess the relationship between the simultaneous movements of both arms. Specifically, task completion time, total traveling distance of the instrument tips, and mean absolute relative phase—a variable for the assessment of bimanual coordination—were calculated for each task and compared between groups.

Results: The experts showed significantly shorter task completion times for all tasks ($P < 0.05$). Significantly higher mean absolute relative phase values were observed for the experts in two tasks ($P < 0.05$). There were no significant differences regarding total travel distance.

Conclusion: Expert users of the da Vinci surgical system performed the designed surgical tasks faster and with higher bimanual dexterity than novices. Bimanual coordination analysis and the tasks used in this study show promise for becoming important components of the objective criteria needed to quantify proficiency in robotic laparoscopy.

INTRODUCTION

Laparoscopy is a minimally invasive surgical technique that has been an invaluable tool for diagnosing abdominal pathology.[1,2] However, several studies have reported a number of serious limitations of the manual instrumentation, including loss of binocularity, inverted perceptual/motor correlation,[3] small working spaces,[4] painful surgical posture and consequent fatigue.[5,6]

Robot-assisted laparoscopic technology has been developed to explore alternative procedures to address these limitations[4,7–9] and researchers have examined the effectiveness of the robotic surgical systems relative to the

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conventional procedures. Yohannes and colleagues showed that robotic laparoscopy allowed surgeons to accomplish suturing and several dexterity skills more quickly than manual laparoscopy.[4] DeUgarte and coworkers also suggested that junior residents can be instructed easily and quickly not only in conventional laparoscopy, but also in robotic surgery.[8] On the other hand, several studies concluded that operative task time was generally prolonged by the use of robotic surgery systems.[7,10,11] Therefore, the effectiveness of robotic laparoscopy is still questionable, although it seems to have great potential. However, no practical criteria or training protocols to evaluate and enhance surgeons' proficiency have been established for robotic laparoscopy. Most institutions employing robotic surgery systems seem to determine surgeons' training and skill level based only on subjective evaluations from a few experts. This is a serious problem which could stunt further growth and dissemination of robotic procedures.

To address this problem, recent research has attempted to identify objective variables that can distinguish between skilled and unskilled performance, as well as to establish a learning curve that can demonstrate traits of skill acquisition in robotic laparoscopy. Hernandez and colleagues used the Objective Structured Assessment of Surgical Skills and motion analysis, including task completion time, path length, and the number of movements made to objectively assess robotic surgical skill and construct learning curves.[12,13] Our research group has previously used extracted real-time kinematics from the da Vinci surgical system application programming interface (API) (Intuitive Surgical, Sunnyvale, CA) to examine proficiency.[14] This allowed the assessment of the actual movements made by the surgeons during a task and the ability to draw objective conclusions about the quality of performance.

Despite these improvements, findings have still been limited, for several reasons. First, direct comparisons between skilled or expert users and novices have been very limited. Second, assessment of bimanual coordination has been ignored, even though surgical tasks usually require simultaneous movements of both arms in a specific relationship. Third, the tasks examined in previous studies lacked in complexity.

In this study, we aimed to objectively assess proficiency in robotic laparoscopy using bimanual inanimate tasks. These tasks were designed to challenge bimanual coordination during performance. We tested experts and novices in the use of robotic surgical tasks. Furthermore, to better examine bimanual coordination, we used variables derived from the API kinematics and a coordination analysis from the area of motor learning and control.[15–19] This analysis is capable of measuring the relationships between the movements of both arms.

MATERIALS AND METHODS

After obtaining approval from Institutional Review Board at University of Nebraska Medical Center (UNMC), six expert users of the da Vinci surgical system, including surgeons and surgical residents of the UNMC robotic surgery laboratory (five men and one woman; mean age, 35.8 ± 3.7 years), and eighteen novice users of the system (first and second year medical students at UNMC; eleven men and seven women; mean age, 24.6 ± 2.1 years) were recruited to participate in this study. The following inclusion criteria were confirmed when screening the expert users: previously taking a training course of the surgical system held by the manufacturer; having experience of animate (human or animal) procedures with the surgical system; and operating the system more than twenty times in the past twelve months. Informed consent according to university guidelines was obtained from each subject prior to their participation.

At the beginning of the test, all subjects received a verbal explanation of the use of the surgical system and the testing procedures from the investigators and they familiarized themselves with the system (but not with the manipulations) for 5 minutes. During this familiarization or warming-up period, the subject was allowed to ask questions and receive further verbal explanation or suggestions from the investigators. After familiarization, the subject was asked to perform three inanimate laparoscopic manipulations with the system:

- Rope running (RR) consisted of running a 560×2 mm polyester rope with ten 20-mm grasping sites by using the right and left surgical instruments and a specific hand-to-hand technique (Fig. 1). This was performed in both directions, running the rope from left to right (task RR1) and from right to left (task RR2).
- Bimanual carrying (BC) consisted of picking up a 15×2 mm rubber piece from a 30-mm metal cap with right and left instruments, respectively, and carrying them to

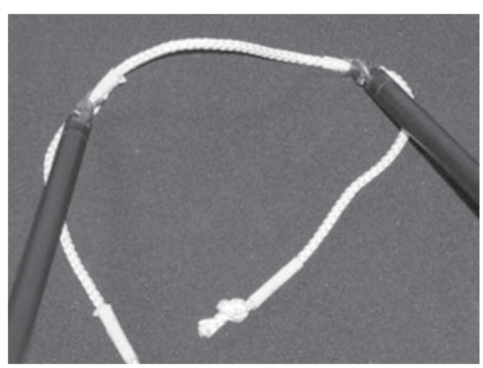

FIG. 1. The rope running manipulation.

the opposite caps simultaneously six times (Fig. 2). This was performed in two directions, picking up the rubber pieces from far-right and near-left caps (task BC1) and from near-right and far-left caps (task BC2).

- Needle passing (NP) consisted of passing a 26-mm surgical needle through the six pairs of holes made on the surface of a latex tube with a specific technique (Fig. 3). This task was performed in only one direction, passing the needle from right to left.

All five tasks were designed to include bimanual skills observed in real surgical procedures that require asymmetric or independent movements of the right and left instruments and, therefore, more out-of-phase movement patterns from the subjects, to achieve quality performance. All subjects completed three trials of each task. During each trial, elapsed time and kinematic variables with respect to the position and angular movement of the surgical instruments were measured by force transducers built within the system and extracted at approximately 11 Hz by the system's API. All collected data were processed using laboratory software built using MATLAB v.6.5 (MathWorks) to obtain linear kinematics with respect to the movement of the surgical instrument tips.

To quantify the nature of the subject's performance, task completion time (T) and total traveling distance (D) of the instrument tips were calculated for each task. Moreover, a coordination analysis was conducted to analyze the extent of bimanual dexterity by quantifying the level of out-of-phase coordination. This type of analysis is commonly used in psychobiological studies for the evaluation of bimanual coordination.[20–23] Central to this approach is the evaluation of the direct relationship between velocity and position using phase portraits. The phase portrait is practically a plot of angular position versus velocity of the moving segment in question (the robot's surgical tip). From the phase portrait, the phase angle Φ can be identified:

$$\Phi = \tan^{-1}[\text{velocity/displacement}] \qquad \text{Equation 1}$$

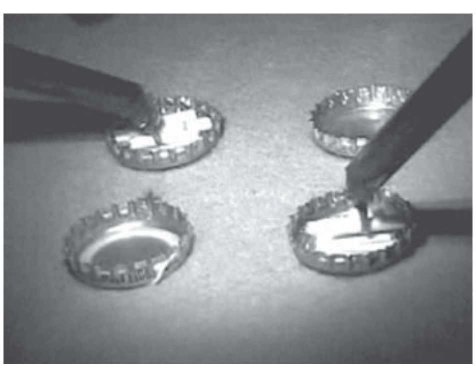

FIG. 2. The bimanual carrying manipulation.

FIG. 3. The needle passing manipulation.

After the phase angle from the right robot surgical tip is calculated, the same procedure can be used to calculate the phase angle of the left. Following this calculation, the subtraction of the two phase angles leads to very interesting results. If the subtracted value is zero then we can say that the two segments move in the same manner or they are in phase (Fig. 4). If the value is 180, we can say that the two segments move in an opposite way or are out-of-phase. Using this procedure we were able to evaluate how the robot's instrument tips are moving—in-phase or out-of-phase.

A dominant direction of each task was identified and a phase portrait was generated for each trial and for both right and left instrument tips using the data set of the normalized linear displacement and velocity. Phase angles for both tips (Φ_{right}, Φ_{left}) were identified from the phase portraits, and relative phases ($\Phi_{\text{RP}} = \Phi_{\text{right}} - \Phi_{\text{left}}$) were subsequently calculated.[18,19] Mean absolute relative phase (MARP) was calculated from the relative phase curves using the following equation:

$$\text{MARP} = \sum_{i=1}^{N} \frac{|\Phi_{RPi}|}{N} \qquad \text{Equation 2}$$

where N is the total number of data points in the relative phase curve.

Practically, MARP is a tool that can quantify if the two robot surgical instrument tips move in a similar fashion. If the two tips move simultaneously in the same direction, the MARP value moves toward zero degrees, or in phase. If they move in opposite directions, the MARP value moves toward 180 degrees, or out of phase.

Mean values of task completion time, total traveling distance of the instrument tips, and MARP were compared between the expert and novice groups for the last of three trials in each task with independent *t*-tests ($\alpha = 0.05$) using SPSS v.13.0 (SPSS, Chicago, IL). In each group, these values were also compared between both directions for the last trials in the rope running and bimanual carrying tasks, as well as between the first and last trials for all tasks, with dependent *t*-tests ($\alpha = 0.05$).

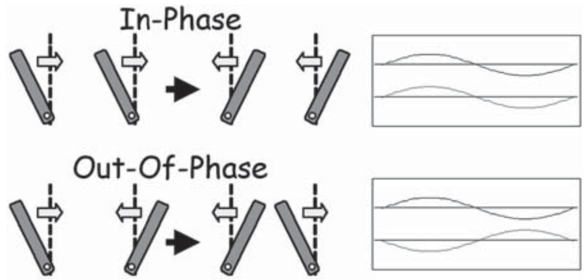

FIG. 4. When two oscillators (instrument tips) move in the same fashion, their phase angle curves are the same and their difference, calculated by mean absolute relative phase (MARP), will approach zero ("In-Phase"). When two instrument tips move in an opposite fashion, their phase angle curves are offset and their difference, calculated by MARP, will approach 180 degrees ("Out-of-Phase").

RESULTS

Differences between groups

The means ± standard deviation for task completion time, total traveling distance of the instrument tips, and MARP for both groups were calculated, with the level of significance set at $P < 0.05$. The expert group revealed significantly shorter task completion time for all five tasks (Fig. 5). The relative differences in task completion time were 30.7%, 23.7%, 43.7%, 42.2 %, and 42.9% for the RR1, RR2, BC1, BC2, and needle passing tasks, respectively. The larger differences were observed in the tasks that required greater task completion times.

No significant differences between groups were found for the total traveling distance of the instrument tips (Fig. 6). However, in all tasks except for the BC2 task, total traveling distance of the instrument tips in the expert group were slightly shorter than those of the novice group, with relative differences of 2.9%, 6.2%, 0.7%, and 11.7% for the RR1, RR2, BC1, and needle passing tasks, respectively. By contrast, in the BC2 task, total traveling distance of the instrument tips for the expert group was 0.7% higher than for the novice group in the BC2.

Significantly higher MARP values were observed in the expert group for the BC2 and needle passing task, with relative differences of 16.7 % and 23.0 %, respectively (Fig. 7). Although there were no significant differences, the MARP values were slightly higher in the expert group for all other tasks, with relative differences of 2.9%, 2.4%, and 8.3% for the RR1, RR2, and BC1 tasks, respectively.

Differences between directions

No significantly different task completion time, total traveling distance of the instrument tips, or MARP values were observed between the RR1 and RR2 tasks and between the BC1 and BC2 tasks in both groups, except that task completion time was significantly shorter for the RR2 task compared with the RR1 task in the novice group.

Differences between the first and last trials

In the novice group, significantly briefer task completion times for all tasks and significantly shorter total traveling distance of the instrument tips for the needle passing task were found during the last trial compared with the first trial. Relative differences were 20.5%, 14.3%, 9.4%, 11.6%, and 24.6% for task completion time in the RR1, RR2, BC1, BC2, and needle passing tasks, respectively, and 12.0% for total traveling distance of the instrument tips in the needle passing task. Differences in the other values were relatively small (1.3% to 7.9%). In the expert group ($n = 4$), significant differences were found only in the task completion time for the BC1 task (31.5% briefer in the last trial) and in the MARP for the needle passing task (31.5% higher in the last trial).

DISCUSSION

This study objectively demonstrated differences in robotic surgical performance between expert and novice users of the da Vinci surgical system by using three variables derived from robotic kinematics and a coordination analysis. This study showed that experts have significantly shorter task completion time for the three surgical

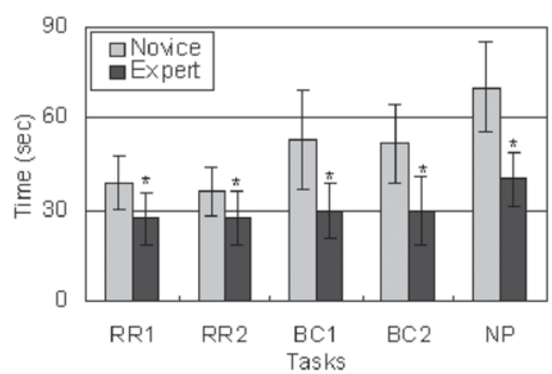

FIG. 5. Mean ± standard deviation values for task completion time for both groups. For the novice group ($n = 18$), RR1 = 39.15 ± 8.53 s, RR2 = 35.81 ± 7.78 s, BC1 = 52.88 ± 16.19 s, BC2 = 51.79 ± 12.83 s, and NP = 69.96 ± 14.90 s. For the expert group ($n = 6$), RR1 = 27.11 ± 8.37 s, RR2 = 27.33 ± 8.40 s, BC1 = 29.75 ± 8.86 s, BC2 = 29.95 ± 10.88 s, and NP = 39.96 ± 8.75 s. RR1, rope running left to right; RR2, rope running right to left; BC1, bimanual carrying from far-right and near-left; BC2, bimanual carrying from near-right and far-left; NP, needle passing from right to left. * = $P < 0.05$ with independent t-test.

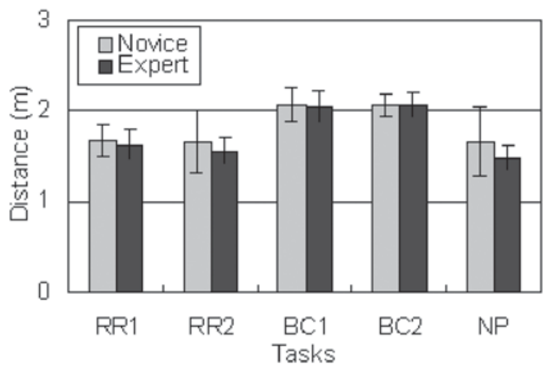

FIG. 6. Mean ± standard deviation values of total traveling distance of the instrument tips for both groups. For the novice group ($n = 18$), RR1 = 1.67 ± 0.18 m, RR2 = 1.65 ± 0.35 m, BC1 = 2.06 ± 0.19 m, BC2 = 2.05 ± 0.12 m, and NP = 1.66 ± 0.38 m. For the expert group ($n = 6$), RR1 = 1.62 ± 0.17 m, RR2 = 1.55 ± 0.14 m, BC1 = 2.05 ± 0.18 m, BC2 = 2.07 ± 0.15 m, and NP = 1.47 ± 0.14 m. RR1, rope running left to right; RR2, rope running right to left; BC1, bimanual carrying from far-right and near-left; BC2, bimanual carrying from near-right and far-left; NP, needle passing from right to left.

manipulations in all five tasks examined. This result was expected and suggested that time score may be able to partially represent the extent of proficiency in robotic laparoscopy. In contrast, this study did not support the validity of the traveling distance as a variable to quantify efficiency of the surgical performance, as this value was only slightly greater for the expert group in most of the tasks. One possible reason for this result is that our task settings could have restricted subjects' free movement and could have guided all subjects in both groups to manipulate the robotic surgical instruments with similar trajectories.

Significantly higher MARP values were observed for the expert group in one of the two tasks for bimanual carrying and needle passing. MARP was also moderately but not statistically significantly higher for the other bimanual carrying task. MARP is often used in motor learning and motion analysis to examine the extent of functional coordination between systems. This variable has been used to quantify whether interacting segments (right and left limbs) display an in-phase or out-of-phase relationship during walking.[15,16,18,19] It has also been used to examine coordination between the movements of the upper extremities when another parameter (speed of movement) is manipulated.[17] In this study, all tasks were designed to require more out-of-phase movement patterns to achieve quality performance. So the higher MARP values from our expert group indicate higher bimanual dexterity (out-of-phase pattern) and, thus, higher quality of performance.

These results demonstrate the feasibility of using the MARP as a coordination profile variable that can quantify a surgeon's proficiency, especially when high bimanual dexterity is required in complex procedures such as bimanual carrying and needle passing. The lack of significant differences for the rope running task was due to the fact that this task was relatively easy to perform, with a high quality of bimanual coordination, by our novice group. This result also suggests that proper selection of experimental tasks is very important when determining surgeon proficiency. While the rationale for the within-session improvement of the expert group MARP value for needle passing is unclear, it is possible that several trials were needed even by the experts to regain an appropriate bimanual coordination pattern in a more complicated task.

As a minor point, this study also showed that there were no significant differences in most scores for two tasks carried out in opposite directions for the same manipulations, rope running and bimanual carrying. This result indicates that the scores examined were not compromised by the system's functions, such as those to overcome weaknesses in the nondominant hand.

To establish clear criteria for practical scoring systems and training protocols and to develop well-grounded algorithms and databases for integrated surgical systems or virtual training devices,[9] the essence of proficiency in robotic surgical skills should be fully identified with objective composite variables. Ultimately, these variables should be monitored by direct measurement in a real-time manner and they should be free from any human judgment or operations in this process. Although conventional variables such as task completion time may partially indicate the extent of proficiency or skill acquisition, they

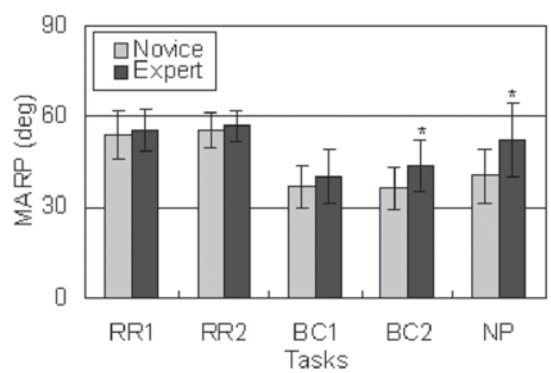

FIG. 7. Mean ± standard deviation values of mean absolute relative phase (MARP) for both groups. For the novice group ($n = 18$), RR1 = 53.78 ± 7.90°, RR2 = 55.34 ± 5.90°, BC1 = 36.75 ± 6.74°, BC2 = 36.23 ± 6.59°, and NP = 40.14 ± 8.66°. For the expert group ($n = 6$), RR1 = 55.40 ± 6.79°, RR2 = 56.68 ± 5.45°, BC1 = 40.07 ± 8.90°, BC2 = 43.51 ± 8.63°, and NP = 52.16 ± 12.24°. RR1, rope running left to right; RR2, rope running right to left; BC1, bimanual carrying from far-right and near-left; BC2, bimanual carrying from near-right and far-left; NP, needle passing from right to left. * = $P < 0.05$ with independent t-test.

may be too straightforward to explain in detail other essential aspects such as quality of performance. Completing a task faster does not mean that it is also completed with improved quality. This might be obvious considering that the novice group rapidly reduced their task completion time for all tasks over the course of only three trials. In this study, we tried to demonstrate an aspect of skilled performance, a coordination profile, using the MARP, and obtained favorable results. However, further assessment will be required to validate these findings, as well as to explore other possible variables from a variety of viewpoints to quantify the essence of proficiency. In addition, larger sample sizes including more experts are required for better assessment.

ACKNOWLEDGMENTS

The authors would like to thank Allison DiMartino for her assistance with subject recruitment and data collection. We also thank Mark Rentschler for his assistance with the data analysis. This study was supported by a grant from the Nebraska Research Initiative awarded to authors Oleynikov and Stergiou.

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