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SURGICAL ENDOSCOPY
and Other Interventional Techniques

Video analysis of endoscopic cutting task performed by one vs two operators

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Abstract
Background: In the performance of complex laparoscopic tasks, one question is whether the task should be distributed between two operators or accomplished bimanually by one operator. The authors hypothesized that superior task performance results when two operators work collaboratively in a dyad team as opposed to one operator performing the task bimanually. Furthermore, in a visually misaligned condition, the performance of a team will be more robust than that of a single operator working alone.
Methods: The suture-cutting task was performed by 24 right-handed subjects in a mock surgical setup using a laparoscopic grasper and a pair of laparoscopic scissors. The cutting task was performed by 8 subjects bimanually (using both limbs) and 16 paired subjects unimanually (using their preferred limbs). The image of the work plane was displayed either vertically or superimposed over the work plane. In half of the conditions, the camera was rotated 45°, causing misalignment between the actual and displayed work planes. Movements were videotaped. Important movement events were identified and used to subdivide the task into subtasks. Durations of the subtasks and attempts for grasping and cutting were analyzed using a mixed-design multivariate analysis of variance (MANOVA).
Results: For a number of subtasks, the dyad group showed shorter durations than the bimanual group. The 45° rotation of the camera degraded both bimanual and dyad performance, resulting in prolonged movement times for all subtasks. The learning process was facilitated by the superimposed display in that grasper and scissor reaching times improved over trials, as compared with the vertical display.
Conclusion: The results indicate the superior role of team collaboration, as compared with the single operator, in a complex remote manipulation such as a laparoscopic cutting task. This enhanced task performance is achieved because of the larger capacity for information processing. These results may have some relevance for optimizing performance of endoscopic surgery.

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Key words: Performance assessment — Bimanual task — Dyad team performance — Surgical skills — Surgical training — Ergonomics

Complex laparoscopic procedures require the simultaneous use of multiple surgical instruments. This case raises the question whether it is better for the instruments to be controlled by two operators or by one operator bimanually. Intuitively, individuals prefer using both hands to perform many tasks. For instance, to accomplish a complex task, such as writing, both hands act simultaneously, yet have slightly different roles. The nonpreferred hand touches and stabilizes the paper, collecting reference and context information. In conjunction with visual feedback, this information is used to guide the movement of the preferred hand [9, 20]. This haptic input is particularly important when visual information is reduced [11]. Visual display of the surgical field is degraded in laparoscopic procedures. Therefore, integration of multiple modalities of sensory information may be the key to improving surgical performance [7, 19]. This suggests that one operator working bimanually in endoscopic surgery may be more efficient than two operators working together.

In this study, we assessed primarily laparoscopic bimanual performance, examining whether bimanual coordination is applicable to the remote setting and comparing the performance with that of two operators working together. We designed an experiment requiring participants to reach, grasp, and lift a thread from a synthetic organ using a laparoscopic grasper held in the one hand, then to cut the thread beneath the grasper using a laparoscopic scissors held in the other hand. The participants were assigned to conduct the task as individuals bimanually or as a dyad team to perform one part of the task unimanually. The performance of each hand and the overall task were analyzed on videotape and evaluated by comparison of the durations for each subtasks. If grasping and holding the thread in one hand indeed facilitates the task performance of the other hand, the cutting performance would be better for the single operator working bimanually than for two operators working as a dyad team.

However, two factors kept us from advancing such a hypothesis. First, in laparoscopic surgery, the nonpreferred hand of the surgeon makes contact with the target by means of a long-shaft instrument. The information about the target collected by the nonpreferred hand is indirect, and may be inadequate for providing the reference and context information regarding the target of the preferred hand. Second, control of a bimanual task is believed to be more complicated and mentally demanding than control of unimanual movements [17, 18]. Using both hands to control surgical instruments could increase the mental workload or attentional demands of the surgeon, consequently degrading surgical performance. An alternative for dealing with such a situation would be to increase the capacity for information processing by adding more operators. It may be better, therefore, to share complex laparoscopic tasks between two operators than to have one operator working bimanually [5].

Our hypothesis was that there would be no difference in the scissors' cutting performance between the single operator bimanual condition and that of the dyad team. We further hypothesized that the overall performance of a dyad team would be better than that of a single operator bimanually.

To further investigate the effects of mental load on surgical performance in both the individual and team settings, we rotated the endoscopic 45° in half of the experimental conditions, causing visual misalignment between the actual and displayed work plane. Operators in this condition had to transform the displayed image mentally to match the actual surgical field, which possibly increased mental workload [3, 6, 21]. We aimed to investigate whether the rotation of the camera made it more difficult for the operators in the dyad team to collaborate with each other, or whether they adapted to the stressful situation more quickly and performed better than a single bimanual operator. We predicted that the performance of the dyad team would be superior to that of the individual bimanual performance when the camera was rotated, increasing mental load.

Our previous work demonstrated that a superimposed image display facilitated the surgeon's decision-making process as well as the laparoscopic task performance [15, 21]. We surmised that the same would apply in the bimanual and team settings. In our study, the image of the work plane was displayed either vertically at eye level or superimposed over the work plane. The superimposed condition was predicted to facilitate both the dyad team and individual bimanual task performances.

Method

Subjects

A total of 24 university students (11 males and 13 females with age of mean 23 years) were recruited and randomly assigned to one of two groups: 8 participants to the bimanual group and 16 to the dyad group. All were right-handed with normal or corrected-to-normal vision and completely naïve to endoscopic procedures and tasks. Each participant provided informed consent and received a small honorarium for their participation.

Although some surgeons may perform better than some university students, there is no evidence that their representational or learning processes are different. Using university students as subjects excluded the possibility of differential effects among surgeons based on surgical experiences in both individual practice and team collaboration during surgery.

Equipment

Tasks were carried out in a black endoscopic training box ($35 \times 30 \times 20$ cm) placed on a wooden table 72 cm above the floor (Fig. 1A). The training box had ports of entry for a 0° laparoscope (Olympus A5254 Laparoscope, Olympus, Heidelberg, Germany), a laparoscopic grasper (Karl Storz Endoscopy, Mississauga, Ontario), and scissors (Ethicon Endo-Surgery, Cincinnati, OH, USA). The entry ports of the instruments formed an isosceles triangle 20 cm between the grasper and scissors and 18 cm from the laparoscope to the scissors (right side of the box) or the grasper (left side of the box). The laparoscope was inserted into the training box with its objective lens 9 cm from the work plane, providing a $\times 2$ magnification. The work plane in the current experiment was on the bottom of the training box. The endoscope was placed with its optical axis focusing on the center of the work plane, ensuring that the illumination and magnification effects were identical, even when the camera was rotated. Although this positioning is uncommon in laparoscopic surgery, it has been used in many experimental setups [10, 21].

At the bottom of the training box was placed a synthetic ear (Sandylion Stick Design, China) simulating human soft tissue. In middle of the ear was an embedded fishing line (MAXIMA MFG, Geretsried, Germany) that protruded from the synthetic tissue. The task was to grasp the visible portion of the thread. The length of the visible part was about 1 cm, constant over all trials.

The work plane was illuminated by the ORC 6000 Xenon Light Source (ORC Lighting, Azusa, California), and the image was collected by a Sony color video camera (DXC-C1, Video Camera, Sony, Tokyo, Japan). Two identical 19-in. color monitors (995E CRT Monitor, La Electronics, Seoul, Korea) were used for displaying the image. For the vertical conditions, a monitor was positioned vertically at eye level 85 cm in front of the subject (Fig. 1B). For the superimposed condition, a monitor (with left/right display reversed) was positioned upside down 75 cm above the training box. The image on the monitor was reflected by a half-silvered mirror (Monarch Mirror, Mississauga, Ontario) located halfway (at 37.5 cm) between the work plane and the monitor. The viewing distance from the participant's eyes to the work plane was about 85 cm. Synchronized with the display, the image of the work plane was recorded via a VCR (SLV-660 HF VHS Player, Sony, Tokyo, Japan) on VHS cassettes (FujiFilm Pro120, Fujifilm, Tokyo, Japan).

Task and procedure

The subjects started with the tips of the grasper and scissors in the middle of their respective start plates located below the synthetic organ. At the spoken signal "ready, go" they began the task of reaching, grasping, and cutting the thread. After the completion of each cutting task, they replaced the tips of the tools on the start plates. Each subject was given three practice trials with the camera in its neutral (0°) position.

All the subjects were right-handed. Thus for the given task, the subjects in the bimanual group held the grasper in the left hand and the scissors in the right hand. For the dyad group, each tool was held in the participants' preferred hands.

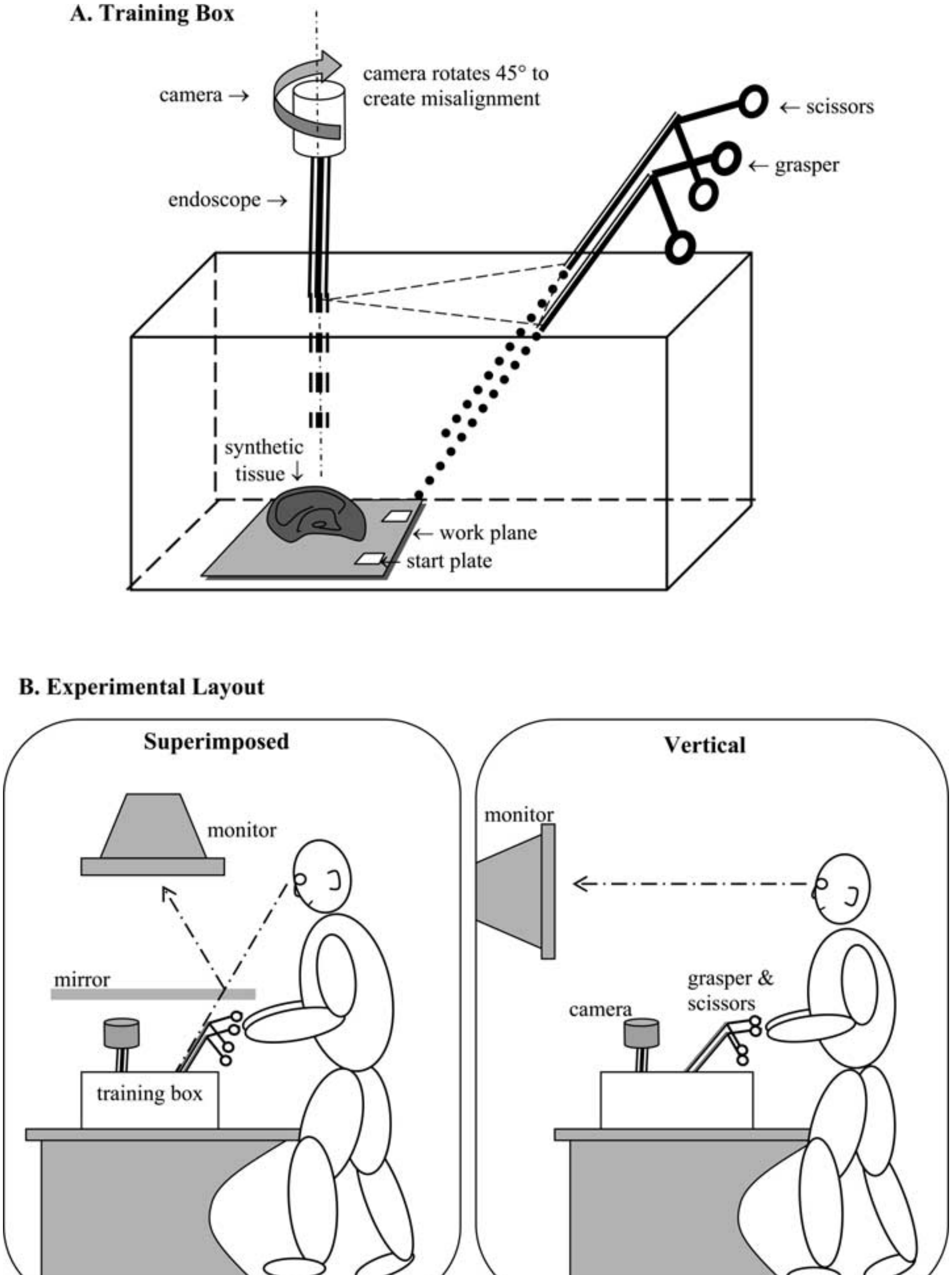

Fig. 1. **A** Endoscopic training box. An endoscope, a grasper, and a pair of scissors enter the training box, forming an isosceles triangle: 20 cm between the grasper and scissors and 18 cm between the endoscope and scissors (right-hand side of box) or grasper (left-hand side of box). The optical axis of the endoscope focused on the center of the work plane, which contained two start plates and a synthetic organ. In half of the experimental conditions, the camera was rotated 45° clockwise about its longitudinal axis, causing visual misalignment between the displayed work plane and the actual work plane. **B** Experimental layout. Superimposed (left) and vertical (right) image displays, with a constant viewing distance of 85 cm between the subjects' eyes and the work plane.

For half of the experimental conditions, the laparoscopic camera was rotated 45° clockwise along the longitudinal axis of the endoscope. This camera rotation caused a visual misalignment between the displayed work plane and the actual work plane (Fig. 1A).

The experimenter varied the order of the image display (vertical and superimposed) and the camera rotation (0° and 45°) so as to counterbalance the experimental conditions across the participants and form a total of four experimental conditions. Under each of the conditions, five trials were performed by each subject in the bimanual group and each pair of subjects in the dyad group. Hence, each person in the bimanual group and each pair in the dyad group performed a total of 20 trials. The tool movements were video-recorded for analysis.

Video analysis

After data collection, videocassettes were analyzed frame-by-frame by two experimenters simultaneously using a Panasonic professional video editing system (DS550, Matsushita Electronic American, Secaucus, NJ, USA) with a Sony TV monitor (Sony Trinitron, CPD-G520P, Sony Electronic America, Oradell, New Jersey). For each trial, a number of events were identified with specific operational definitions, and the temporal data were read from the time counter imbedded in the video editing system. By subtracting timed event data, subtask durations were obtained. We then converted all durations to seconds using the method specified in the Appendix.

A number of issues were considered in the selection of the movement events. First, the movement events had to be exhibited by all subjects. Movement behaviors exhibited by only some of the subjects were not considered events. Second, the events had to have a clear spatial alteration during the movement that allowed it to be distinguished from the continuing movement using video analysis technology. Third, of the events that met the first two criteria, we selected only those that helped in describing movement characteristics of the cutting task. To make meaningful interpretations of the movement, we relied on our knowledge of prehension [14], because reaching and grasping by the

Table 1. Events and dependent measures

Event and event definitions	
Grasper events	Scissors Events
1. *Lift off*: the first frame when the tips of the grasper break contact with the start plate.	1. *Lift off*: the tips of scissors break contact with the start plate.
2. *First contact with thread*: the first frame when any part of the grasper jaw makes contact with the thread.	2. *Significant reach*: after thread hold, the first frame when the scissors move forward to the thread.
3. *Jaw starts opening*: the first frame when the aperture of grasper jaws start increasing.	3. *First contact with thread:* the first frame when any part of the scissors jaw makes contact with the thread.
4. *First jaw closed*: first frame when the grasper jaw is closed.	4. *Jaw starts opening*: the first frame when the aperture of scissors jaws start increasing.
5. *Thread held*: the first frame when the thread is held between the grasper jaws.	5. *First jaw closed*: the first frame when the scissors jaws are closed.
Note: If the thread is held at the first attempt, the time of the closed jaw is the same as the time of the thread held.	6. *Thread cut*: the frame when the thread is cut by the scissors.
	Note: If the thread is cut at the first attempt, the time of the closed jaw is the same as the time of the thread cut.

Dependent measures

1. *Total task time* (*TT = scissors event 6—grasper event 1*): from the time the grasper is lifted to when the thread is cut.
2. *Grasper time* (*GT = grasper event 5—grasper event 1*): from the time the grasper is lifted off the start plate to the time the jawsare firmly closed around the thread. If the thread is held at the first attempt, *GT = grasper event 4—grasper event 1.*
3. *Grasper reaching time* (*GRT = grasper event 2—grasper event 1*): from the time the grasper is lifted off to when the grasper first contacts with thread.
4. *Grasper jaw time* (*GJT = grasper event 4—grasper event 3*): from the time when the grasper is opening to the first moment when the scissors tips are closed. If the thread is held at the first attempt, *GJT = grasper event 5—grasper event 3.*
5. *Scissors time* (*ST = scissors event 6—grasper event 5*): from the time when the thread is held to when the thread is cut.
6. *Scissors reaching time* (*SRT = scissors event 3—scissors event 2*): from the time when the scissors significantly move to the thread to the first moment when the scissors tips contact the thread.
7. *Scissor jaw time* (*SJT = scissors event 5— scissors event 4*): from the time when the scissors is opening to the first moment when the scissors tips are closed. If the thread is cut at the first attempt, *SJT = scissors event 6—scissors event 4.*
8. *Number of grasper closings*: number of times the grasper jaws are closing and reclosing.
9. *Number of scissors closings*: number of times the scissors jaws are closing and reclosing.

Note: sometimes events were not performed in this order. For example, jaw closing might have occurred before the first contact of the jaw with the thread. However, this did not affect the way time intervals were computed

laparoscopic grasper and by the laparoscopic scissors both be viewed as prehensile movements. With these considerations, we defined the five grasper events and six scissors events outlined in Table 1 and Fig. 2.

The unique event in the scissors movement was what we called "significant reach," the moment when the scissors were voluntarily or intentionally moved toward the target to cut the thread. In the bimanual task, this event occurred after the grasper held the thread when the operator's attention shifted from the grasper to the scissors. However, in the dyad task, although the scissors sometimes moved toward the thread before the thread was grasped, the scissors movement was more deliberate after the thread was held in the grasper. To make this event comparable between the bimanual and the dyad tasks, we arbitrarily prescribed significant reach to be the event in which the scissors started to reach for the thread, following the event of thread held.

Table 1 outlines the dependent measures we obtained by subtracting temporal data between events. In addition to the aforementioned temporal measures, there were two supplementary dependent measures: the number of grasper closings and the number of attempts at scissors closing until the thread was held and cut.

Statistical analysis

The dependent measures were analyzed in terms of 2 groups (dyad team and singer operator bimanual) × 2 displays (vertical and superimposed) × 2 camera rotations (0° and 45°) × 5 trial mixed designed analyses of variance (ANOVAs), with repeated measures for the last three factors. Means and standard errors are reported for significant effects, with an a priori α level of 0.05.

Results

The results are summarized in Table 2. Group effects were revealed for total time ($p = 0.042$), grasp time ($p = 0.004$), grasper jaw time ($p = 0.009$), and number of grasper closings ($p = 0.005$). Explicitly, the dyad team used less time totally (12. 1 ± 10.0 s) than individuals bimanually (18.3 ± 12.8s). The shorter total time for the team condition was composed of a shorter grasper time (5.1 ± 2.8 s) and a shorter grasper jaw time (3.9 ± 2.6 s) than for the bimanual performance (grasper time = 8.1 ± 6.6 s; grasper jaw time = 6.6 ± 6.3 s). However, the scissors movement times did not show significant differences between groups. The grasper closings were fewer for the dyad team (1.4 ± 0.8) than for the single bimanual operator (1.9 ± 1.1). The number of scissors closings did not differ between the two groups.

For camera rotation, within-subject analysis showed an effect for all temporal measures of both the grasper and the scissors movements (Table 2). When the camera was rotated 45° along its longitudinal axis, all movement durations were lengthened, as compared with the 0° camera position. However, the number of closings by both the grasper and the scissors did not vary with

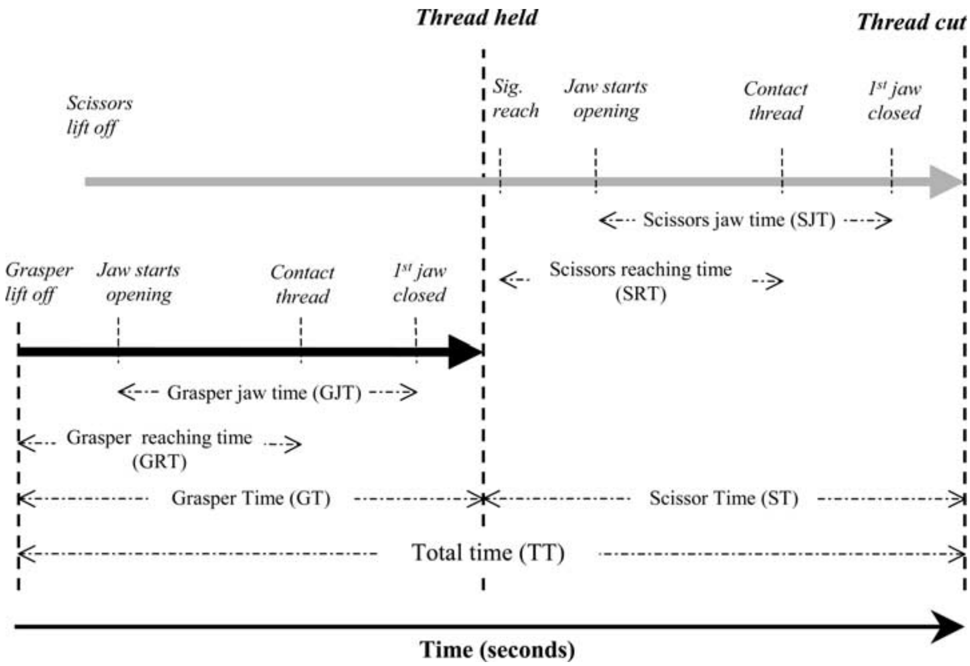

Fig. 2. Movement events and subtask durations. The black thick arrow represents the movement of the grasper. The gray thick arrow represents the movement of the scissors.

Table 2. Summary of means and standard errors of dependent measures for main effects

		Group		Camera rotation		Display		Trial				
		Single operator	Dyad team	0°	45°	Vertical	Superimposed	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Total time (s)	Mean	18.3	12.1[a]	12.3	18.1	16.7	13.7	15.5	17.9	13.9	15.1	13.5
	SD	12.8	10.0	6.8	14.9	12.6	11.1	9.6	18.0	10.2	11.2	10.2
Grasper time (s)	Mean	8.1	5.1[b]	5.6	7.6	6.4	6.7	7.8	6.5	5.6	6.9	6.1
	SD	6.6	2.8	3.7	6.4	4.6	5.9	6.6	5.4	3.2	6.3	6.9
Grasper reaching time (s)	Mean	4.9	3.5	3.6	4.7[b]	4.3	4.0	5.0	4.4	3.7	3.7	4.0[a]
	SD	2.9	1.7	2.2	2.7	2.4	2.6	3.4	2.3	1.7	2.2	3.6
Grasper jaw time (s)	Mean	6.6	3.9[b]	4.4	6.1[b]	5.0	5.5	6.4	5.2	4.3	5.4	5.0
	SD	6.3	2.6	3.6	6.0	4.5	5.5	6.0	5.4	3.0	6.1	6.2
Scissors time (s)	Mean	10.2	7.0	6.7	10.5[a]	10.2	7.0[a]	7.7	11.4	8.3	8.2	7.4
	SD	9.1	9.5	4.8	12.1	11.2	6.9	4.5	15.8	8.6	8.2	4.7
Scissors reaching time (s)	Mean	5.5	3.8	3.9	5.4[a]	5.1	4.2	4.8	5.6	4.0	4.6	4.4
	SD	4.5	3.1	2.9	4.7	3.8	4.0	2.8	5.9	2.4	4.4	3.0
Scissors jaw time (s)	Mean	7.7	8.5	6.2	10.0	9.7	6.5[a]	7.2	10.7	7.8	8.2	6.7
	SD	8.8	9.3	4.7	11.6	10.6	6.8	4.4	15.7	7.5	7.8	4.6
Grasper closing number	Mean	1.9	1.4[b]	1.6	1.7	1.7	1.6	1.8	1.7	1.4	1.6	1.6
	SD	1.1	0.8	1.0	1.0	1.0	1.0	0.2	0.1	0.1	0.1	0.2
Scissors closing number	Mean	1.2	1.3	1.2	1.3	1.4	1.2	1.2	1.3	1.4	1.3	1.2
	SD	0.5	0.9	0.7	0.7	0.9	0.4	0.0	0.1	0.2	0.1	0.0

[a] $p < 0.05$, significant differences between marginal means
[b] $p < 0.01$

camera rotation. Testing of grasper reaching time showed interactions between the camera rotation and the group ($p = 0.046$). As shown in Fig. 3, grasper reaching time increased significantly when the camera was rotated 45°, as compared with a 0° rotation. This increase was more pronounced when the task was performed bimanually by one operator than when the task was performed by two operators (bimanual: at 0°, 4.0 ± 0.4 s, at 45°, 5.6 ± 0.2 s; dyad: at 0°, 3.2 ± 0.5 s, at 45°, 3.7 ± 0.3 s).

A display effect was shown for the scissors time ($p = 0.021$) and the scissors jaw time ($p = 0.012$). Specifically, the scissors and scissors jaw times were shorter when the display was superimposed (scissors time, 7.0 ± 6.9 s; scissors jaw time, 6.5 ± 6.8 s) than when the image was displayed vertically (scissors time, 10.2 ± 11.2 s; scissors jaw time, 9.7 ± 10.6 s). Other temporal measures such as total time, grasper reaching time, and scissors reaching time showed similar trends (Table 2), but were not statistically significant.

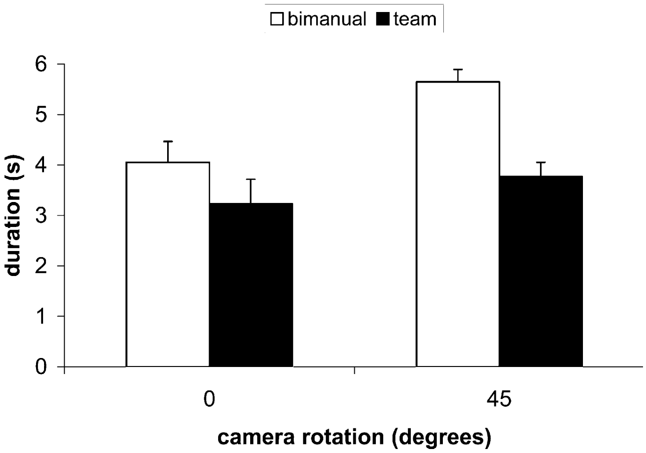

Fig. 3. The grasper reaching time increases when the camera is rotated 45° clockwise. The increase is more pronounced in the bimanual group than in the team group.

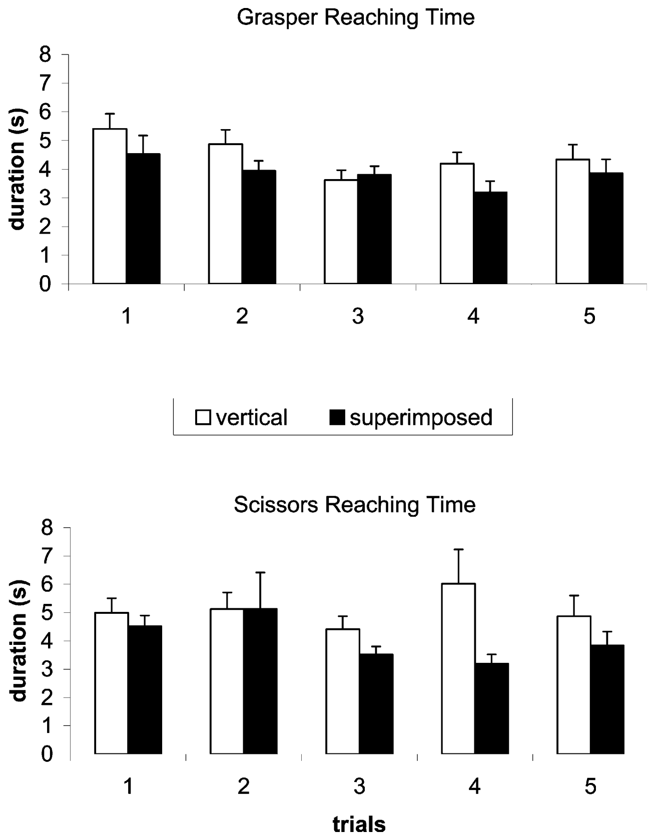

Fig. 4. As practice continues, grasper reaching time (top) and scissors reaching time (bottom) decrease when the image is superimposed over the work plane. However, these two measures fluctuate across trials when the image is presented vertically in front of the operator(s).

The effect of the trials was shown for grasper reaching time ($p = 0.008$), which was reduced with practice. A similar tendency was observed in the total time and grasper time. There also was a significant effect of trial interaction on grasper reaching time ($p = 0.019$) and scissors reaching time ($p = 0.038$). Specifically, the grasper reaching and scissors reaching times were reduced with practice (Fig. 4). However, trials interacted with the image display method. When the display was superimposed, the grasper reaching and scissors reaching times were significantly reduced as trials progressed, whereas in vertical display condition, performance time was not reduced as the trials progressed. Hence, these results suggest that a superimposed display location facilitates learning a remote manipulation task, as compared with a vertical display.

Discussion

Our first intention was to determine whether in remote manipulation tasks such as laparoscopic procedures grasping and holding a target by one hand facilitates the manipulation by the other hand. Our hypothesis was that intralimb facilitation, documented extensively in natural manipulation, would not be the case in remote manipulation. Our hypothesis was supported because the task of cutting with the scissors performed by subjects in the dyad team did not significantly differ from that performed by a single operator working bimanually.

Our next goal was to assess the remote bimanual performance of a single operator, as compared with the performance of two operators working together. Our hypothesis was that performance would be better for the dyad. This hypothesis was supported. The total performance time for the dyad team conditions was shorter (12.1 s) than for the single operator bimanual conditions (18.3 s). In addition, the total grasper movement time was shorter (5.1 s) and the grasper jaw movement time was shorter (3.9 s) for the dyad team condition than for the single operator bimanual condition (grasper time, 8.1 s; grasper jaw time, 6.6 s). It was noted that the better performance of the grasper by the dyad team might be associated with the use of the preferred hand. For bimanual performance, the grasper was held in the nonpreferred hand. To confirm the effects of lateral hand differences, a further experiment is necessary, in which the grasper in the dyad team will be controlled by the nonpreferred hand.

Intuitively, some thought that bimanual performance by a single operator would be better because two hands are better than one. The motor control literature shows that the nonpreferred hand provides a spatial context for the preferred hand [9, 11, 17]. In the dyad team condition, the participants used only one hand. Why then was performance by the dyad team better in such a remote manipulation setting? The reasons are that the spatial reference and context information collected by the nonpreferred hand to facilitate performance of the preferred hand in bimanual manipulation was not generalizable to the remote bimanual setting. In addition, fewer mental demands for each operator in the dyad team may be an asset in the performance of a complex laparoscopic task with only one hand per operator.

In laparoscopic surgery, it is difficult to extract the target's frame of reference through remote contact with the long-shafted laparoscopic tool. Also, the fulcrum effect in laparoscopic manipulation considerably reduces the ability of surgeons to perceive the location of the surgical site [8]. Collection of context information about the target requires that the surface of the target be contacted by the hand directly [13]. Obviously, direct contact is impossible in laparoscopic surgery. Some authors argue that tactile feedback, although reduced, is still present with the laparoscopic procedure [1]. But such tactile information is indirect and altered, making it difficult to rebuild context information of the target tissue and to guide performance of the preferred hand.

When tasks are shared by two operators in a dyad team, the individual bimanual task is converted into two unimanual tasks, which reduces the mental workload for each operator. A clear outcome of team performance is that multiple tasks can be performed simultaneously. In the dyad setting of our study, the scissors were moved to the vicinity of the thread while the grasper was still grasping the thread. Anticipatory movements of the scissors definitely helped to shorten the total task time in the dyad team performance. In contrast, the single operator failed to show significant scissors movements during the time of thread grasping.

However, it is important to note that coordinating with another operator also adds extra workload or attention demand for each of the team members. In addition to the taskwork associated with tasks, tools, and the environment, teamwork involves the interpersonal interactions with each team member (e.g., exchange of information, development and maintenance of communication, and coordination of actions) [2]. To reduce the teamwork burden, each team member must time-share the requirement for interaction and coordination. According to a shared mental model proposed by Bowers et al. and Salas et al. [2, 16], when the knowledge of task, equipment, and environment is well defined and shared by each of the team members, overall team performance is enhanced. In this experiment, the participants in each dyad team were clearly informed of the task goal, understood his or her role in the task, and were working in the same environment. They developed efficient time-share patterns that resulted in a better task performance, as compared with bimanual performance.

We are aware that the laboratory grasping and cutting task in this study differs from the surgical tasks in real laparoscopic procedures. Laparoscopic procedures, however, can be hierarchically decomposed to basic surgical tasks [4], such as the one simulated in the current study. The fixed thread location in this experiment enabled standardized presentation of the grasping and cutting task in this study. However, this standardized position allowed for transporting of the scissors before the thread was held by the grasper. In contrast, the subsequent action in many surgical scenarios cannot be initiated until the preceding action is completed.

In many cases, the preceding action not only provides a basis for the subsequent movement, but also works with the subsequent action to achieve a complex task goal. In laparoscopic knot tying, for example, wrapping a loop of the thread using the preferred hand cannot start until the tail of the thread is held by the nonpreferred hand. While the wrapping is performed by the preferred hand, the nonpreferred hand will move the tail of the thread, adjusting the tension of the thread to facilitate the wrapping performance. The submovements performed by the two limbs are so perfectly collaborated that some scientists believe a high-level coordinative structure should be constructed for the temporal or spatial synchronization of a bimanual movement [12]. This type of coordinative structure between limbs is difficult to build between two operators.

Admitting the differences in building coordination between an interlimb and interoperator task does not conflict with the findings of this study. Although not comprehensive, the results of this study shed light on the structure of the intra-operator coordination in the surgical context.

In addition, impacts of increasing mental workload rooted in the laparoscopic settings on the surgeons' performance ought to be addressed. As shown, camera rotation creates a difficult perceptual motor mapping situation that significantly increases the mental workload for participants regardless whether they are working bimanually or in a team [21]. However, interaction between camera rotation and operator indicated that the dyad team had a larger capacity to absorb the impact of camera rotation than single individuals performing bimanually (Fig. 3). This means that distributing the workload among members in a team is a possible solution to the problems caused by camera rotation.

Relative to the vertical display, superimposition of the image over the work plane reduces the complexity of sensorimotor transformations and decreases the mental workload caused by the visual misalignment for the participants no matter what type of instruments they are holding or to which group they are assigned. Therefore, the beneficial effects of superimposing the display apply to the movement of both grasper and scissors.

Conclusion

In performing a laparoscopic reaching, grasping, and cutting task, task sharing between two operators in a dyad team produced significantly better performance as compared with one operator performing the task bimanually. The superior task performance of a dyad team is the result of the larger capacity for information processing. When the mental workload is increased under the visual misalignment condition, task performance is reduced in both the team and bimanual settings; in contrast. Technology that helps to reduce the mental stress by superimposing the image over the work plane facilitates task performance and skill learning.

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Appendix

Temporal data were recorded from the VCR counterclock, which was synchronized with the video recordings. The counter was based on 60 min, 60 s, and the number of frames (30 frame/s time intervals), with the counter increasing as the time duration increased. Thus, once the counter read 00:00:29, the next frame increased the counter to read 1 s, indicated by 00:01:00. When counter read 00:59:29, the next frame increased the counter to 01:00:00. In contrast, when temporal data are inputted to Microsoft EXCEL, in which data are sorted and analyzed, EXCEL requires data to be in the format of 60:60:60 (conventional time format) for the software to "recognize" it. Therefore, when inputting VCR counterclock data into EXCEL, we multiplied the last two digits by 2 to make it a ratio of 60 rather than 30. Time durations between defined events were then calculated by subtracting the respective time codes and converted them to seconds.

The conversion steps are as follows:

$$\begin{aligned} \text{VCR counterclock} &= 00{:}31{:}27 \\ \text{Total time duration} &= 00{:}31{:}54 \\ &= 31 \text{ seconds} + 54/60 \text{ seconds} \\ &= 31.9 \text{ seconds} \end{aligned}$$

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