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SURGICAL ENDOSCOPY
and Other Interventional Techniques

Ergonomics and human factors in endoscopic surgery: a comparison of manual vs telerobotic simulation systems

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Abstract
Background: Minimally invasive surgical techniques expose surgeons to a variety of occupational hazards that may promote musculoskeletal disorders. Telerobotic systems for minimally invasive surgery may help to reduce these stressors. The objective of this study was to compare manual and telerobotic endoscopic surgery in terms of postural and mental stress.
Methods: Thirteen participants with no experience as primary surgeons in endoscopic surgery performed a set of simulated surgical tasks using two different techniques — a telerobotic master — slave system and a manual endoscopic surgery system. The tasks consisted of passing a soft spherical object through a series of parallel rings, suturing along a line 5 -cm long, running a 32-in ribbon, and cannulation. The Job Strain Index (JSI) and Rapid Upper Limb Assessment (RULA) were used to quantify upper extremity exposure to postural and force risk factors. Task duration was quantified in seconds. A questionnaire provided measures of the participants' intuitiveness and mental stress.
Results: The JSI and RULA scores for all four tasks were significantly lower for the telerobotic technique than for the manual one. Task duration was significantly longer for telerobotic than for manual tasks. Participants reported that the telerobotic technique was as intuitive as, and no more stressful than, the manual technique.
Conclusions: Given identical tasks, the time to completion is longer using the telerobotic technique than its manual counterpart. For the given simulated tasks in the laboratory setting, the better scores for the upper extremity postural analysis indicate that telerobotic surgery provides a more comfortable environment for the surgeon without any additional mental stress.

Key words: Endoscopic techniques — Robotics — Ergonomics — Minimally invasive surgery

Minimally invasive surgical methods have greatly improved patient recovery time; however, manual methods often require surgeons to maintain awkward and static postures of both the trunk and the upper extremities. Moreover, manual endoscopic surgery involves more awkward and static movements of the upper extremities than open surgery. It also limits natural changes in body posture, may induce fatigue, and requires relatively high muscular loading, putting the surgeon at risk for fatigue and injury [13]. Many of these issues are design-related. For example, the instruments used in manual endoscopic surgery have less efficient handle-to-tip force transmission than the instruments used in open surgery, and are associated with excessive flexion and ulnar deviation of the surgeon's wrist due to fixed-point insertion and the large external arc of arm movements necessitated by the increased length of the instruments [13]. Furthermore, Berguer et al. found that manual endoscopic surgery is more mentally stressful and requires greater concentration than open surgery [3]. Finally, many endoscopic surgeons also report significantly more finger numbness and eye strain than surgeons who operate using mainly open techniques [5].

Recent technological advances in computer-assisted surgical systems include the use of telerobotic systems whereby surgeons control the "master" instruments in a comfortable and very natural manner, while in turn the computer controls the endoscopic instruments and video cameras through the "slave" robotic arms. The computers transmit the natural movements of the surgeon's

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hands to the endoscopic instrument through the robotic arms. The system extends the surgeon's capabilities beyond conventional surgical techniques, thus adding new capabilities that previously had not been possible with conventional surgery [1].

These systems use three-dimensional imaging to provide additional visual cues to the surgeon [2]. Hence, a normal operative field and the hand–eye orientation typical of open surgery can be maintained. Because the system is operated under direct, real-time control, open surgical techniques can be performed at the console and then instantly converted into minimally invasive surgery at the surgical site.

Telerobotic endoscopic surgery offers potential solutions to the ergonomic pitfalls posed by its manual counterpart, without adversely affecting surgical performance. Telerobotic systems provide surgeons with mechanical advantages and significantly reduce the external arc of arm movements. Nio et al. found that telerobotic endoscopic surgery can be performed as well as or even more precisely than manual endoscopic surgery [10]. Furthermore, the master instruments are positioned for easy access by the surgeon and are designed with an eye towards comfort. To date, no study has yet examined the ergonomic advantages for the surgeon using a telerobotic system similar to that studied by Berguer et al. [3].

Therefore, we designed a study to compare the job analysis scores in terms of exertion and upper extremity posture of a group of surgeons using the two different endoscopic methods — manual and telerobotic. Through a repeated-measures experimental design comprised of a set of standard tasks, we tested the null hypothesis that there are no differences between the two methods.

Materials and methods

The study used a repeated-measures design in which 13 medical trainees completed simulated surgical tasks with manual and telerobotic endoscopic systems. Both the institutional review board of the Virginia Commonwealth University and the Human Participants Committee of the Harvard School of Public Health approved all protocols. The experiment was carried out at the campus of the Virginia Commonwealth University Health Science Center.

Thirteen volunteers with no experience as primary surgeons in either manual or telerobotic endoscopic surgery were recruited to participate in the study. Four participants were medical students; the remaining nine were junior medical or surgical residents. Five participants had experience as primary surgeons using the open technique.

Each study participant performed the following four simulated surgical tasks: (a) passing a soft spherical object through a series of rings, (b) suturing, (c) running a 32-in ribbon, and (d) cannulation (insertion of a rodlike object into the lumen of a tube). The sphere-passing task simulated passing items from one grasper to another within a restricted work space. The task consisted of passing a 1.5-cm spherical object composed of a soft material through seven 2-cm diameter metal rings (Fig. 1). The rings were oriented vertically and parallel to one another, and were spaced 1 cm from one another. For the suturing task, participants were instructed to place three running sutures into a Simulab silicone wound model (Simulab Corporation, Seattle, WA, USA) using 2.0 silk material on a curved tapered needle (Fig. 2). To keep techniques standardized, the initial knot was pretied. No final knot was made after completion of the three suture passes. The third task consisted of running a 32 ¼- in soft ribbon from end to end using two needle holders. The ribbon had a zigzag pattern (Fig. 3).

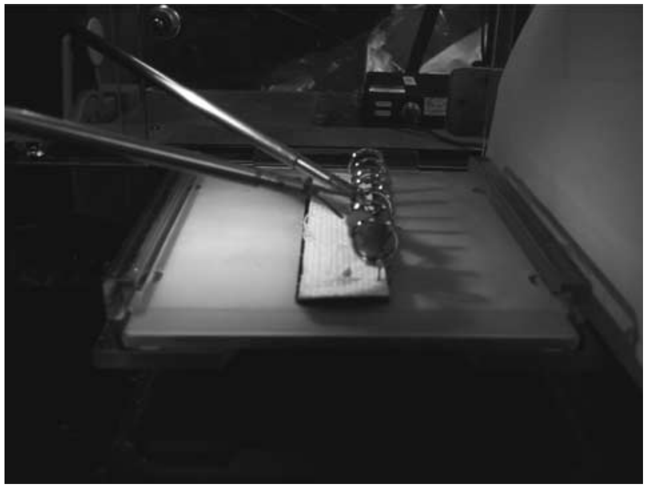

Fig. 1. Passing a 1.5-cm soft sphere through seven 2-cm–diameter metal rings (sphere-passing).

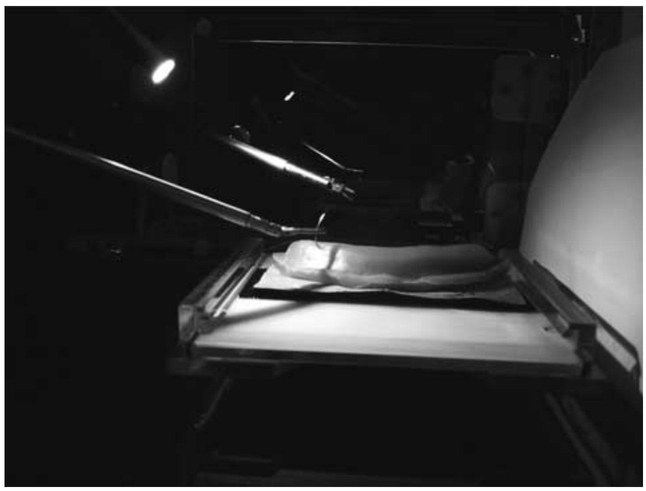

Fig. 2. Placement of three running sutures into a Simulab silicone wound model (suturing).

This task simulated running tissue such as bowel for visual inspection to assess for lesions. Finally, the cannulation task consisted of passing a 1-inch-long yellow pipe cleaner through the lumen of a 1/2-inch-long orange neoprene tube length (Fig. 4). The lumen was 3 -mm in diameter. Participants were allowed to sandwich the tube between the floor plate of the simulator box and one of the needle driver tips if they wished. Most elected to hold the tube within a single needle driver's tips while passing the pipe cleaner through with the other needle driver.

Participants were given a description of each task and of both operative techniques. After being instructed in how to operate both the manual laparoscopic instruments and the telerobotic system, they performed each task using both the manual and telerobotic endoscopic surgery techniques. Participants performed all manual simulated surgery from a standing position and all telerobotic simulated surgery from a seated position. Randomization ensured that some participants completed the four tasks using the telerobotic technique first, whereas the others completed the four tasks using the manual technique first. Participants were allotted a maximum of 15 mins to complete each task.

The experiment was conducted on an inanimate simulator workstation that was developed at Medical Informatics Technology Applications Consortium (MITAC) to reflect standard laparoscopic instrument position and the movements seen in minimally invasive surgery (Fig. 5). The inanimate simulator is a polypropylene box with three access ports, configured so as to enable the placement of standard

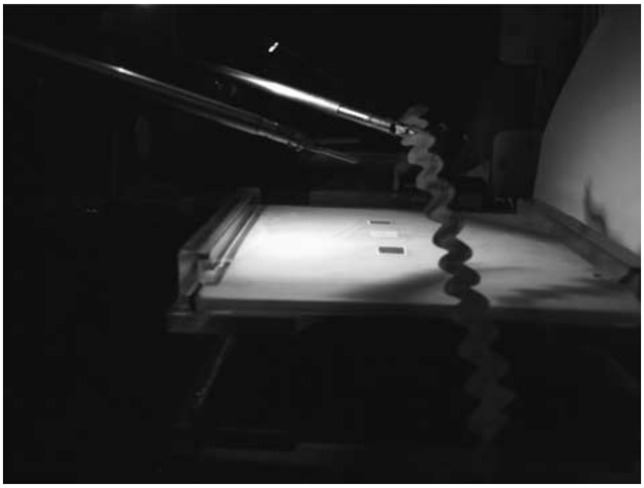

Fig. 3. Passing or "walking" a 32-in ribbon from end to end using two needle holders (ribbon walk).

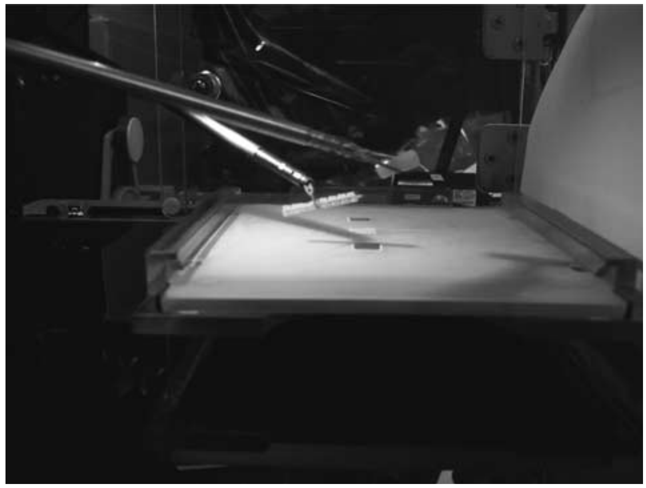

Fig. 4. Preparing to pass a 1/2- inch-length in pipe cleaner through the lumen of a Neoprene tube of in length (cannulation).

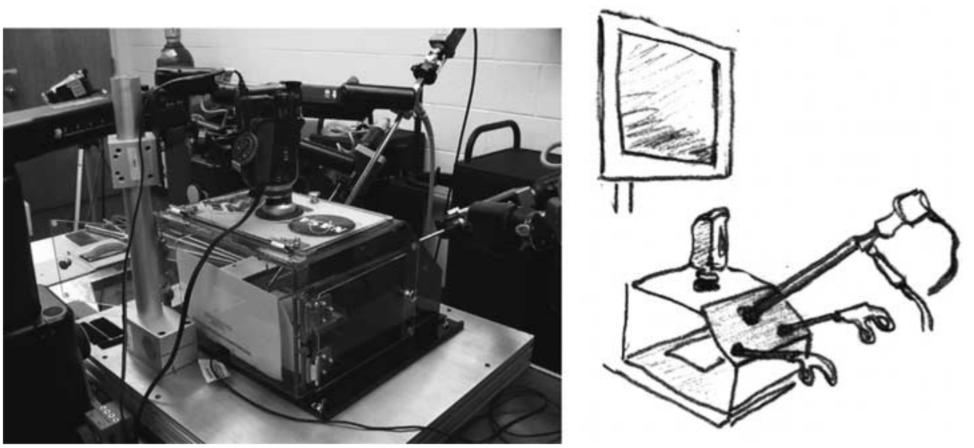

Fig. 5. **A** An inanimate simulator workstation developed to reflect standard laparoscopic instrument position and movements seen in minimally invasive surgery. The two robotic arms of the Zeus Surgical Robotic System are positioned in the simulator box. **B** Standard laparoscopic instruments placed in the simulator box.

laparoscopic surgical instruments, and a video imaging system. A standard laparoscopic CCD video endoscope (Stryker Endoscopy, San Jose, CA, USA) was placed through the center access port and was stabilized by Alpha port hardware (Computer Motion, Goleta, CA, USA). Stabilizing the video-endoscope in this configuration has been proven to improve the quality of image capture in performing laparoscopic surgical procedures [12]. The remaining two access ports, one on either side of the center port, were used to place the laparoscopic instruments used to perform the tasks being tested.

For the telerobotic setup, the two robotic arms of the Zeus Surgical Robotic System (Intuitive Surgical, Sunnyvale, CA, USA) were placed in the simulator box (Fig. 6). The two arms, fitted with needle grasper instruments with micro-wrist action, were controlled by the participant, who was seated at a remote control console in a chair with armrests. For the manual endoscopic technique, two standard laparoscopic needle holders were placed in the simulator box. The manual instruments were similar to the robotic instruments but lacked micro-wrist flexion and extension capability. Two-dimensional video monitors were used for both manual and telerobotic simulated endoscopic surgery. Movement, rotation, and wrist scaling for the telerobotic system were all set to 5.0.

A Sony mini-DV camera was positioned so that the left frontal–lateral aspect of each participant was in view as the tasks were being performed. The mini-DV camera displayed elapsed time in seconds. All tasks were recorded on mini-DV tapes for later review. Two trained independent observers then applied biomechanical models to the video images to predict internal tissue exposures. Interrater reliability was excellent, ranging from 0.85 to 1.00 for 15 of 16 scores, with an isolated value of 0.69 for scoring the cannulation procedure using the Job Strain Index (JSI).

The JSI was used to assess exposure to distal upper extremity hazards. Moore and Garg have previously described JSI methodology and preliminary validation [8]. The index is based on multiplicative interactions among task variables consistent with physiological, biomechanical, and epidemiological principles. The JSI score represents the product of six multipliers that correspond to the following six task variables: (a) intensity of exertion, (b) duration of exertion, (c) exertions per minute, (d) hand/wrist posture, (e) speed of work, and (f) duration of task per day [8]. Each task variable is rated according to five levels. The JSI is a semi-quantitative job analysis methodology that results in a numerical score. Higher JSI scores have been correlated with an increase in mean incidence rate for upper extremity disorders [8].

Increasing levels of intensity of exertion imply increasing amounts of strain on the distal upper extremity. The duration of exertion is the average duration of exertion per average exertional cycle time. For example, if the average exertional cycle time is 60 s, and the average duration of exertion is 30 s, the percentage duration of exertion is 50%. A longer duration of exposure is associated with greater strain than a shorter duration of exposure for a given intensity of exertion and a constant number of efforts per minute. Efforts per minute is the number of exertions per minute and can be thought of as the frequency. In general, increasing efforts per minute increases strain for a given intensity of exertion. "Posture" refers to the anatomical position of the hand or wrist relative to neutral position. It reflects the intrinsic compressive stresses to the contents of the extensor and flexor compartments about the wrist. Posture rating levels can range from "very good" for essentially neutral positions to "very bad" for deviation to extreme ranges. Speed of work estimates the perceived task pace and ranges from the most favorable rating of "very slow" to the least favorable rating of "very fast". Duration of task per day reflects the total time a

Fig. 6. Two Zeus robotic arms placed in the simulator box (*top*). The Zeus Surgical Robotic System control console (*bottom*). Note the preservation of natural operative field and hand–eye orientation on the video display terminal.

task is performed each day. It is expressed as hours and is designed to reflect no effect on strain if a task is performed for 4–8 h per day, decreased strain with decreasing durations per day, and increased strain with durations > 8 h. Because participants were instructed to complete each task at a comfortable pace, the rating for speed of work was set to "slow" and the multiplier for the duration of task per day was set at 4 h.

To further validate the study results, the Rapid Upper Limb Assessment (RULA) was also used to assess the postures of the neck, trunk, and upper limbs, along with muscle function and the external loads experienced by the participant's body. This method uses diagrams of body postures and scoring tables to provide an evaluation of exposure to the following risk factors: (a) numbers of movements, (b) static muscle work, (c) force, (d) work postures determined by equipment, and (e) time worked without a break [7]. Although a detailed description of RULA methodology is beyond the scope of this paper, a brief explanation is as follows: The body is divided into segments that comprise two groups. The first group includes the upper and lower arm and wrist: the second group includes the neck, trunk, and legs. This methodology ensures that any awkward or constrained postures of the whole body are included in the assessment.

The range of movement for each body part is divided into sections according to preset criteria derived from interpretation of the relevant literature. The sections are numbered. "The number 1" is given to the range of movement of working posture where the risk factors present are minimal. Higher numbers are assigned to parts of the movement range, with more extreme postures representing greater loading on the structures of the body segment. The scoring system also takes into account the additional load on the musculoskeletal system caused by excessive static muscle work and repetitive motions. Based on the above criteria, a grand score that can range from 1 to 7 is generated. This score estimates the risk of injury due to musculoskeletal loading. Higher scores indicate a higher probability of musculoskeletal injury. A score of 1 or 2 indicates that a given job posture is acceptable if not maintained or repeated for long periods. A score of 3 or 4 that indicates further investigation is needed and changes may be required. A score of 5 or 6 indicates that changes are required soon. A score of 7 indicates that changes are required immediately [7]. McAtamney and Corlett have previously reported on the initial validation and reliability studies of RULA [7].

During video image review, the time to complete each task for the telerobotic and manual techniques was obtained by correlating the onset and completion of each task with an elapsed time display on the video monitor. Time was recorded to the nearest second.

Immediately after completing all tasks, each participant completed a questionnaire that compared the intuitiveness and perceived mental stress for all four telerobotic endoscopic surgery tasks to all four manual endoscopic surgery tasks. Each participant was asked the following four questions: (a) How intuitive was the manual endoscopic technique? (b) How intuitive was the telerobotic (Zeus-assisted) endoscopic technique? (c) How much mental stress did you experience using the manual endoscopic technique? and (d) How much mental stress did you experience using the telerobotic (Zeus-assisted) endoscopic technique? Intuitiveness and perceived mental stress were graded on a scale from 1 to 10, with 1 being the least favorable response and 10 being the most favorable.

The Wilcoxon- signed- rank exact test was used to compare differences, between the two techniques in the RULA, JSI, task duration, and intuitive and perceived mental stress metrics. Significance was defined as a two-sided *p*- value of < 0.05. Statistical analysis was performed using StatXact-5 (Cytel Software Corporation, Cambridge, MA, USA) for Windows.

Results

All participants succeeded in completing the sphere-passing, ribbon-walking, and cannulation tasks using both techniques (manual and telerobotic). Four participants did not complete the suturing task using the telerobotic technique within the allotted 15 min. One participant did not complete the suturing task using the manual technique within the allotted time. Another participant abandoned the suturing task using the manual technique after complaining of significant discomfort in her hands. Seven participants completed the four tasks using the telerobotic technique first, followed by the manual technique. The remaining six used the manual technique first and then repeated the same tasks using the telerobotic technique.

The JSI scores for all four tasks were statistically significantly better using the telerobotic technique compared to the manual technique (Fig. 7). The median JSI score for sphere-passing was 13.5 (range, 9.0–27.0) for the manual technique and 3.0 (range, 2.3–4.5) for the telerobotic technique. The median JSI score for suturing was 20.3 (range, 13.5–40.5) for the manual technique and 6.8 (range, 4.5–13.5) for the telerobotic technique.

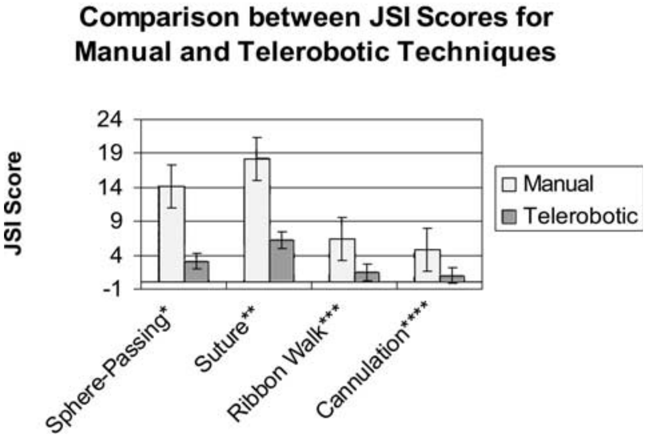

Fig. 7. Comparison between scores on the Job Strain Index (JSI) for the manual and telerobotic techniques. A higher JSI Scores is correlated with an increase in the mean incidence rate for upper extremity disorders. $^{*}p < 0.0002$, $^{**}p < 0.0002$, $^{***}p < 0.0002$, $^{****}p < 0.0002$.

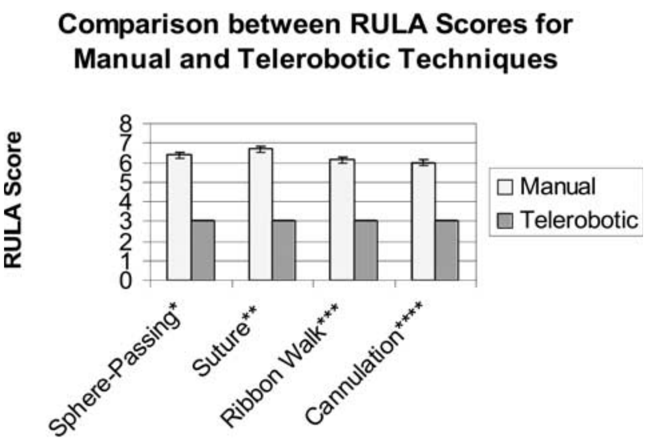

Fig. 8. Comparison between scores on the Rapid Upper Limb Assessment (RULA) for the manual and telerobotic techniques. RULA Scores range from 1 to 7. A score of 1 or 2 indicates a low probability of injury due to musculoskeletal loading; higher scores indicate a higher probability of injury. $^{*}p < 0.0002$, $^{**}p < 0.0005$, $^{***}p < 0.0002$, $^{****}p < 0.0002$.

The median JSI score for ribbon-walking was 6.8 (range, 4.5–13.5) for the manual technique and 1.5 (range, 1.1–3.4) for the telerobotic technique. The median JSI score for cannulation was 6.8 (range, 3.0–9.0) for the manual technique and 1.1 (range, 0.4–1.7) for the telerobotic technique.

The RULA scores for all four tasks were statistically significantly better for the telerobotic technique compared to the manual technique (Fig. 8). The median RULA score for sphere-passing was 6.0 (range, 4.0–7.0) for the manual technique and 3.0 (range, 3.0–4.0) for the telerobotic technique. The median RULA score for suturing was 6.0 (range, 5.0–7.0) for the manual technique and 3.0 (range, 3.0–5.0) for the telerobotic technique. The median RULA score for ribbon-walking was 6.0 (range, 4.0–7.0) for the manual technique and 3.0 (range, 3.0–4.0) for the telerobotic technique. The median RULA score for cannulation was 6.0 (range, 5.0–7.0) for the manual technique and 3.0 (range, 3.0–4.0) for the telerobotic technique.

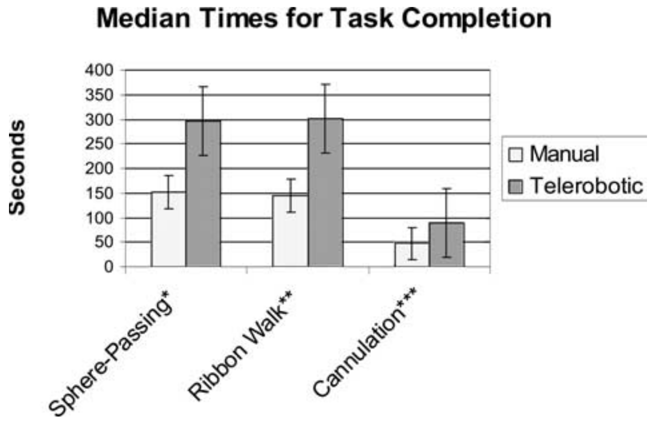

Fig. 9. Median times on the sphere-passing, ribbon walk, and cannulation tasks. $^{*}p < 0.0034$, $^{**}p < 0.0002$, $^{***}p < 0.0068$.

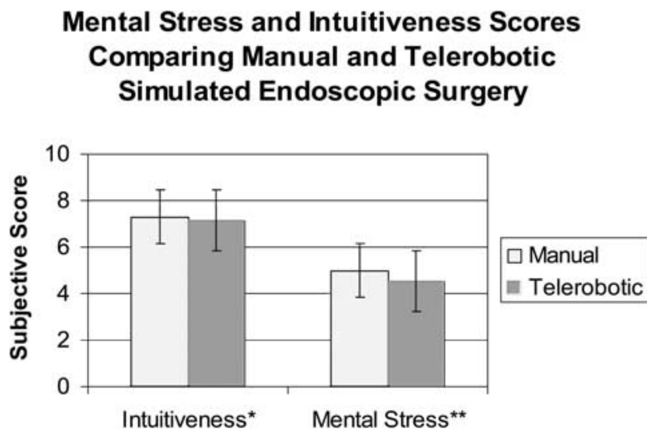

Fig. 10. Mental stress and intuitiveness scores comparing manual and telerobotic simulated endoscopic surgery. $^{*}p < 0.65$, $^{**}p < 0.40$.

Time duration in seconds for all tasks except suturing was significantly longer for the telerobotic technique than for the manual one (Fig. 9). No task duration comparison was performed for suturing because several participants failed to complete this task. The median time to complete sphere-passing was 151 s(range, 67–421) for the manual technique and 297 (range, 135–430) for the telerobotic technique. The median time to complete ribbon-walking was 145 s(range, 65–330) for the manual technique and 302 s(range, 139–481) for the telerobotic technique. The median time to complete cannulation was 47 s(range, 21–105) for the manual technique and 90 s(range, 57–187) for the telerobotic technique.

No statistically significant difference between the manual and telerobotic simulated endoscopic surgery was found for either the mental stress or the intuitiveness score (Fig. 10). The median intuitiveness score was 7 (range, 5–10) for the manual technique and 8 (range, 5–9) for the telerobotic technique. The median mental stress score was 6 (range, 1–8) for the manual technique and 5 (range, 1–7) for the telerobotic technique.

Discussion

Previous studies have shown that manual endoscopic surgery requires surgeons to perform awkward movements of the upper extremities, limits natural changes in body posture, and requires relatively high muscular loading. Such exposure puts surgeons at risk for fatigue and injury [9]. Our results suggest that telerobotic techniques offer potential solutions to these problems by providing surgeons with mechanical advantages and significantly improving exposure assessment scores for physical risk factors associated with work-related musculoskeletal disorders.

In this repeated-measures study, two different exposure assessment tools (JSI and RULA) quantified upper extremity posture and exertion while participants performed four simulated surgical tasks. The JSI and RULA scores for all four tasks demonstrated the statistical significance that telerobotic simulated endoscopic surgery exposes the surgeon to less risk of musculoskeletal injury than manual simulated endoscopic surgery.

Simulated surgery may not be predictive of actual surgery, with its many unpredictable variables. Nevertheless, this controlled repeated-measures experiment using an endoscopic surgical simulator box provided an objective means of evaluating the physical ergonomics of both manual and telerobotic endoscopic surgery systems. Body posture measurements were required to obtain the JSI and RULA scores. Although random errors may have been introduced in measurements estimated from video analysis, we want to emphasize the excellent interreter reliability achieved, as well as the fact that both the JSI and RULA methodologies have already undergone preliminary validation. Furthermore, Rucker and Moore provided additional evidence of JSI's external and predictive validity in a study of distal upper extremity disorders at two manufacturing plants [11].

For all tasks except suturing, the time to completion was longer when participants used the telerobotic technique. Because several participants failed to complete the suturing tasks within the allotted maximum time (15 min), it was not possible to compare duration for this task. None of the participants had experience as primary surgeons using the endoscopic technique. Additionally, the participants had to familiarize themselves with the telerobotic system. Had the participants been familiar with the telerobotic control system, the differences in task completion times might not have been as significant.

Participants also rated intuitiveness and perceived mental stress for the manual and telerobotic techniques on a scale from 1 to 10. Despite the fact that the participants had to familiarize themselves with the telerobotic endoscopic surgery system, we found no difference between the two techniques in intuitiveness or mental stress.

Although some problems still need to be resolved, the use of telerobotic endoscopic surgery systems opens up a vast array of possibilities never before imagined with conventional surgical techniques. For example these system offer increased three-dimensional accuracy, increased precision of movements, reproducibility of repeated procedures, and the ability to perform surgery from a distance [4, 6]. Technological advances and an increased demand for telerobotic surgery systems may soon result in decreased cost.

Telerobotic surgical technology offers one other type of benefit to surgeons. Because the surgeon is removed from direct contact with the operative field, the chance of acquiring a bloodborne pathogen infection such as HIV or hepatitis C is greatly reduced. This aspect would be particularly advantageous in the case of orthopedic surgery requiring much mechanical manipulation, such as grinding, drilling, chiseling, and hammering.

As technology advances, we can expect to see ever more efficient telerobotic surgical systems. Systems that seem to be on the cutting edge today will soon be phased out in favor of newer systems, which in turn will be replaced in the not so distant future. Nevertheless, the generalizability of our findings will remain valid for several reasons. First, the advantage arising from preservation of a normally oriented view of the surgical field will surely be improved upon or at least be maintained, as new telerobotic systems are developed. Second, the mechanical advantages for the human surgical operator will no doubt continue to improve as these systems evolve. Thus, our finding that telerobotic endoscopic surgery is ergonomically more favorable than its manual counterpart should in theory hold true for more advanced systems.

In conclusion, telerobotic endoscopic surgery is ergonomically more favorable, equally intuitive, and no more mentally stressful than manual endoscopic surgery when basic operative tasks are performed in a simulated environment. Given identical tasks, the time to completion is longer using telerobotic techniques than manual ones for surgeons with no primary experience in endoscopic surgery.

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