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SURGICAL ENDOSCOPY
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Changes in postural mechanics associated with different types of minimally invasive surgical training exercises

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Abstract
Background: Doctors who perform minimally invasive surgery commonly report upper extremity fatigue or joint and muscle pain. The goal of this study was to investigate the changes in postural parameters associated with different laparoscopic training tasks and graspers.
Methods: Three different training tasks (targeted object release, rope passing, and cable tying) were performed with three types of laparoscopic graspers. Joint angles were determined using video analysis, and centers of pressure (COP) were measured with force platforms.
Results: Cable tying proved to be the most challenging training task and involved greater joint angle excursions and COP excursions and velocities. Grasper 2 reduced shoulder and wrist flexion–extension over the selected tasks.
Conclusion: Training tasks should be designed to simulate surgical procedures because different tasks require distinct combinations of joint rotations. Joint rotations and postural balance should be considered when an optimal grasper is selected for a particular training task.

Key words: Biomechanics — Ergonomics — Force platforms — Laparoscopy — Motion analysis — Posture

Although minimally invasive surgery (MIS) often provides patients with a less traumatic alternative to open surgical procedures, there is much to be learned about its effects on the surgeons themselves. Doctors who perform MIS procedures commonly report upper extremity fatigue as well as joint and muscle pain. The Society of American Gastrointestinal Endoscopic Surgeons Task Force on Ergonomics conducted a survey to assess the incidence of musculoskeletal symptoms among laparoscopic surgeons [2]. Among 149 responders, 8% to 12% reported frequent neck and upper extremity pain associated with the performance of laparoscopic surgery. This is not surprising given that MIS often requires awkward postures, such as protracted standing and prolonged flexure of the torso and neck, which potentially induce work-related injury [11]. In addition, the long-handled, rigid design of laparoscopic instruments and the fulcrum effect of small laparoscopic trocars provide limited degrees of freedom during laparoscopy. These ergonomic constraints may result in movements that approach the limits for safe joint motion.

Ergonomic analysis has been proposed as a method both for gaining insight into the possible redesign of effective laparoscopic instruments and for evaluating the musculoskeletal impact of particular surgical tasks [9]. Although there are numerous techniques for determining musculoskeletal injury risks [8], finding the most appropriate measures for assessing minimally invasive surgical procedures remains a challenge.

Previous MIS ergonomic studies used video analysis and electromyography to critique laparoscopic instrument design. The measurements obtained from these studies have been used to examine the ergonomic features of instrument length, working angle, and handle design [3, 5–7]. In addition, video analysis has been used to determine surgeon postures and to assign ergonomic stress scores during standardized laparoscopic cholecystectomy [10].

In this study, we used video analysis to track operator movements during a series of three MIS training tasks with three different laparoscopic graspers. We compared the joint rotations associated with these common training tasks, aiming eventually to design laparoscopic bench training that corresponds to the movements involved in actual laparoscopic surgery. Additionally, force platforms were used to measure centers of pressure (COP), providing information regarding postural balance. Although force platforms are used commonly to analyze quiet standing, perturbed

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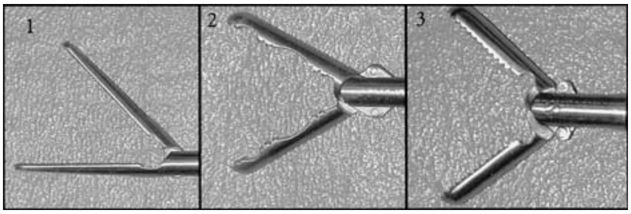

Fig. 1. Photograph demonstrating the differences between the single-action end-effector of grasper 1 (1) and the dual-action end-effectors of Graspers 2 and 3 [2, 3].

standing, and functional standing tasks, COP data for surgical tasks are not well documented.

The goals of this study were to analyze the changes in postural parameters associated with different MIS training tasks, and to investigate the differences in postural parameters as a function of grasper type. It was hypothesized that the training tasks considered the most physically challenging would result in greater COP disturbances and increased joint angular rotations. It also was hypothesized that certain graspers would prove to be preferential for particular tasks in terms of reduced joint angle excursions at the wrist and shoulder joints.

Methods

Three subjects from the Department of Surgery at the University of Kentucky with varying levels of laparoscopic experience volunteered to participate in this pilot study. After informed consent was obtained, these subjects performed a series of experimental trials that involved three separate MIS training tasks and three different surgical graspers. The tasks were executed within a standard MIS training box (U.S. Surgical, Norwalk, CT, USA) using a videoendoscopic setup (Stryker Endoscopy, Santa Clara, CA, USA).

The training tasks involved a targeted release of a small object, a simulated bowel inspection or rope-passing drill, and a cables-tying exercise. Each training task incorporated basic laparoscopic skills. Targeted object release consisted of grasping a pea and placing it into a small opening of an inverted cup. The rope-passing drill involved uncoiling a rope by successively passing it along its length between graspers. Cable tying was completed by placing one end of a plastic cable through a slotted connection on the other end of the cable.

The training tasks were performed with three different styles of inline finger-looped graspers. A nonratcheted grasper with a single-action blunt-end effector (grasper 1, 42.5 cm long; 122 g) 42.5 cm long; 122 g) and two models of ratcheted graspers with double-action blunt-end effectors (grasper 2, 37.5 cm, 122 g; grasper 3, 41.5 cm, 138 g) were used (Fig. 1).

The order of the tasks and graspers was randomized. The table height was adjusted according the subject's height to achieve a starting posture that included 90° of elbow flexion with the shoulder and upper arm in neutral. A verbal prompt was used to start the training task trials, which continued until the completion of the task. Targeted object release trials were limited to a duration of 10 s, and both the rope-passing and cable-tying trials were limited to a duration of 45 s. If the trial was completed before the time limit, the trial measurements were cropped to include only the execution of the training task. If the subject was unable to complete the task within the time limit, then the trial was not further analyzed.

The subjects stood on force platforms (Bertec Corp., Columbus, OH, USA) that yielded three-dimensional ground reaction forces and moments during the experimental trials. These measurements were further processed to derive the COP. As each subject performed the training tasks, 37 reflective markers were tracked using a six-camera motion analysis (Motion Analysis, Santa Rosa, CA, USA) video system. The markers were placed predominantly on the upper body, with five markers on the torso, four markers on the head, four markers on each upper arm, three markers on each forearm, two markers on each wrist, and one marker on each hand. The subjects wore two additional reflective markers surrounding each elbow joint during a static calibration of anatomic landmarks. The force platforms were sampled at 960 Hz, and the reflective markers were digitized at 60 Hz. All data were passed through a fourth-order, symmetric, low-pass Butterworth filter with a cutoff frequency of 6 Hz.

In ergonomic studies, COP measurements frequently are used to examine postural control during quiet standing and in response to perturbations [11]. In our study, COP indicated where the subject's weight was centered within his or her base of support. The base of support was defined by the outer edges of the feet and represented the theoretical limit for which the COP was bounded. Excursions of COP were determined by finding the difference between the maximum and minimum COP values in the anteroposterior (A/P) and mediolateral (M/L) directions. These excursions are related to the amount of postural sway that occur during a training task. Maximum A/P and M/L COP velocities quantified the speed of postural adjustments and were calculated by taking the first derivative of the COP with respect to time.

Segmental orientations were determined using groups of three markers for the pelvis, trunk, head, upper arms, forearms, and hands [4]. Dynamic and reconstructed marker positions were combined to designate coordinate axes for the aforementioned segments. Three successive Euler rotations (flexion–extension, abduction–adduction, and internal–external rotations) were used to define the joint angles between adjacent sets of segmental coordinate axes [1]. Maximum and minimum joint angles indicated the postural extremes achieved during the training tasks. Joint angle excursions were calculated by finding the difference between the maximum and minimum joint ranges of motion that occurred during an experimental trial. These joint angle excursions provided insight into postural coordination and the relative contributions to movement associated with the different training tasks and graspers.

The experimental protocol called for six repetitions of targeted object release, six repetitions of rope passing, and three repetitions of cable tying for each grasper (45 trials per surgeon). However, the data for one subject were incomplete because of time constraints on the participating surgeon. From these experiments, 92 trials were digitized with minimal obscuring of the video markers. To avoid the introduction of bias into the data, matched comparisons of targeted object release and rope passing were made for two surgeons, three graspers, and five repetitions (60 trials). Similarly, comparisons between cable tying and the other two tasks were made for one surgeon, three graspers, and three repetitions (27 trials). Multivariate analysis of variance (ANOVA) (SAS Institute, Cary, NC, USA) was used as a protected procedure to test the statistical dependence of the COP excursions, maximum COP velocities, maximum joint angles, and joint angle excursions on training task, grasper type, and task–grasper interactions. Pairwise *t*-tests were used for post hoc analysis, and each dependent variable was considered significant at *p* values less than 0.05.

Results

Rope passing had significantly greater COP excursions in the A/P and M/L directions than the targeted object release (Fig. 2). In addition, cable tying had significantly greater A/P and M/L COP excursions than the rope-passing drill. Similarly, rope passing as compared with targeted object release and cable tying as compared to rope passing both had significantly greater maximum COP velocities in the A/P and M/L directions (Fig. 2). Figure 3 shows the outer boundaries of the COP measurements for representative examples of each training task. This illustrates the successive increases in the COP excursions that occurred in targeted object release, rope passing, and cable tying. Force platform parameters appeared to vary with the type of grasper used, but none of these differences proved to be statistically significant for this set of experiments.

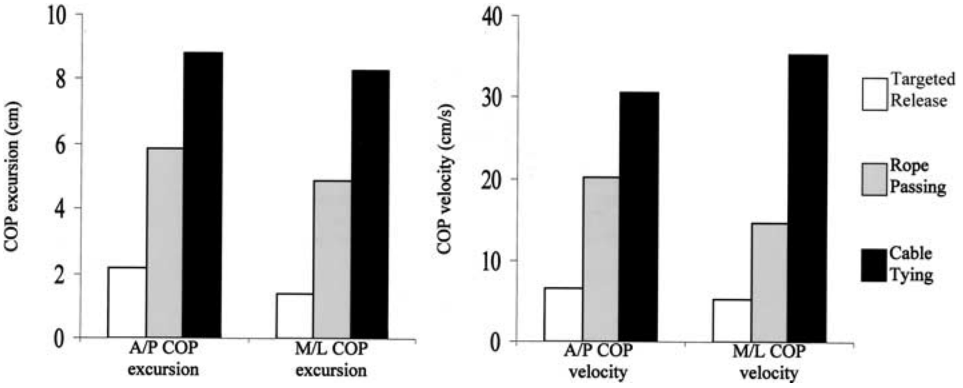

Fig. 2. Center of pressure (COP) excursions and COP maximum velocities as a function of training task. Anteroposterior and mediolateral COP excursions and COP maximum velocities were significantly greater during cable tying than during rope passing, and during rope passing than during targeted object release ($p < 0.05$).

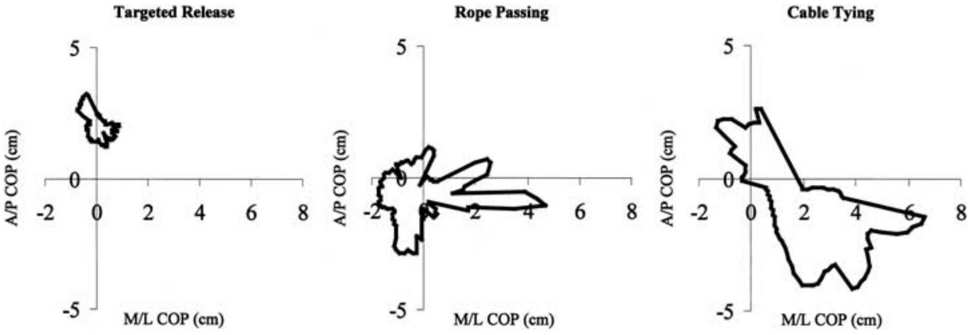

Fig. 3. Outer boundaries of the Center of pressure (COP) measurements for representative examples of each training task. The degree to which the COP shifted during the training tasks increased in both directions from targeted object release to rope passing to cable tying.

Shoulder and wrist joint angle excursions showed the greatest changes in comparisons of different training tasks (Table 1). Because targeted object release resulted in the lowest values for joint angle excursions, it can be considered a baseline task. As such, the targeted object release predominantly required forearm pronation–supination, wrist flexion–extension, and shoulder flexion–extension to complete the task. The rope-passing drill required additional shoulder and wrist joint angle excursions, as compared with targeted object release. Furthermore, cable-tying tasks involved increased shoulder and wrist joint angle excursions, as compared with rope passing. Maximum joint angles displayed statistical dependencies similar to those joint angle excursions.

Several differences in joint excursions resulted from the type of grasper used. Shoulder flexion–extension was significantly reduced with the use of grasper 2, as compared with graspers 1 and 3 (grasper 1, 62.4°; grasper 2, 55.6°; grasper 3, 62.5°). In addition, wrist flexion–extension also was reduced significantly with the use of grasper 2, as compared with graspers 1 and 3 (grasper 1, 88.6°; grasper 2, 66.3°; grasper 3, 84.0°). In the examination of individual tasks, shoulder adduction–abduction was significantly increased with the use of grasper 2, as compared with grasper 1, for cable tying (grasper 1, 50.2°; grasper 2, 60.1°; grasper 3, 56.9°). As before, maximum joint angles closely followed the dependencies found with joint angle excursions.

Discussion

In terms of training task difficulty, subjects considered cable tying to be the most challenging task, followed by the rope-passing drill. Both the COP excursions and the maximum COP velocities increased in accordance with these perceptions of task difficulty. Interestingly, as the tasks grew more challenging, COP measurements were greater in both the A/P and M/L directions, consistent with complex, multiplanar movements. The outer boundaries of the COP measurements effectively illustrated the differences in COP excursions between the different tasks. As a point of comparison, A/P COP excursions have been measured at 0.4 cm, whereas M/L COP excursions have been measured at 0.2 cm during quiet standing [12]. For this study, A/P COP excursions for targeted object release were only five times greater than the values for quiet standing, whereas M/L COP excursions for cable tying were 40 times greater than these same values.

In general, higher COP excursions indicate increased postural sway, which becomes a threat to postural stability as the COP approaches the bounds of the base of support. However, very small COP excursions also may be a sign that a task involves an overly rigid posture that requires additional muscular stiffness to maintain. Confusion over the ideal range of COP excursions can be reduced by simultaneously considering the maximum COP velocities. The high maximum COP velocities that occur during rapid postural adjustments may be in response to postural instability. Potential drawbacks to using COP velocities are the detection of inadvertent postural adjustments unrelated to the task and the amplification of measurement noise during differentiation. However, COP measurements were of interest not only for postural balance analysis, but also as potential ergonomic indicators in surgical settings. These ergonomic measurements would be more easily incorporated into

Table 1. Joint angle excursions required for the completion of different training tasks

	Targeted release (°)	Rope passing (°)	Cable tying (°)
Shoulder flexion–extension	42.8	45.9	70.5[a]
Shoulder adduction–abduction	41.1	46.3[a]	55.7[a]
Shoulder internal–external rotation	35.1	41.1[a]	80.3[b]
Forearm pronation–supination	80.5	87.7[a]	103.1[b]
Wrist flexion–extension	48.7	84.8[a]	116.7[b]
Radial–ulnar deviation	31.3	61.8[a]	78.5[a]

[a] Significant changes, as compared with targeted object release ($p < 0.05$)
[b] Significant changes in cable tying, as compared with rope passing ($p < 0.05$)

the operating suite than video motion analysis and electromyography, which both require equipment to be placed on the surgeons' arms. Force platforms placed in the floor of a dedicated surgery suite can be sealed to allow their surfaces to be scrubbed. Another option for COP measurements is the use of pressure sensitive inserts that would be placed in the shoes of a surgeon.

Whereas COP measurements provided insight into overall postural stability, video analysis focused on the differences that occur at individual joints for each task studied. Targeted object release, which included movements common to all tasks such as elbow flexion–extension and wrist rotations, was the simplest task in terms of joint angle excursions. As expected, rope passing involved increased forearm pronation–supination, wrist flexion–extension, and radial–ulnar deviation as the string was run from one grasper to the other. Cable tying, considered the most difficult task, required gross adjustments in the form of shoulder joint rotations and increased levels of fine forearm pronation/supination (Table 1). A potential application of video analysis is to compare the joint rotations associated with the variety of training tasks and the joint rotations required for actual surgical procedures. Furthermore, additional experiments including surgeons with varying levels of experience may show differences in postural mechanics as a function of skill level.

Video analysis also was used to examine differences in joint rotations that were dependent on the choice of grasper. Although it is acknowledged that the selection of graspers used in this study was arbitrary and the sample size small, joint angle and postural differences were seen according to the grasper type used. Grasper 1 was associated with reduced shoulder abduction–adduction during cable tying, which may result in less ergonomic stress on the shoulder joints. Grasper 2 was a promising choice for these tasks because it resulted in reduced wrist flexion–extension. The wrist has been previously implicated as the joint with the highest ergonomic stress during laparoscopic cholecystectomy [10]. However, a reduction in a given joint rotation may not imply a more favorable overall ergonomic profile, but may correspond to an unfavorable position at an adjacent joint. Therefore, the position of the entire upper torso and extremities should be considered during motion analysis. The results of this study suggest that the combined use of video and force platform analysis may provide insight into an optimal choice of grasper for a particular surgical task. When force platform measures were used, the differences between graspers were subtler than the differences between tasks. Additional subjects and repetitions are required before definitive conclusions can be reached.

Conclusion

Although laboratory training exercises may enhance laparoscopic skills, the tasks may be ergonomically hazardous for the trainee. In the designing of training exercises, surgical movement requirements should be considered because each task resulted in a unique coordination of joint rotations and postural balance. Cable tying proved to be the most challenging training task in this study, in terms of both higher COP excursions and velocities and increased joint angle excursions. Rope-passing drills were found to be of intermediate difficulty, requiring increased postural balance and wrist rotations, as compared with targeted object release. Because of the influence exerted by the grasper type on joint motion and postural balance, there may be more ergonomically sound choices for grasper selection depending on the task. Video analysis was a valuable tool for determining the complex joint motion of the upper body, and can be used in designing training tasks or analyzing alternative graspers. Measurements of COP were consistent with perceived task difficulty and may provide practical ergonomic indicators in a surgical environment wherein video analysis may not be feasible.

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