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Impact of novel shift handle laparoscopic tool on wrist ergonomics and task performance

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Abstract

Background—Laparoscopic tool handles causing wrist flexion and extension more than 15° from neutral are considered “at-risk” for musculoskeletal strain. Therefore this study measured the impact of laparoscopic tool handle angles on wrist postures and task performance.

Methods—Eight surgeons performed standard and modified Fundamentals of Laparoscopic Surgery (FLS) tasks with laparoscopic tools. Tool A had three adjustable handle angle configurations, i.e., in-line 0° (A0), 30° (A30), and pistol-grip 70° (A70). Tool B was a fixed pistol-grip grasper. Participants performed FLS peg transfer, inverted peg transfer, and inverted circle-cut with each tool and handle angle. Inverted tasks were adapted from standard FLS tasks to simulate advanced tasks observed during abdominal wall surgeries, e.g., ventral hernia. Motion tracking, video-analysis, and modified NASA-TLX workload questionnaires were used to measure postures, performance (e.g., completion time and errors), and workload.

Results—Task performance did not differ among tools. For FLS peg transfer, self-reported physical workload was lower for B than A70, and mean wrist postures showed significantly higher flexion for in-line than pistol-grip tools (B and A70). For inverted peg transfer, workload was higher for all configurations. However, less time was spent in at-risk wrist postures for in-line (47%) than pistol-grip (93–94%), and most participants preferred Tool A. For inverted circle cut, workload did not vary across configurations, mean wrist posture was 10° closer to neutral for A0 than B, and median time in at-risk wrist postures was significantly less for A0 (43%) than B (87%).

Conclusion—The best ergonomic wrist positions for FLS (floor) tasks are provided by pistol-grip tools and for tasks on the abdominal wall (ventral surface) by in-line handles. Adjustable handle angle laparoscopic tools can reduce ergonomic risks for musculoskeletal strain and allow versatility for tasks alternating between the floor and ceiling positions in a surgical trainer without impacting performance.

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Keywords

Laparoscopic tools; FLS tasks; Ergonomics; Wrist postures; Handle angles; NASA-TLX

Introduction

Laparoscopic surgery has revolutionized the delivery of surgical care resulting in reduced perioperative morbidity, improved recovery, and cosmetic outcomes for patients [1, 2]. However, limitations in degrees of freedom of movement during laparoscopic procedures impose challenges for the surgeon beyond those in conventional open procedures. As a result, laparoscopic surgeons are experiencing increased physical strain that may contribute to the widely reported musculoskeletal fatigue, pain, and injuries among minimally invasive surgeons ([1, 3-5]). These injuries impact not only productivity due to missed work days; Davis et al. [6] found 53% of surveyed surgeons reported musculoskeletal pain and injuries which impact their performance in the operating room.

A likely contributor to the reported musculoskeletal symptoms is the ergonomic limitation of the laparoscopic workplace and tool design [1, 2, 7-13]). Stomberg et al. [5] observed that laparoscopic tasks demand extreme and static postures; including more wrist supination and deviation than open surgeries[9]. Laparoscopic surgeons often need to apply more force to instruments, bend wrists more, and hold arms higher than in conventional surgery due to tool length and handle design. The ramifications of inadequate laparoscopic instrument design [7, 14-17] are complaints ranging from pain and numbness to nerve lesions, and studies have reported paresthesia in the hand or finger, rotator cuff strain, and cervical radiculopathy among surgeons performing laparoscopic procedures [1, 18-23].

Several handle designs are available with varying angle configurations (e.g., 0° for in-line and ~70° for pistol), actuation methods (e.g., lateral pinch, palmar pinch, power grip), and grip designs (e.g., ring handle, shank handle) [16, 24-26]. Preliminary work has suggested that in-line handles (0° angle between handle and grasper) may require higher levels of muscle activity than the pistol-grip ring handles [10]; however, limited work has examined how more complex tasks, such as those observed in advanced procedures that require a higher range of motion (ROM) are impacted by tool design.

We hypothesized that for complex tasks, a novel laparoscopic tool handle that has the ability to shift between in-line and pistol positions improves the ergonomic position of surgeons while performing laparoscopic tasks. This prototype tool was specifically designed to accommodate versatility of movement requiring multiple angles between the floor and abdominal wall in procedures such as laparoscopic cholecystectomy and ventral hernia repair, respectively. The aim of this study is to objectively evaluate the wrist ergonomics, technical performance, workload, and instrument usability of a laparoscopic handle with multiple angle configurations during simulated laparoscopic skills tasks using an advanced state-of-the-art Motion Analysis Laboratory to measure accurate, real-time three-dimensional wrist postures, validated multidimensional National Aeronautics and Space Administration Task Load Index (NASA-TLX), usability questionnaires, and performance,

i.e., task completion, errors as defined by the Fundamentals of Laparoscopic Surgery (FLS), and performance scores adapted from FLS.

Materials and Methods

Participants

Eight attending minimally invasive surgeons with three or more years of minimally invasive surgery (MIS) experience (four with surgical glove sizes 7 or smaller and four with 7.5 or larger) who reported performing surgical tasks on the ventral surface of the abdomen were invited to participate in this study.

Experimental setup

This IRB-approved study was conducted at the institution's state-of-the-art Motion Analysis Laboratory comprised of a high-speed, real-time computerized video motion analysis system utilizing 10 infrared cameras to measure human body kinematics and four in-floor force plates to measure underfoot loading. The spatial distribution of the cameras is optimized to yield reliable bilateral motion data with sampling speeds up to 900Hz, displacement accuracy to 1mm, and rotational measurement accuracy to 1 degree. All skills tasks were mounted on an adjustable box trainer (Stryker Endoscopy, San Jose, CA) used in Surgical Abdominal Wall (SAW) ventral hernia repair simulation [27]. The laparoscope was held in positions with a pneumatic Wingman™ system (Stryker Endoscopy). Monitor, trainer, and trocar heights were adjusted to surgeon's preference.

Laparoscopic tools

Two laparoscopic graspers were investigated: the prototype Tool A (Shift Handle™, Stryker Endoscopy, San Jose, CA) with three adjustable handle angles and the commercially available Tool B (Storz Clickline™, Storz Endoskope, El Segundo, CA). Tool A has a handle that can be adjusted to 0° or in-line (A0), 30° (A30), and 70° (A70) or pistol configurations with respect to the grasper shaft (Figure 1). Tool B is commonly used in MIS (i.e., large market share in hand instruments) and has pistol grip 70° handle angle similar to Tool A (A70); however, the pistol-grip handle is non-adjustable (Figure 1). Small and large handle sizes for Tool A were available and used based on glove size (7 and 7.5, respectively). Only one size handle was available for Tool B, which may potentially be confounder, but this limitation reflects the real-life handle size limitation for commercially available Tool B.

Task

Each participant performed three laparoscopic skill tasks with up to 5 minutes to complete each task. Tasks were the standardized FLS Peg Transfer (Peg Floor) and two modified FLS tasks, i.e., Inverted Peg Transfer (Peg Ceiling) and Inverted Circle Cut (Circle Ceiling) (Figure 2). The modified tasks were developed to simulate the surgical target location required during procedures on the anterior abdominal wall (e.g. laparoscopic ventral hernia repair). By mounting standardized tasks on the ceiling of the trainer, the target skills remained similar to the validated FLS tasks but the positioning of the instruments and camera angle changed to more closely simulate anterior abdominal wall procedures.

The FLS Peg Transfer task (FLS-4710, VTI Medical, Waltham, MA) [28] was performed using two graspers (PN 33310 MD, Storz; PN 250-080-283, Stryker) with the four different handle configurations shown in Figure 1. The Peg Ceiling task was adapted from the standard FLS task [28] based on recommendations by surgeon collaborators. The pegboard was mounted upside down on the ceiling of the SAW trainer, used for ventral hernia repair simulation [27], and the dexterity blocks adhered to the pegboard via a ferromagnetic system (Figure 2). Although validation is still underway, the magnets were tested by collaborating surgeons to make sure the magnet strength held the object without making it too difficult to remove. Task objectives, graspers, and dexterity blocks for the task were the same as the standard FLS task. The Circle Cut Ceiling task was the standard FLS task mounted on the ceiling of the trainer (FLS-4715 and FLS-4770). Participants used a scissor (PN 34310 MS, Storz; PN 250-080-267, Stryker) and grasper end-effector to cut a pre-stamped circle on gauze suspended on the ceiling (FLS-4770). The rationale for the inverted tasks was to simulate the higher ROM and required dexterity for advanced laparoscopic procedures that require manipulating tissues on the abdominal wall of the patient, e.g., ventral hernia repair that requires adhesiolysis, and positioning mesh and tacks on the anterior abdominal wall of the patient. By adapting the previously validated FLS tasks, the inverted tasks simulated a dramatically different surgical positioning and extended the required wrist ROM compared to the standard FLS tasks. Other FLS tasks such as suturing were not tested upside down since the tools tested were graspers and not needle drivers. Validation studies for content validity, response process, and internal structure validity [30] for the tested tasks are underway; however, surgeons noted that the peg up and circle cut up had similar components that simulate the complexity of tasks performed during laparoscopic ventral hernia repair.

Study protocol

To test the effect of the two tool handles, participants used Tool A in three handle configurations, i.e., 0°, 30°, and 70°, and Tool B (Figure 1). The four tool handle configurations (A0, A30, A70, and B) were ordered among participants using a 4×4 Latin square randomization design, blocked by small and large glove size groups. The same handle order was followed by a participant for each of the three tasks: Peg Floor, Peg Ceiling, and Circle Ceiling. Consistent handle order for each task was implemented to control for tool order effect by keeping the Latin square design consistent across tasks and participants. Before beginning the tasks, participants received up to five minutes for familiarization with the apparatus and all the tools and tool configurations. During this familiarization period, a study team member provided instructions for each tool and explained each handle configuration as the surgeon practiced grasping and transferring the dexterity blocks on the FLS Peg Transfer task. Participants performed each task with every tool and handle angle configuration in their randomized sequence and received at least a minute break between each tool handle configuration to fill out questionnaires. After completing a task with all four tool configurations, a five minute break was provided before moving on to the next task. During this time, the participants compared the four tool handles for the previous task. A total of 12 trials (three tasks with four handles) were completed by each expert surgeon.

Data collection

Dependent variables measured in this study included the primary outcome of wrist posture measures and secondary outcomes of task performance (time, errors and FLS score) and subjective ratings of workload and tools.

The participants' upper extremity motion during the simulated surgical tasks was captured simultaneously with a commercially available Raptor 12 Digital RealTime system (Motion Analysis Corp., Santa Rosa, CA, USA), the state-of-the-art optical motion tracking system utilizing 10 infrared cameras and skin-mounted retro-reflective markers. Twenty-one markers were used to track the head, truck, and upper-extremity motion. Post-processing of the kinematic data was performed in Visual3D (C-Motion Inc., Bethesda, MD) as previously published by Morrow et al. [31]. For each task and tool combination, the wrist flexion/extension angle (ROM and mean angle) and the percent time of the task spent in postures that increase injury risks ($>15^\circ$ flexion and extension from neutral as described in McAtamney & Corlett [32] and in Figure 3b) were quantified and defined as “awkward” and at-risk. Wrist ROM was the difference between minimum and maximum angle observed during each task.

Performance was measured in real-time or from videos recorded from the endoscopic camera by one study team member experienced in scoring FLS tasks. In addition to task completion times, performance was scored using a 300-point system, where points decrease with every second needed to complete the task, and 15-point or 10-point penalties were assessed for each unrecoverable error (defined as blocks that fall out of the field-of-view) or for each cut that deviate more than 2mm inside or outside the stamped circle, respectively [29].

Participants also completed the validated multidimensional National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire that contains six 20-point subscales on mental demand, physical demand, temporal demand, performance, effort, and frustration [33]. Originally developed for NASA astronauts, this questionnaire has been published in over 500 articles regarding use in industries including aviation, military, and healthcare [34]. This tool has also been used in surgery to distinguish workload differences between surgical techniques, laparoscopic tools, and procedures [17, 35]. After completing the task using all tools, participants ranked instrument from best to worst on a one to four ordinal scale.

Statistical analysis

To detect differences in the primary outcome of awkward or at-risk wrist angles ($>15^\circ$ from neutral), a priori analysis found that a study of eight participants would be powered to detect differences among four different tool handle configurations. For the purpose of this study, each of the three adjustable handle angles was treated as an individual tool factor level in this study. All dependent measures except for percent time spent in at-risk postures and tool preference rankings satisfied parametric analyses assumptions. Thus, analyses of the task performance, wrist (flexion/extension means and ROM), and subjective data (each workload subscale on NASA-TLX) were completed using a one-way, repeated measures, within-factor

ANOVA ($\alpha=0.05$). For significant main effects, post-hoc comparisons were performed using Bonferroni correction factor. In addition, post-hoc comparisons using Fisher's Least Significant Differences (LSD) tests ($\alpha=0.05$) were conducted to identify potential trends among tools. Potential confounders, e.g., glove size, were adjusted for, if necessary, using repeated measures ANCOVA. For the non-parametric data, i.e., % time in at risk postures and subjective rankings data, related-samples non-parametric Friedman's tests with Dunn-Bonferroni multiple comparison tests were performed. All statistical analyses were conducted using SPSS (v22, IBM Corp).

Results

Eight surgeons (four women, four men) with self-identified intermediate to expert levels of MIS experience provided informed consent and participated in this study. The attending surgeons recruited for this study all had experience with surgery on the ventral wall of patients' abdomens. Additionally, the practice of each participating practicing faculty consisted primarily of MIS, with all performing complex cases on the ventral wall, e.g. laparoscopic ventral hernia repair procedures. Mean experience at the attending level was 11 ± 5 years, and their ages ranged from 35 to 54 years old. The study was designed to balance participant glove sizes (Table 1), i.e., four standard (<7.5) and four large (>7.5), to control the effect of different hand sizes observed in the surgeon population and further evaluate the small and large handled prototype tool.

Performance

Performance times and scores for each task are summarized in Table 2. Mean task completion times were fastest for configuration A30 for the Peg Floor ($98s\pm29s$) and Ceiling tasks ($205s\pm62s$) and fastest with the configuration A0 for the Circle Cut Ceiling ($183s\pm67s$). Mean performance scores, which penalize errors, were best using configurations A30 for Peg Floor (200 ± 32), A70 for Peg Ceiling (90 ± 79), and A0 for Circle Ceiling (72 ± 55).

Using repeated measures ANOVA with Bonferroni correction, performance times, errors, and scores were not significantly different among tools (Table 2). Comparisons of trends with Fisher's Least Significant Differences test ($\alpha=0.05$) found that mean performance scores were 14 points better for A30 than A0 during the Peg Floor task. For the Peg Ceiling task, mean performance scores were 31 points better for A30 than A0.

Objective measurement of wrist postures

Although tool configuration was a significant factor for observed time in wrist *extension* $>15^\circ$ for Peg Floor task ($\chi^2(3)=11.7$, $p<0.01$), subsequent multiple pairwise comparisons found no differences among tool configuration (Figure 3b). For the Peg Ceiling ($\chi^2(3)=14.3$, $p<0.01$) and Circle Ceiling ($\chi^2(3)=9.6$, $p<0.05$) tasks, participants spent over 75% of task time in awkward at-risk postures (defined in Figure 3a) in all configurations except for A0 (Figure 3b). Specifically, task time (median [IQR]) spent in wrist *extension* $>15^\circ$ for the Peg Ceiling was less ($p<0.05$) for A0 (47% [28-81%]) than both pistol-grip configurations (A70: 93% [78-100%] and Tool B: 94% [83-100%]); A30 (87% [57-99%]) did not differ from the other configurations. For the Circle Ceiling task, the task time spent in the *extension* $>15^\circ$

during the Circle Ceiling task was less ($p<0.05$) for A0 (43% [13-66%]) than Tool B (87% [73-91%]); A30 (81% [40-92%]) and A70 (83% [36-97%]) did not differ from the other configurations.

For % time in wrist *flexion* $>15^\circ$ (Figure 3c), tools differed significantly only on the Peg Floor task, where at risk postures were observed more frequently ($p<0.01$) on A0 (60% [21-98%]) than the A70 (0% [0-0%]) and Tool B (0% [0-5%]), both pistol-grip configurations; A30 (12% [0-53%]) did not differ from the other configurations.

Observed wrist flexion and extension angles on the dominant hand are summarized in Figure 4. For the Peg Floor task, mean wrist postures on A0 ($17^\circ\pm13^\circ$) differed significantly from A70 ($-7^\circ\pm7^\circ$) and Tool B ($-5^\circ\pm10^\circ$). In addition, mean angle for the A30 ($7^\circ\pm10^\circ$) differed from A70 ($-7^\circ\pm7^\circ$) and Tool B ($-5^\circ\pm10^\circ$) configurations.

For the Peg Ceiling task, A0 ($-14^\circ\pm7^\circ$) differed significantly from both A30 ($-23^\circ\pm9^\circ$) and A70 ($-28^\circ\pm12^\circ$) tool configurations. Although the mean wrist angle for Tool B was $-26^\circ\pm14^\circ$, the large standard deviation among participants resulted in no significant differences between Tool B and the other handle configurations (Figure 4).

For Circle Ceiling, wrist angles differed significantly after Greenhouse-Geisser correction for sphericity among the tool configurations (Figure 4). Mean wrist angle for A0 ($-14^\circ\pm8^\circ$) was 10° closer ($p<0.05$) to neutral postures than Tool B ($-24^\circ\pm11^\circ$). Tools A30 and A70 were not statistically different from the other configurations.

Subjective measurement of wrist postures

The large variation in wrist posture (Figure 4) is partially due to different grasper holding strategies among participants. Some participants chose to rotate their instruments to the side while performing the Peg Ceiling and Circle Ceiling tasks (Figure 5b). This occurred more often with configurations A70, A30, and B; however, wrist flexion $>15^\circ$ was frequently observed with this strategy (Figure 5b). In a more extreme example, some participants rotated the instrument upside down (Figure 5c). These compensatory practices were not used as often with configuration A0.

Self-reported results

No statistically significant differences or trends among tools were observed for mental demand and frustration ratings. Participants rated the physical demands during Peg Floor (Figure 6) 50% less ($p<0.05$) while using Tool B (4 ± 2) than A70 (8 ± 4). Workload *trends* among tools were observed for temporal, performance, and effort dimensions of the NASA-TLX using Fisher's LSD test at $\alpha=0.05$ (Figure 6). Temporal demand for Peg Floor using Tool B (4 ± 2) trended three points lower than A70 (7 ± 3) and A0 (7 ± 4), and effort using the Tool B (6 ± 2) trended lower than A70 (8 ± 4). For the Peg Ceiling task, temporal demands using A30 (7 ± 3) trended lower than Tool B (9 ± 3) and A70 (9 ± 5). Performance and effort using A30 (9 ± 5 and 10 ± 5) trended 3-4 points lower than A70 (13 ± 5 and 13 ± 4). For Circle Ceiling, physical demand using the A0 (10 ± 4) trended lower than Tool B (11 ± 4), and effort using A0 (10 ± 4) trended lower than A70 (13 ± 6).

Median rankings, where surgeons rated their tool preference from best to worst, are shown in Figure 7. For Peg Floor, trends were observed as participants ranked Tool B better ($p=0.10$) than the other tool configurations (Figure 7); five participants ranked Tool B as the best tool and five ranked A0 as the worst. For the Peg Ceiling task, rankings were highest for A30 with half of participants ranking it as the best tool configuration overall. In contrast, four (50%) participants ranked Tool B as the worst. Statistically, the impact of tool configuration on rankings for Peg Ceiling was significant ($p < 0.05$); however, multiple comparisons with Bonferroni correction found no statistical difference among the tool configurations. Rankings among the configurations did not differ for the Circle Cut Ceiling task.

Discussion

The purpose of this study was to measure the impact of laparoscopic tool handle configurations (A0, A30, A70, and B) on task performance, awkward wrist postures, and self-reported workload during simulated surgical tasks in order to assess laparoscopic surgeon risk for musculoskeletal injuries.

Although mean performance times and scores for A30 trended better than the other tools on the peg tasks and better for A0 on the Circle Ceiling tasks, task completion time, number of errors, and performance scores did not differ statistically across the tool handle configurations (Table 2). Previous studies on the impact of tool handle angles on surgical performance have similarly been inconclusive. While Ahmed et al. [36] observed that laparoscopic porcine bowel suturing quality and errors were better using the a 40° angle tool than a 0° (in-line) and 80° (pistol-grip), Uchal et al. [37] found no significant differences in performance between in-line and pistol-grip angled tools in simulated suturing. Consistent with Ahmed et al. [36], where 40° outperformed the 0° and 80°, surgeons in the present study ranked the 30° configuration (A30) better overall for the Peg Ceiling task. This finding suggests that conventional in-line or pistol handle angles may not be optimal and options for angles between these two extremes (such as 30°) may be preferred. Since Tool A offers three different handle angles, this may be an option for improving surgeon ergonomics by allowing appropriate handle angles for different surgical tasks throughout a procedure without having to switch out instruments, instead shifting the handle angle to attain better wrist postures. However, it is important to note that participants perceived higher physical workload while using A70 than Tool B despite similar pistol-grip handles (Figure 6). Several participants commented on the bulkier handle, and additional work is warranted to reduce the weight and size of the prototype Tool A.

Upper extremity ergonomics while using laparoscopic tools have long been cited as a potential factor that impacts surgeon's musculoskeletal health and surgical performance [1, 2, 7, 15, 22]. Extreme (awkward at-risk) and static postures are known to reduce the efficiency of muscle action and increase pressure, friction, and transverse forces to soft tissues and tissue structures (e.g., carpal tunnel), resulting in musculoskeletal strain, fatigue, and discomfort [7, 38]. To prevent wrist injuries, the threshold of 15° has been a widely used metric for safe wrist posture and has been further supported by physiology studies [32, 39]. Using these guidelines, tools with a pistol-grip angle (A70 and B) resulted in significantly

more neutral and safer wrist posture than A0 (Figures 3-4) for the Peg Floor task. In contrast to the findings for Peg Floor, time spent in at-risk postures was doubled for the pistol-grip positions than the in-line position of A0 (Figure 3) for the inverted ceiling tasks. In addition, angles were 10-14° (71-100%) further from neutral postures for the pistol-grip positions than in-line (Figure 4). This suggests that different instruments or tools that allow changing handle angles to an appropriate position to minimize at-risk wrist postures (such as Tool A) should be used for tasks that are performed in different areas of the abdomen to allow for improved ergonomics and reduced musculoskeletal risk.

It is important to note that the risks for wrist strain and discomfort while using the pistol-grip configurations (A70 and B) during the inverted tasks may be underreported in the present study. Specially, several surgeons were observed to reduce musculoskeletal strain and discomfort when using the pistol tools for the inverted tasks by rotating the pistol handles to the side (Figure 5b) or turning the pistol handles upside-down (Figure 5c). Although the handles were not originally designed to accommodate these compensation strategies, participants explained that they were “protecting [their] wrist” with this strategy and further studies are warranted to examine how protective strategies influence surgical posture, musculoskeletal symptoms, and NASA-TLX results. Additionally, the simulated task durations were much shorter than the duration of a surgical procedure, and prolonged exposure to at-risk postures may increase surgeon musculoskeletal strain and discomfort.

Reducing musculoskeletal injury risks in MIS extends beyond tool designs; it requires a comprehensive approach involving workplace layout, table height, monitor position, surgical team positioning, fitting right tool to the task, and increasing ergonomic awareness [40-42]. Even though an in-line tool improved wrist ergonomics for the difficult simulated tasks on the ventral plane, the median time surgeons were in postures that are known to increase musculoskeletal injury risks was 43-47% (Figure 3). To further reduce the high prevalence of musculoskeletal pain and discomfort among MIS surgeons [1, 43], other strategies are needed, e.g., ergonomic guidelines in the OR and patient positioning. For example, table heights in the present study were adjusted to each surgeon's preference before every task, but some surgeons requested heights that were beyond the range of adjustability of the trainer. Although similar limitations in equipment and patient anatomy currently exist in the operating room preventing the mitigation of ergonomics risks by positioning, the findings from this study suggest that shiftable handle angles can provide a means for accommodating the workplace and patient positioning constraints to improve wrist ergonomics while not impacting performance.

Limitations

Although this study was powered to find differences in wrist angles with eight participants, the variety of observed participant postures while holding and operating the instruments (Figure 5) was much greater than expected, and the analysis of differences among tools in self-reported workload, rankings, and performance data may be limited by the small sample size. However, several trends were observed on the impact of tool handles on these dependent measures, and an expanded study is warranted to investigate these trends.

This study may be limited by variation in FLS experience among participants. Mean experience for all participants was 11 ± 5 years at the attending level, but only half had experience performing FLS tasks and none had previous experience performing the novel inverted tasks. However, the impact of FLS experience and potential learning curve effects was minimized through the use of a Latin Square Design that blocks tool order among participants.

Finally, additional studies are needed improving the task design and testing protocol. The design of the inverted skills tasks was adapted from validated FLS tasks with guidance from surgeon collaborators across institutions, and additional task validation studies are underway. The testing protocol in the current study was designed to study how different tool angles impact wrist ergonomics and performance during three simulated tasks; thus, participants were not allowed to shift Tool A during the task. Further studies are needed to measure the frequency a surgeon may choose to shift the tool to address task and environment constraints and the impact of shifting on wrist ergonomics and performance.

Conclusions

Laparoscopic tool handle angles impact surgeon's risk for wrist musculoskeletal strain and discomfort. Although wrist ergonomics were better for pistol-grip than in-line tools during the standardized FLS peg transfer, use of pistol-grip tools doubled the percent time surgeon spent in at-risk postures and increased wrist extension angles by 70-100% compared with the in-line tool during more technically advanced simulation tasks performed on the ceiling of the trainer. Tools with a shiftable handle may allow surgeons to achieve more comfortable and neutral body postures during simulation tasks or actual surgical procedures that require considerable tool movements within the abdomen without impacting surgical performance.

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Fig. 1. Tool A and Tool B laparoscopic instruments with all available angle configurations for Tool A, i.e., 0° (A0), 30° (A30), and 70° (A70), as tested

Fig. 2. FLS peg transfer task (a), inverted peg transfer task mounted on the ceiling of the Park Trainer (b), and inverted circle cut task (c)

Fig. 3.

a) Illustration of at risk wrist flexion and extension >15° linked to increased musculoskeletal injury risks. b-c) Median time spent in wrist extension >15° (b) and flexion >15° (c) among participants for the Peg Floor (top), Peg Ceiling (middle), and Circle Ceiling (bottom) by handle configurations. Red shading in the pie charts indicates the % time spent in postures linked to musculoskeletal injury risk. Unshaded area indicates % time spent in neutral postures of flexion (b) and extension (c). Pairwise post-hoc comparisons are indicated with symbols to the left of each pie chart. Different symbols indicate a significant difference between tool configurations.

Fig. 4.

Box plots of mean wrist angles and range of motion across participants for each tool configuration and task trial. Negative wrist angles indicate extension and positive flexion. Pairwise post-hoc comparisons are indicated with symbols above each box plot. Different symbols indicate a significant difference between tool configurations.

Fig. 5. Observed handle holding strategies: a) Expected grasp for handles, b) Sideways turn of the instrument handles, and c) Rotation of instrument handles upside down.

§ Indicates trends across tools detected by Fisher's LSD test ($\alpha=0.05$)

Fig. 6.
Self-reported workload as quantified by the a) physical, b) temporal, c) performance, and d) effort subscales of the NASA-TLX. Statistical differences are indicated with * and trends with §

Fig. 7. Median and interquartile range of overall tool rankings by task, where 1 is best and 4 is worst

Table 1
Descriptive statistics of participants' demographics for each glove size group

	Participants	Men/Women	Handedness (Right/Left/Both)	Experience (years)	Height (cm)	Weight (kg)
7.5 glove size	4	4 / 0	3 / 1 / 0	14±4	178.9±4.9	83.8±8.3
<7.5 glove size	4	0 / 4	3 / 0 / 1	8±5	170.9±4.5	70.3±4.7

Table 2
Mean and standard deviation of performance times, errors, and scores by task and tool configuration, better performance indicated by faster times, fewer errors and higher scores

	Tool Configurations	Time (seconds)		Unrecoverable Errors		Performance Score	
		Mean	±SD	Mean	±SD	Mean	±SD
Peg Floor	A0	114	±21	0.0	±0.0	186	±21
	A30	98	±29	0.1	±0.4	200	±32
	A70	117	±50	0.4	±0.7	181	±54
Peg Ceiling	B	105	±35	0.0	±0.0	195	±35
	A0	222	±54	1.6	±1.4	59	±51
	A30	205	±62	1.1	±1.6	90	±83
	A70	208	±122	1.6	±1.7	90	±79
	B	221	±88	0.9	±1.7	79	±69
Circle Cut Ceiling	A0	183	±67	6.1	±4.7	72	±55
	A30	209	±89	5.6	±4.2	45	±53
	A70	233	±78	6.0	±5.5	27	±70
	B	208	±65	5.8	±6.3	63	±68