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SURGICAL ENDOSCOPY
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Ergonomic principles of task alignment, visual display, and direction of execution of laparoscopic bowel suturing

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Abstract
Background: Laparoscopic suturing is technically a demanding skill in laparoscopic surgery. Ergonomic experimental studies provide objective information on the important factors and variables that govern optimal endoscopic suturing. Our objective was to determine the optimum physical alignment, visual display, and direction of intracorporeal laparoscopic bowel suturing using infrared motion analysis and telemetric electromyography (EMG) systems.
Methods: Ten surgeons participated in the study; each sutured 50-mm porcine small bowel enterotomies toward and away from the surgeon in the vertical and horizontal bowel plane with either isoplanar (image display corresponds with actual lie of the bowel) or nonisoplanar (bowel displayed horizontally but mounted vertically in the trainer and vice versa) display. The end points were the placement error score, execution time, leakage pressure, motion analysis, and telemetric EMG parameters of the surgeon's dominant upper limb.
Results: Suturing was demonstrably easier in the vertical than in the horizontal plane, resulting in a better task quality (placement error score, $p < 0.0001$; leakage pressure, $p < 0.005$) and shorter execution time ($p < 0.05$). Nonisoplanar display of the surgical anatomy degrades performance in terms of both task efficiency and task quality. On motion analysis, a wider angle of excursion and lower angular velocity were observed during the vertical suturing with isoplaner display. Compared to horizontal suturing, supination at the wrist was significantly greater during vertical than horizontal suturing ($p < 0.05$). Within each category (vertical vs horizontal suturing), the direction of suturing (toward/away from the surgeon) did not influence the extent of pronation/ supination at the wrist. In line with the degraded performance, significantly more muscle work was expended during horizontal suturing. This affected the forearm flexors ($p < 0.05$), arm flexors and extensors ($p < 0.005$ and $p < 0.05$, respectively), and deltoid muscles ($p < 0.005$) and was accompanied by significantly more fatigue in the related muscles. Small bowel enterotomies sutured toward the surgeon in both the vertical and the horizontal planes exhibited less placement error score than when sutured away from the surgeon, with no significant difference in the motion analysis and EMG parameters.
Conclusions: Optimal laparoscopic suturing (better task quality and reduced execution time) is achieved with vertical suturing toward the surgeon with isoplanar monitor display of the operative field. The poorer task performance observed during horizontal suturing is accompanied by more muscle work and fatigue, and it is not improved by monitor display of the enterotomy in the vertical plane.

Key words: Laparoscopic suturing — Planar visual display — Motion analysis — Telemetric electromyography — Ergonomics

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Tissue approximation is a challenging task during laparoscopic surgery. The technique is more akin to a microsurgical rather than open surgical approach. Although there have been improvements in the instrumentation and techniques, laparoscopic intracorporeal suturing remains technically demanding. However, it is essential for operations on the gastrointestinal and biliary tract, and it is likely to play an essential role in the development of laparoscopic vascular surgery. Although laparoscopic stapling devices are in established usage for intracorporeal gastrointestinal and bilioenteric anastomoses, stapling with linear cutting devices necessitates suture closure of the residual enterotomy left by the limbs of the stapler. The ability tosuture intracorporeally also enables the surgeon to deal with complications, such as repair of iatrogenic injuries, that otherwise would require conversion and it provides a fall-back remedy in the event of failure of mechanical stapling devices [7].

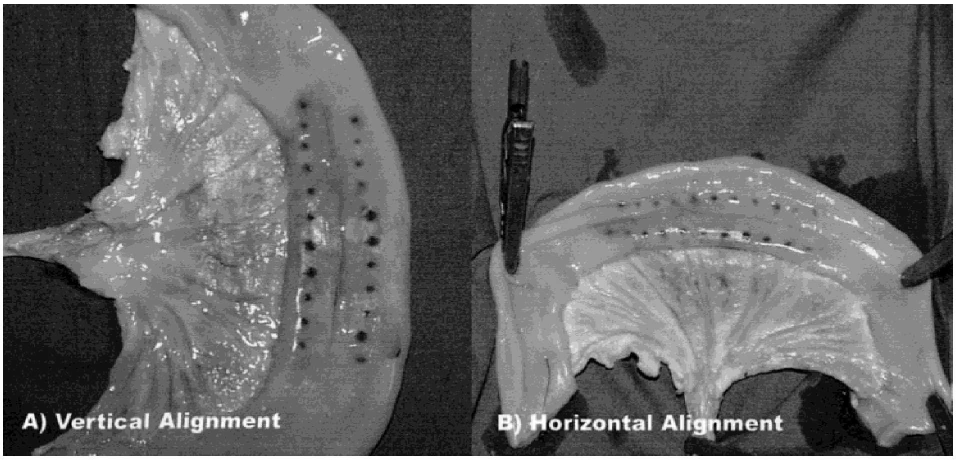

Fig. 1. Task plane within the operative field: (**A**) vertical and (**B**) horizontal.

There are important considerations and principles that govern efficient and safe intracorporeal suturing, the most important of which are the correct setup and visual perception. The setup entails surgeon's position relative to the instruments and intended suture line. Both influence the ease of execution and the quality of the tissue approximation at the suture line. Coaxial alignment of the visual path and triangulation of the camera and operating ports are important in the ergonomic setup, together with port positioning, which not only determines the correct angle of access but also provides a fulcrum for the instruments. This should be about halfway between the tip and the handle, thus translating to a 1:1 ratio of movement between the handle and tip [2]. Execution of the task is also influenced by spatial relationships, reference points, and interpretation of anatomy, and these are dependent on correct visual perception of the displayed image by the surgeon.

The present study was undertaken to determine the influence on performance of intracorporeal suturing of task plane within the operative field (vertical versus horizontal; Fig. 1), direction of task execution (suturing toward and away from the surgeon), and camera orientation to task display (image and task are in the same plane or not). An infrared motion analysis system and telemetric electromyography were used to study the joint movements (angles and angular velocity), muscle work, and fatigue of the dominant upper limb of the surgeon during laparoscopic intracorporeal suturing.

Materials and methods

Ten surgeons with varying degrees of laparoscopic experience participated in the study. Nine surgeons were right-handed and one was left-handed. Each surgeon sutured one enterotomy in each of six experimental setups in a randomized fashion. The enterotomy was 50 mm long and placed on the antimesenteric border of a 100-mm piece of pig's small bowel clamped to a nonreflective surface. The technique for closure of the enterotomy was standardized and consisted of 11 seromuscular continuous stitches using 180-mm thread, 3-0 Polysorb on a 23-mm ski needle (EL-415, USSC, Auto Suture European Services Centre, Elancourt, France). Each surgeon was instructed to drive the needle into the tissue using a finger loop-type needle driver (26173 SK, Karl Storz, Tuttlingen, Germany) in premarked dots placed 5 mm from the edge and from each other, starting with an intracorporeal knot and finishing with a terminal Aberdeen knot.

The setup was standardized by placing the monitor on an adjustable stand so that its center could be placed at eye level for each surgeon at a distance of 1 m. The endoscopic trainer was placed on a table of adjustable height so that when the surgeon held the needle drivers with the shoulder adducted, the elbow formed a right angle. The optical axis, port locations, and intra/extracorporeal instrument length ratio were set up to maximize the optimal ergonomic setup [2–4]. The vision system consisted of a 30° endoscope 10 mm in diameter coupled to a single chip camera (endovision 9050-PB, Karl Storz) and a high-resolution monitor (Model PVM-1443MD, Sony, Tokyo).

Performance assessment

The performance parameters used in the study were the suture placement error score, the execution time, and leakage pressure. The placement error score was measured by the sum of the distances between the far entry and exit points and the dots. The execution time was defined as the interval between the moment when the surgeon grasped the handle of the needle drivers to when the instruments were released on completion of the task. The leakage pressure was measured by using a simple colored-water manometry U-tube system with an inflow tap to one end of the sutured enterotomy. The height at which colored water started to leak from any part of the suture line was defined as the leakage pressure.

Motion analysis

A video-based motion analysis system was used to record the shoulder and elbow angles and supination and pronation of the forearm of the test subjects during the experimental task. The system (Kinemetrix Model 5.0-3D/3MBM, MIE Medical Research, Leeds, UK) consists of three infrared-sensitive video cameras and associated computers, calibration frame, software, and displays. Each camera lens is surrounded by forward-pointing infrared light-emitting diodes (Fig. 2). These illuminate retroreflecting markers (placed on specific sites on the test subjects) that appear with very high contrast in the video image. Each video frame is analyzed through software to find the three-dimensional coordinates of the center of the markers. Further software analysis provides the angles formed by marker triplets and derived values such as velocity and angular velocity.

The motion analysis parameters were the angles and the angular velocities obtained for the elbow and shoulder joints and forearm supination/pronation movements. To achieve this, five markers (10 mm in diameter) were fixed onto the skin of the subjects by double-sided adhesive tape. The sites of the markers were the middle of the clavicle, the tip of the coracoid process, the lateral epicondyle, the styloid process of the radius, and the head of the ulna. The shoulder angle was defined as the inner angle between the line joining the clavicle and coracoid markers and the line joining the coracoid and epicondyle markers. The elbow angle was defined as the inner angle between the line joining the coracoid and epicondyle markers and the line joining the epicondyle and styloid markers. The pronation/supination angle was obtained from the angle between the plane defined by the lateral epicondyle, the styloid process of the radius, and the head of the ulna markers in relation to a reference position, which is the zero or starting position at the midprone plane. Angular velocity at the

Fig. 2. One of the video cameras of the motion analysis system surrounded by infrared light-emitting diodes.

shoulder and elbow joints and supination/pronation angles were calculated from the recorded data. A data analysis program (Matlab, Math Work, Natick, MA, USA) was used to apply a low-pass filter and calculate the medians of the angles and angular velocities.

Electromyographic radio telemetry system

The MT8 radio telemetry system is a wireless precalibrated electromyography (EMG) system (MIE Medical Research). It incorporates Myo-Dat software, which collects up to eight channels of data. The data can be analyzed to provide integrated EMG, frequency spectrum, activity spectra, and other parameters that were not used in the study.

Integrated EMG is the summation of EMG signals from a specific muscle or a group of muscles during the time of the test. The EMG is integrated on 0.6 low-pass filter. Because during fatiguing contractions of muscles a shift of the frequency spectrum toward lower values occurs, such changes can be used to indicate the occurrence of muscular fatigue [6]. Delta m spectrum analysis is the MIE term for analyzing a series of blocks of EMG data using the median frequency of the power density spectrum of the EMG signal. By plotting the median frequency and applying a linear regression line (which represents the average fatigue over the time of the test), the degree of fatigue that the muscle is experiencing is indicated by the slope of the line. A negative slope indicates fatigue. The value of fatigue is therefore expressed by the angle of the slope (theta,°). A positive slope indicates that the muscle is recruiting more fibers to work and the angle is allotted a positive value.

The EMG parameters used in the study were the integrated EMG to indicate the total muscle work during the test time and Delta m spectrum as an index of muscle fatigue. The signals generated by the forearm flexors and extensors, the arm flexors and extensors, and the deltoid muscle were recorded. Three self-adhesive surface circular electrodes (3M Red Dot, 2239, Postfach, Germany), each of 60 mm diameter, were placed over each group of muscles. In each group a large surface area was covered to capture electrical signals from many muscles in each compartment with approximately similar functions. Another software was used to combine the Myo-Dat data with data from the Kinemetrix system so that motion analysis and EMG data could be recorded and analyzed simultaneously.

Statistical analysis

Because the data were of skewed distribution, nonparametric tests (Mann–Whitney *U* and Kruskal–Wallis tests) were used as appropriate, with significance value set at $p < 0.05$.

Results

Task quality and efficiency with vertical vs horizontal suturing and the effect of isoplanar and nonisoplanar display of the anatomy

The data on placement error scores, execution times, and leakage pressures (Table 1) demonstrate that suturing is easier in the vertical than in the horizontal plane and, hence, results in a better task quality (placement error score, $p < 0.0001$; leakage pressure, $p < 0.005$) and shorter execution time ($p < 0.05$). In addition, the data provide evidence that nonisoplanar display (NIPD) of the surgical anatomy (vertical anatomy displayed as horizontal and vice versa) degrades performance in terms of both task efficiency (execution time) and task quality (placement error scores and leakage pressure). With isoplanar display (IPD), which gives the best performance, better suture placement was observed during suturing toward the surgeon, but this was not accompanied by differences in the execution time or leakage pressure of the closed enterotomies.

Motion analysis

With respect to the motion analysis in the shoulder and elbow joints during vertical versus horizontal suturing (Table 2), significant differences were only found in the elbow joint with IPD. The wider angle of excursion and lower angular velocity during vertical suturing are indicative of smoother joint movements. There was no difference between suturing toward and away from the surgeon in the vertical alignment. The shoulder and elbow angles adopted by the surgeons during horizontal suturing were narrower (exaggerated adduction and flexion, respectively) with higher angular velocity than suturing in the vertical alignment toward and away from the surgeon ($p < 0.05$). NIPD was associated with higher shoulder angular velocity ($p < 0.05$) and narrower angle and higher angular velocity at the elbow ($p < 0.0001$).

The pronation/supination data are shown in Table 3. Supination at the wrist was significantly greater during vertical than horizontal suturing ($p < 0.05$). Within each category (vertical vs horizontal suturing), the direction of suturing (toward/away from the surgeon) did not influence the extent of pronation/supination at the wrist. During horizontal suturing, NIPD led to more pronation when suturing was performed away from the surgeon.

Muscle work and fatigue

There was no difference in the parameters of muscle work and fatigue between the two directions of suturing (toward vs away from the surgeon) during vertical and horizontal suturing, with the exception of more integrated muscle work of the arm extensors with vertical suturing away from vs toward the surgeon ($p < 0.05$). In line with the degraded performance observed with horizontal compared to vertical suturing, significantly more muscle recruitment (work) was expended during horizontal suturing (Table 4). This affected the forearm flexors ($p < 0.05$), arm flexors and extensors ($p < 0.005$ and $p < 0.05$, respectively), and deltoid muscles ($p < 0.005$) and was accompanied by significantly

Table 1. Placement error score, execution time and leakage pressure (median, interquartile range)

	Enterotomy mounted vertically				Enterotomy mounted horizontally			
	IPD toward	IPD away	NIPD	p^a	IPD toward	IPD away	NIPD	p^a
Placement error score (mm)[a]	7.9 (4.3)[b]	9.4 (5.3)	11 (6.3)	<0.005	14 (4)	16.5 (4.1)	17.9 (9.8)	<0.05
Time (min)	26 (3.7)[c]	26 (2.5)	27.5 (4.3)	0.05	28 (5)	29 (4)	31 (4.3)	<0.0001
Leaking pressure (mm Hg)	23.8 (8.2)[d]	23.8 (9.5)	17 (13)	<0.005	17 (8.5)	16.5 (12.3)	9 (7.3)	<0.005

[a] Kruskal–Wallis test
[b] $p < 0.0001$ vertical IPD versus horizontal IPD toward surgeon (Mann–Whitney *U* test)
[c] $p < 0.005$ vertical IPD versus horizontal IPD toward surgeon (Mann–Whitney *U* test)
[d] $p < 0.05$ vertical IPD versus horizontal IPD toward surgeon (Mann–Whitney *U* test)
IPD, isoplanar display (the enterotomy is displayed in the position in which it is mounted inside the trainer); NIPD, nonisoplanar display [the image displays (by rotation of camera) a false orientation of the enterotomy, i.e., a vertically mounted enterotomy is displayed as horizontal and vice versa]

Table 2. Motion analysis parameters of shoulder and elbow joints during suturing (median, interquartile range)

	Enterotomy mounted vertically				Enterotomy mounted horizontally			
	IPD toward	IPD away	NIPD	p^a	IPD toward	IPD away	NIPD	p^a
Shoulder								
Angle(°)	113.3 (92.5)	113.3 (58.2)	113.8 (48.9)	NS	89.5 (48.7)	89.3 (40.5)	89.8 (33.5)	NS
Angular velocity(°/sec)	10.2 (9.3)	11 (2.8)	11 (2.8)	NS	12.5 (8.4)	12.4 (7.9)	14.3 (6.8)	NS
Elbow								
Angle(°)	80.6 (29.7)[b]	79.8 (31)	68.8 (22.2)	NS	63.5 (22.5)	59.4 (23.4)	60.3 (28.1)	NS
Angular velocity(°/sec)	11.1 (11)[c]	10.1 (10.6)	11.3 (5.7)	NS	15.2 (12.3)	16.1 (11.1)	16 (10.3)	NS

[a] Kruskal–Wallis test
[b] $p \leq 0.05$ vertical IPD vs transverse IPD toward (Mann–Whitney *U* test)
[c] $p \leq 0.0001$ vertical vs transverse IPD toward (Mann–Whitney *U* test)
IPD, isoplanar display (the enterotomy is displayed in the position in which it is mounted inside the trainer); NIPD, nonisoplanar display [the image displays (by rotation of the camera) a false orientation of the enterotomy, i.e., a vertically mounted enterotomy displayed as horizontal and vice versa); NS, not significant

Table 3. Motion analysis at wrist joint, pronation, and supination (median, interquartile range)

	Enterotomy mounted vertically				Enterotomy mounted horizontally			
	IPD toward	IPD away	NIPD	p^a	IPD toward	IPD away	NIPD	p^a
Pronation(°)	57.5 (28.2)	59.9 (22.1)	61.5 (17.5)	NS	47.1 (30.3)	47.1 (31.1)	60.7 (20)	NS
Supination(°)	61.5 (29.6)[b]	59.1 (27.8)	59.1 (30.1)	NS	48.5 (28.9)	46.5 (24.7)	49.9 (20.8)	NS

[a] Kruskal–Wallis test
[b] $p < 0.005$ vertical versus horizontal IPD toward surgeon (Mann–Whitney *U* test)
IPD, isoplanar display (the enterotomy is displayed in the position in which it is mounted inside the trainer); NIPD, nonisoplanar display [the image displays (by rotation of the 30° telescope) a false orientation of the enterotomy, i.e., a vertically mounted enterotomy displayed as horizontal and vice versa]; NS, not significant

less fatigue in the related muscles during vertical suturing (Table 5). No differences were observed between IPD and NIPD, except that these was more integrated muscle work of the arm extensors with NIPD during vertical suturing ($p < 0.05$).

Discussion

The main finding of this investigation is that intracorporeal laparoscopic suturing is easier to perform in the vertical than in the horizontal plane. This is reflected by shorter execution time, better task quality, less muscle recruitment, and thus muscle fatigue in the dominant limb. Altering the display so that a horizontal suturing task is seen by the surgeon in the vertical plane (by appropriate rotation of the camera) does not improve the task performance; in fact, it appears to degrade it.

There are good ergonomic reasons why vertical suturing is easier than horizontal suturing. In the first instance, the active needle driver is more in line with the longitudinal axis of the forearm and the hand, and this avoids forced flexion at the wrist joint, which is known to degrade the grip strength by 15% [1]. In addition, reduced forced flexion minimizes the radial/ulnar deviation needed at the wrist [1] and thus contributes to the precision of movements at the hand and hence to the accuracy of suture placement. As a result, a better and quicker suture closure is achieved. In contrast, horizontal suturing necessitates exaggerated adduction at the shoulder joint and an awkward stance leading to increased fatigue at the deltoid muscle during suturing along this plane. Also, it disturbs the coaxial alignment of the hand–instrument–tissue and the manipulation angle of the instruments. During horizontal suturing, the needle cannot be inserted into the tissue at the ideal penetration angle

Table 4. Integrated EMG (μV) of different muscle groups for different enterotomy alignments (median, interquartile range)

	Enterotomy mounted vertically				Enterotomy mounted horizontally			
	IPD toward	IPD away	NIPD	p^a	IPD toward	IPD away	NIPD	p^a
Forearm								
Flexors	2.5 (2.1)[b]	3.7 (3.3)	4 (5.1)	NS	4.1 (9.6)	5.5 (9.6)	10.9 (8.5)	0.035
Extensors	2.6 (1.6)	2.7 (8.6)	3.6 (8.7)	NS	2.8 (10.5)	4.5 (10.5)	9 (12.9)	NS
Arm								
Flexors	6.5 (8.6)[c]	6.5 (10.8)	7.9 (10.1)	NS	15 (5.7)	15.6 (6)	15 (4.3)	NS
Extensors	3.5 (8)	11.5 (12.6)	14.5 (13.1)	0.003	6.5 (12.6)	7.5 (11.7)	16 (7)	NS
Deltoid	14 (14.8)[c]	15.6 (15.3)	16.1 (13)	NS	24.2 (27.4)	24.2 (24)	26.5 (30.2)	NS

[a] Kuskal–Wallis test
[b] $p < 0.05$ vertical vs horizontal IPD toward (Mann–Whitney *U* test)
[c] $p < 0.005$ vertical vs horizontal IPD toward (Mann–Whitney *U* test)
IPD, isoplanar display (the enterotomy is displayed in the position in which it is mounted inside the trainer); NIPD, nonisoplanar display [the image displays (by rotation of the camera) a false orientation of the enterotomy, i.e., a vertically mounted enterotomy displayed as horizontal and vice versa]; NS, not significant

Table 5. Delta m spectrum (theta,°) indicative of fatigue of different muscle groups (median, interquartile range)

	Enterotomy mounted vertically				Enterotomy mounted horizontally			
	IPD				IPD			
	Toward	Away	NIPD	p^a	Toward	Away	NIPD	p^A
Forearm								
Flexors	16.5 (12)	16.5 (16.3)	14 (50.3)	NS	4.8 (105.6)	−1.2 (84.1)	−46.3 (65.3)	NS
Extensors	7.2 (43.9)[b]	7.2 (48.5)	5.9 (60.4)	NS	1.3 (41.5)	−16 (38.8)	−16 (44.8)	NS
Arm								
Flexors	18.6 (41)[b]	18.6 (51.9)	16.3 (49.1)	NS	−13.5 (31.9)	−13.6 (35)	−14.5 (37.3)	NS
Extensors	24.5 (67)[c]	16.5 (90.2)	−18.5 (80)	NS	−25.1 (72.9)	−26.1 (57.6)	−26.1 (64.4)	NS
Deltoid	16.1 (59.3)[b]	13.3 (58.3)	−20 (55.8)[d]	NS	−35.3 (30.6)	−35.3 (30.2)	−35.1 (20.6)	NS

[a] Kruskal–Wallis test
[b] $p < 0.005$ vertical vs horizontal IPD toward surgeon (Mann–Whitney *U* test)
[c] $p < 0.05$ vertical vs horizontal IPD toward surgeon (Mann–Whitney *U* test)
[d] $p < 0.005$ NIPD vs vertical toward the surgeon
IPD, isoplanar display (the enterotomy is displayed in the position in which it is mounted inside the trainer); NIP, nonisoplanar display [the image displays (by rotation of the camera) a false orientation of the enterotomy, i.e., a vertically mounted enterotomy displayed as horizontal and vice versa]; NS, not significant

(80°–100°) and a needle-holding angle of >90° cannot be achieved, both of which are acknowledged to be important in accurate suturing [5].

There are both ergonomic and possible perceptual reasons why changing the visual display by rotation of the camera so that a horizontal enterotomy appears vertical (and vice versa) does not materially improve performance. In the first instance, there are no major differences in the muscle recruitment and joint movements. In addition, the surgeon is aware of the real lie of the anatomy and, hence, NIPD is less intuitive and may require more perceptual cerebral processing. Evidence for this was obtained in our study by the increased fatigue in the arm extensors and deltoid muscles.

Although suturing toward the surgeon gives more visual clues of the suture line than suturing away from the surgeon, the differences in the task quality observed in this study were restricted to a lower suture placement error score when the suturing was conducted toward the surgeon. The two directions of suturing were not accompanied by any significant differences in the motion analysis of the joints of the dominant upper limb during either vertical or horizontal suturing. We do no have an explanation for this observation, although the technology used in this study is restricted to motion analysis and telemetric EMG in the dominant limb and thus coordination between the dominant and assisting limbs cannot be investigated. We acknowledge that this is a limitation of this experimental approach.

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