The mechanical master–slave manipulator: an instrument improving the performance in standardized tasks for endoscopic surgery

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Abstract

Background: This study aimed to evaluate the feasibility and efficacy of a mechanical minimally invasive manipulator for endoscopic surgery. In contrast to currently available motorized master–slave manipulators, this mechanical manipulator consists of two purely mechanical, hand-controlled endoscopic arms with joints that allow seven degrees of freedom (DOF).

Methods: For the study, 30 medical students performed four different tasks in a pelvic trainer box using either two conventional endoscopic needleholders or a set of mechanical manipulators. The exercise consisted of four different tasks: repositioning of coins, rope passing, passing of a suture through rings, and tying of a surgical knot. All experiments were recorded on videotape (S-VHS), and the data were analyzed afterwards by an independent observer using a quantitative time-action analysis.

Results: A significant difference in the number of total actions (including failures) favoring the mechanical manipulator group was shown in most exercises. A significant difference in failures per task was shown in favor of the mechanical manipulator group as well. There was no significant difference shown in the total time per exercise.

Conclusions: The tasks clearly demonstrated the efficacy of the mechanical manipulator, although some technical flaws emerged during the experiments. Considering the fact that a first prototype of the mechanical manipulator was tested, modifications are to be expected in a next model. These experiments show the potential of the mechanical manipulator, and it is expected to be a competitive and economical instrument for endoscopic surgery in the near future.

Key words: Master–slave surgery — Surgical skills — Mechanical manipulator — Minimally invasive manipulator

The purpose of endoscopic surgery is to reduce surgical trauma to patients, resulting in less operative morbidity, faster recovery, and reduction in costs [1, 17]. The design of endoscopic instruments, based initially on conventional surgical tools, are long with only four degrees of freedom (DOF) in positioning (Fig. 3). These straight instruments have to pivot about a point of incision through the abdominal wall, which introduces a mirroring and a variable scaling of the hand movements controlling the tip of the instrument. The surgeon must compensate for this scaling and fulcrum effect [5].

With conventional endoscopic instruments and their limited number of DOF for positioning, it is impossible to approach the tissue from different directions (Fig. 1), and almost impossible to perform delicate and complex surgical actions. The handles of these long instruments force the surgeon to use his hands in an unsupported and unnatural posture with a large distance between both hands. The ergonomic quality of laparoscopic instruments is relatively poor [3, 20]. Due to the length and the orientation of these instruments, the surgeon often must operate in an uncomfortable posture with extreme wrist positions.

Furthermore, vision in laparoscopic surgery is two-dimensional. The image of an endoscopic camera is projected on a monitor. Largely because of these characteristics, the learning curves for minimally invasive surgery are long and steep [11, 19]. Especially for complex procedures, the applicability of minimally invasive surgery has not yet been widely embraced.

Recently introduced robotic surgical systems have facilitated complex endoscopic surgery, such as micro-

Fig. 1. Schematic master-slave system. The instrument tip and the surgeon's handle has six degrees of freedom in positioning. With a kinematic coupling between the handle and the tip, the instrument tip moves exactly in the same direction as the handle. This kinematic link can be implemented electronically (using sensors, actuators, and the like), as with robotic devices, or mechanically (using push bars, pulleys, and the like), as with a mechanical manipulator (picture by Mark Wentink).

anastomoses in coronary artery bypass grafting [10, 12] and aortic anastomosis [14, 22]. These systems are designed to translate the surgeon's hand movements to the tip of the endoscopic instrument in a remote operative field using a computer-assisted master-slave system (Fig. 2). The advantages of these systems are three-dimensional visualization and inclusion of a "wrist" at the end of the instruments, providing articulated motion in seven DOF: three translations, three rotations, and the opening/closing action [7]. The wrist movements of the surgeon's hands are translated to the movements of the instrument tip, maintaining the same spatial relation.

Although it seems that these robotic surgical systems have their advantages, and although various series are reported in which these systems have been successfully applied for clinical purposes [6, 18], their disadvantages are not to be taken lightly. These systems are large, bulky, and expensive. Another limitation of these systems is the lack of force feedback [2, 4, 15]. The feedback from the operation field consists merely of visual information. Lowering the costs and making the system more manageable are mandatory if these systems are to become a standard tool for endoscopic surgery.

In an attempt to overcome some of the aforementioned limitations of robotic systems, a mechanical master-slave manipulator for minimally invasive surgery was developed. The mechanical manipulator is a relatively small, economical, and mechanical alternative for robotic surgical systems with the additional value of force feedback. It consists of a balanced parallelogram

mechanism with a deflectable endoscopic instrument attached at one end and a surgeon's handle at the other end. Instead of an electrical link, the instrument and handle are connected by a mechanical link such that movement directions of the handle correspond to identical movement directions of the instrument tip in seven DOF. In addition, with a set of these devices, the two handles have the same spatial orientation in relation to each other as the instrument tips. As compared with conventional endoscopic instruments, the mechanical manipulator improves the ergonomics for the surgeon, enabling a positioning of his or her hands in a natural orientation to each other, providing improved eye-hand coordination, intuitive manipulation, and an ergonomic posture (Figs. 2 and 3).

The first phantom experience indicated that the system functions properly, and that suturing is feasible [9]. We hypothesised that working with the mechanical manipulator would be more intuitive, and that the extra DOF would offer advantages over conventional endoscopic instruments. To test these hypotheses, we defined simple and reproducible manipulation experiments in which these extra functionalities would play a role. These experiments were used subsequently to compare manipulation between working with conventional endoscopic instruments and working with the mechanical manipulator.

Methods and materials

For this study, 30 medical students, all with no surgical experience, performed four different experiments in a trainer box. Defined actions and failures per experiment are presented in Table 1. The participants were randomized to perform the experiments with either two conventional endoscopic needleholders (Karl Storz, Tuttlingen, Germany) or a set of mechanical manipulators.

To exclude bias, both setups were identical. The trainer boxes were identical, and all experiments were performed with the instruments positioned in the same orientation to the target area for both groups. The endoscope, positioned in a holder (PASSIST) [8] between the instruments and parallel to the surgeon's natural line of sight [21], was not controlled during the experiments. A 10-mm 0° stereoscopic endoscope and three-dimensional camera (Carl Zeiss Ltd., Oberkochen, Germany) in combination with a Cardio View Head-Up-Display (VISTA Medical Technologies, Inc., Carlsbad, CA, USA) (Fig. 3) was used in all the experiments to provide the subjects with a stereoscopic image, claimed to be beneficial in using instruments with additional DOF [7].

Due to the simple nature of the tasks, the participants were not allowed to rehearse the exercises before the experiments. They were, however, allowed a 1-min period to familiarize themselves with the setup [7, 13, 16].

Experiment 1: Coin repositioning

For this simple pick and place experiment, a 1-Eurocent coin had to be taken out of a receptacle with the left-hand instrument and presented to the right-hand instrument. Subsequently, the subject was to put the coin into a second receptacle. This sequence of picking up, passing over, and dropping was repeated two times. The same order of sequences then was repeated, starting with the right-hand instrument. Unintentional or incorrect dropping of a coin was counted as a failure. The number of defined actions was counted, and the total time was recorded from picking up the first coin to dropping the last coin into the last receptacle.

Fig. 2. The mechanical manipulator in the experimental setup. The picture shows two parallelogram mechanisms coupled to the table rail. The inset shows that movement directions of the handle correspond to identical movement directions of the instrument tip in all degrees of freedom.

Table 1. Defined actions and failures

Actions/failures:	Definitions
Coins	
Grasping coin	Grasping a coin
Lifting coin	Elevating coin from receptacle
Transferring coin	Moving coin toward next receptacle
Handing over coin	Handing coin over from one instrument to the other
Dropping coin	Dropping coin correctly into receptacle
Unintentionally dropping coin	Unintentional dropping coin during exercise
Incorrectly dropping coin	Dropping coin outside the receptacle or into the wrong receptacle
Rope	
Grasping rope	Grasping the rope at the correct place
Dropping rope	Dropping rope
Misgrasping rope (out of place)	Grasping rope, but at the wrong place
Misgrasping rope (no rope)	Grasping without touching rope
Rings	
Grasping needle	Each grasping of the needle or suture during exercise
Passing ring	Passing a ring
Dropping needle	Dropping the needle during exercise
Floating needle	Dropping needle while passing ring; needle does not fall, but hangs in the ring
Misgrasping	Grasping without touching the needle
Wrong direction	Passing a ring in wrong direction
Missing ring	Moving toward ring without passing it
Half passing	Passing the ring halfway and subsequently taking the needle back from the ring
Knot	
Making loop	Making a loop with the suture
Grasping suture	Grasping the suture
Pulling through	Pulling the suture through the loop
Mislooping	Making a loop without success
Misgrasping	Grasping without touching the suture
Mispulling	Pulling the suture without passing the loop

Experiment 2: Rope passing

In this experiment, the two instruments had to work together during the manipulation. The subject had to grasp a marked rope (25×0.3 cm) alternately with the left and the right instruments at indicated points while keeping the rope above the floor of the training box. The rope was fastened at both ends and had 11 predetermined, marked grasping points. The subject had to pass the rope through twice, once grasping the rope with both instruments on the same (left) side and once grasping the rope on both sides, on the right side with the right instrument and on the opposite (left) side with the left instrument. Grasping without touching the rope, grasping the printed lines between the marked areas, or dropping the rope was counted as a failure. Time from picking up the rope to total run-through was recorded, and the number of defined actions was counted (Fig. 4).

Experiment 3: Passing a suture through rings

The purpose of this task was to pass a surgical needle with a piece of suture (Prolene 4-0) through eight rings following a preindicated direction. Failures were determined as dropping the needle, "floating" the needle in a ring without grasping it, grasping without touching the needle, not following the indicated direction, missing the ring with the needlepoint, and passing the ring only halfway. The total number of actions and the time from first grasping the needle to totally passing the last ring was recorded (Fig. 5).

Experiment 4: Tying a surgical knot

A suture (Vicryl 3-0) was used to tie a surgical knot consisting of one knot using two forward loops followed by one knot using a backward

Fig. 3. Conventional endoscopic instruments (left) have four degrees of freedom (DOF): two rotations around the incision in the skin (DOF 1 and 2), the rotation of the instrument around its axis (DOF 3), and the in-out translation of the instrument (DOF 4). By adding two extra DOF (right) (DOF 5 and 6), the orientation of the instrument tip can be varied independently from the instrument shaft, enabling the surgeon to approach the tissue from different directions. The opening and closing of the instrument is the seventh DOF (picture by Mark Wentink).

loop. The scored failures were “mislooping” the suture, grasping without touching the suture, and pulling the suture without passing the loop. The total number of actions and the total time needed to complete the task were recorded.

Statistical analysis

All the experiments were recorded on videotape (S-VHS), and the data were analysed afterward by an independent observer using a quantitative time-action analysis to determine the efficacy, counting the actions and the time needed per task. Failures were counted as a measure for efficiency. A quantitative time-action analysis was performed, through which a measure of efficiency in time and actions was determined. Table 1 shows the definitions for actions and failures per experiment.

Statistical analysis was performed using SPSS 12.0.1 for Windows. A Mann Whitney *U* test was used to compare differences between the two methods. The data show medians of time and actions with the corresponding range. A *p* value less than 0.05 was considered statistically significant.

Results

All the participants successfully completed the experiments, although six participants in the mechanical manipulator group had problems with the knot-tying experiment (see Discussion section).

Tables 2 and 3 show the results of the time-action analysis. Table 2 shows the median time and range needed per experiment for completion of the task. There was no statistically significant difference shown in the time needed to complete each exercise. In Table 3, median actions and the range needed per experiment are shown per action, as well as the median failures and

Fig. 4. Experiment 2: Band-passing, manipulating a marked band with two instrument by grasping it at the same side (minimally invasive manipulator experiment).

Fig. 5. Experiment 3: Passing a suture through rings, following a predefined path (laparoscopic experiment).

range per experiment. Table 3 and Fig. 6 show the median total of actions (including failures) and the range needed per experiment.

There were significantly fewer actions recorded in the mechanical manipulator group for all exercises except the knot-tying experiment. Subanalysis of the different exercises showed that grasping actions were significantly fewer in the mechanical manipulator group for the coin exercise (experiment 1: median, 7 [range, 6–13] vs median, 10 [range, 6–18]; *p* = 0.01) and the rings exercise (experiment 3: median, 30 [range, 25–45] vs median, 38 [range, 22–99]; *p* = 0.03). Failures were shown to be

Table 2. Time (seconds) per exercise necessary to complete exercise (median)

	Laparoscopy (<i>n</i> = 15)		Mechanical manipulator (<i>n</i> = 15)		<i>p</i> Value
	Time	Range	Time	Range	
Coins	301	126–622	339	151–600	NS
Rope	393	183–890	349	144–581	NS
Rings	704	407–1,320	814	506–1,529	NS
Knot	211	68–804	237 (<i>n</i> = 9)	128–1,395	NS

NS, not significant

Table 3. Number of actions necessary to complete exercise (median)

	Laparoscopy (<i>n</i> = 15)		Mechanical manipulator (<i>n</i> = 15)		<i>p</i> Value
	Actions (<i>n</i>)	Range	Actions (<i>n</i>)	Range	
Coins					
Grasping coin	10	6–18	7	6–13	0.01
Lifting coin	9	6–16	6	6–13	0.01
Transferring coin	8	6–16	6	6–13	0.03
Handing over coin	9	6–18	6	6–14	0.04
Dropping coin	6	6–6	6	6–6	NS
Failures	5	1–12	1	0–8	< 0.001
Total (including failures)	48	32–86	32	30–67	< 0.001
Rope					
Grasping rope	22	20–36	21	21–23	NS
Failures	10	3–29	1	0–8	< 0.001
Total (including failures)	35	24–64	23	21–31	< 0.001
Rings					
Grasping needle	38	22–99	30	25–45	0.03
Passing ring	8	8–8	8	8–8	NS
Failures	21	10–101	16	5–31	NS (0.068)
Total (including failures)	67	44–208	55	40–82	0.02
Knot			(<i>n</i> = 9)		
Making loop	6	3–10	6	3–21	NS
Grasping suture	2	2–6	2	1–15	NS
Pulling through	2	2–2	2	0–3	NS
Failures	6	0–20	3	0–35	NS
Total (including failures)	15	7–35	10	6–73	NS

NS, not significant

Fig. 6. Total number of (median) actions per exercise plus range.

significantly fewer in the mechanical manipulator group for the coin exercise (experiment 1: median, 1 [range, 0–8] vs median, 5 [range, 1–12]; $p < 0.001$) and rope

exercise (experiment 2: median, 1 [range, 0–8] vs median, 10 [range, 3–29]; $p < 0.001$). In the rings and the knot experiments, no significant difference in failures was shown, although a trend in the rings experiment was shown in favor of the mechanical manipulator group (median, 16 [range, 5–31] vs median, 21 [range, 10–101]; $p = 0.068$).

Discussion

The experiments were designed as simple tasks that could be executed in both groups, mainly due to the level of our participants' inexperience. They had to carry out the experiments with no surgical/endoscopic experience whatsoever to prevent a bias in the learning curve attributable to experience in either laparoscopy or robotic surgery. The experiments, however, were representative and resembled experiments used in the residents program for endoscopic surgery. Furthermore, we selected a larger number of participants than similar studies [7, 13] to exclude bias attributable to eye-hand

Fig. 7. Experiment 4: Knot tying. A complication in this exercise is that with the minimally invasive instruments, the suture is caught in the grasper mechanism.

coordination. The range in time needed to complete the exercise (Table 2) shows that we succeeded in compiling homogeneous groups in this respect.

The set of mechanical manipulators was a first set of prototypes, and therefore was technically not yet perfected. During testing, technical flaws emerged, which will be corrected in a next prototype. It was noted that the handles were not positioned quite favorably, resulting in an additional number of failures, such as dropping of the needle in experiment 3. Furthermore, one of the mechanical manipulators showed excessive friction in one DOF (in-out), which made it harder to manipulate in a small range, as in experiment 3.

In the knot-tying experiment, another flaw of design was noted. Six participants had trouble sliding a loop from one of the instruments. The joints at the tip of the instruments were not protected in the design, making it an easy trap in which a piece of suture could get caught. This happened in 6 of the 30 cases, and it proved to be nearly impossible to get the suture out without damaging it (Fig. 7).

The aforementioned observations were very enlightening, and they most certainly will be considered in building a new set of prototypes.

Even with the described limitations of the mechanical manipulator, it was shown that an additional number of DOF in an endoscopic instrument is favorable. Although there were no time differences in the experiments, there was a significant difference in the number of actions and failures in the first three experiments. In the laparoscopy group, extra regrasping actions were needed to reposition the coin, rope, or needle inside the

grasper tips to be able to fulfil the exercises, leading to extra failures as well. The extra DOF in the mechanical manipulator group facilitated the exercises because the coins, rope, and rings were accessible from different angles. As a result, the participants needed fewer actions and had a smaller number of failures than those in the laparoscopy group.

Considering the modifications to be expected in a next set of mechanical manipulators, it has been shown that the instrument has potential. Along with robotic devices in an experimental or clinical setting, the mechanical manipulator is expected to be a competitive and economical instrument for endoscopic surgery in the near future.

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