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A new remote-controlled endoscope positioning system for endoscopic solo surgery

The FIPS Endoarm

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Abstract. In the field of endoscopic solo surgery, the assistance received by the surgeon from ergonomical positioning devices is extremely important. They aid in both the retracting of instruments and the positioning of the endoscope. However, passive systems derived from open surgery have not proved satisfactory. Therefore, we set out to develop a remote-controlled arm capable of moving a rigid endoscope with about four degrees of freedom, while maintaining an invariant point of constraint motion coincident with the trocar puncture site through the abdominal wall. The system is driven by means of speaker-independent voice control or a finger-ring joystick clipped onto the instrument shaft close to the handle. When the joystick is used, the motion of the endoscope is controlled by the fingertip of the operating surgeon, which is inserted into the small ring of the controller in such a way as to make the motion of the fingertip correspond directly to the motion of the tip of the endoscope. A study was performed to compare the two different interfaces available for the system. With both interfaces, the guiding system allows for transparent and intuitive operation. Its set-up is easy; it is safe and reliable to use during the intervention; and it is faster than human assistance. With its improved ergonomy, this new generation of remote-controlled endoscope positioning system represents a further step toward the diffusion of solo surgery techniques in minimally invasive therapy. In our opinion, this prototype creates a valid compromise between human and robotic control of rigid endoscopes.

Key words: Endoscopic surgery — Instrumentation — Retractors — Robotics — Solo surgery

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In recent years, advances in technology have improved the quality and efficiency of many operative procedures in minimally invasive surgery. Since the advent of endoscopic surgery, the vision of the operating surgeon has depended on the help of an assistant surgeon whose responsibility it was to position the endoscope. To perform this task, the assistant has to keep the surgical point of interest in the center of the video image, thus providing sufficient target magnification and maintaining a stable horizontal image. Experience has shown that the assistant can seldom achieve what the operating surgeon would consider an optimal position. The application of robotic technology to solo surgery has the potential to increase both the precision of action and cost-effectiveness of endoscopic surgery.

Although several prototypes have been introduced, there are currently only two remote-controlled serial systems available on the market: the AESOP system (Computer Motion, Goleta, CA, USA) and the Endoassist (Armstrong Healthcare, UK). In collaboration with the Karlsruhe Research Center (Germany), we have developed a prototype of a new robotic system (Fig. 1), with the aim of improving the system architecture and the human-machine interface.

Materials and methods

Technology

The geometry of an endoscope guiding system for laparoscopic surgery should take account of the principle of the invariant point of motion [3, 5] where the trocar enters the abdominal cavity. The kinematic principle chosen for the FIPS project was similar to that of the passive TISKA Endoarm [6]. It establishes a remote center of motion, assuring that no lateral force is exerted around the trocar puncture site. The principle of maintaining the invariant point of motion through mechanical constraints was defined by Mueglitz et al. [3]. They described a robotic motion principle along virtual axes, intersecting at the point of trocar insertion. This

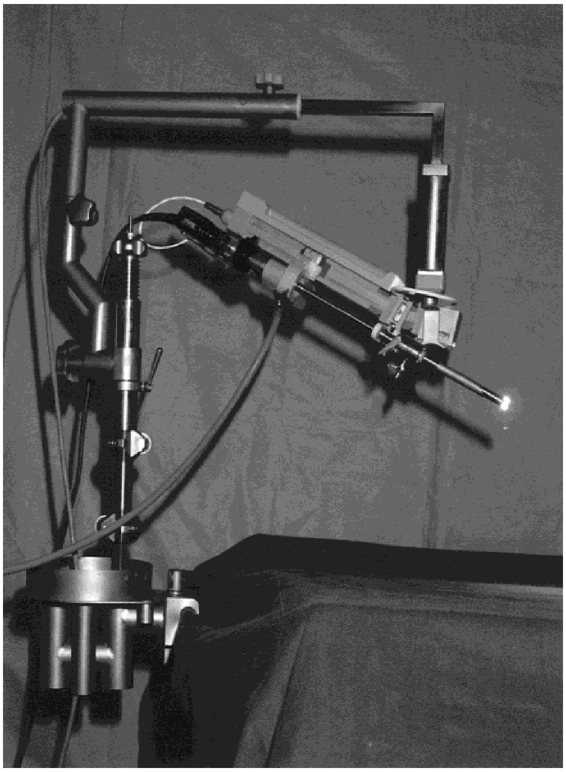


Fig. 1. The FIPS Endoarm, current prototype.

set-up is of particular importance for the control scheme of electrically driven robotic devices.

The FIPS camera guiding system (Fig. 2) is composed of a power supply unit, an operating table attachment, and an endoscope guiding device with two different human-machine interfaces: a finger-ring joystick (Fig. 3) and a voice control facility. The finger-ring joystick can be used as hand-held controller, or it can be clipped onto the handle of the operating instrument used. The tip of the second finger of the operating hand is inserted into the ring; its intuitive movements along the three spatial axes correspond to identical movements of the endoscope. The voice control device (DASA, Germany) can either be used as a speaker-independent system, or it can be programmed by the surgeon to recognize his or her voice.

The kinematic design of the system (Fig. 2) comprises a first axis right through the point of incision. A second axis intersects the first perpendicularly at the point of incision. A small C-arch mechanism connects the two axes. This geometry permits only movements around the arch, whose center coincides with the point of incision. Thus, a remote center of motion is established at the point of intersection of the two axes. When the trocar tube and the inserted endoscope are moved, they are guided precisely through the invariant point of trocar insertion, without any force being exerted on the abdominal wall. Translation and rotation around the longitudinal axis of the instrument are assisted by electric motors, completing the four degrees of freedom necessary to guide the endoscope in the abdominal cavity.

After the device has been attached to the operating table, it can be covered with a sterile plastic sac. A special technique allows the precise definition of the sterile area. The carrier system of the FIPS device is attached to the standard rail by means of a larger rail, which is screwed under the sterile drape covering the operating table. This larger rail is shaped with round edges to prevent tears to the draping tissue and to allow an easy translation of the base along the operating table. The whole arm is covered by a transparent plastic tube, which is fixed to the base of the carrier system. Thus, the boundaries of the sterile field are clearly defined. The entire arm is made of stainless steel and may be gas-sterilized if required.

Experimental evaluation

Evaluation of the prototypes was performed simultaneously with the technical development of the device. The experiments were carried out on phantom models with integrated animal organs; these conditions represent reliable and reproducible experimental conditions. The Tübingen Lap-Trainer (Coburger Lehrmittelanstalt, Coburg, Germany) was equipped with porcine liver segments including the gallbladder to simulate laparoscopic cholecystectomy. Conventional laparoscopic OR equipment (video unit, HF, etc.) and a regular set of instruments were used. The prototype was used to guide the optic in combination with a TISKA Endoarm used as a retracting instrument during the procedure. All devices were positioned on the right side of the operating table, opposite the surgeon.

The experiments involved three surgeons, all skilled in endoscopy. The voice-controlled FIPS Endoarm used in the speaker-independent mode was compared with the joystick controller. A control group working with human assistance was also included. Each surgeon performed 15 experiments randomized among the three groups, for a total of 45 experiments.

At the end of each experiment, intuitiveness of handling, practicality of use under OR conditions, and mechanical stability of the FIPS system were judged subjectively on a scale from 1 to 10. The procedure time was broken down into segments related to different tasks, including: *set-up time,* for draping the phantom and setting up external devices; *positioning time,* for positioning trocars under vision, connecting devices to their instruments, and positioning the optic; *intervention time,* for performing the complete dissection of the gallbladder; *extraction time,* for extracting the gallbladder; *breakdown time,* for removing trocars under vision and placing external devices aside.

Statistical analysis was conducted with the JMP system (SAS Institute, Cary, NC, USA) using ANOVA, the Wilcoxon test, and the Tukey-Kramer test.

Results

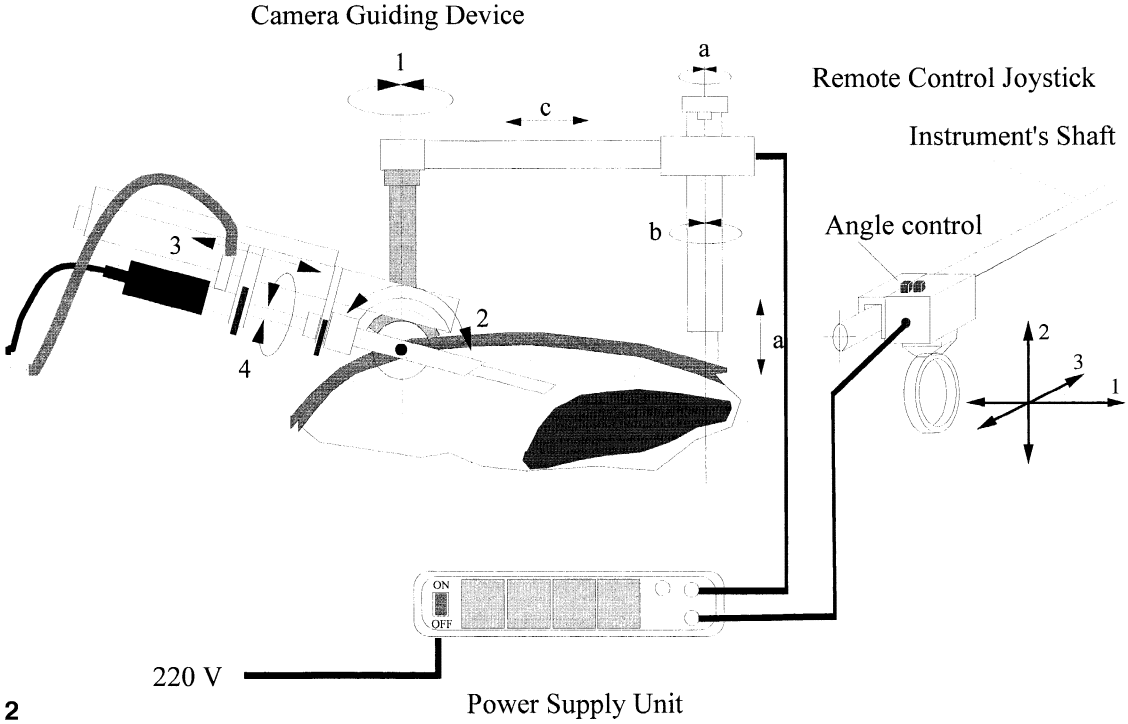
The evaluation of the prototype was carried out on phantom models and confirmed by animal experiments. We found that the overall handling of the system was simple and did not require specific training. The trocar tube can be mounted easily on the guiding device.

The results are shown in Figs. 4–7. All statistical results yielded by tests for interval variables were confirmed by rank tests. Both interfaces were judged to be intuitive, with an advantage for the joystick solution (7.3 vs 6.5, $p < 0.05$). A slight advantage in intervention time was found for the voice-control solution (11:57 vs 13:40, NS). Voice control was limited by the small movement of the endoscope that could be achieved; repetition of a sequence of identical commands was required to cover long distances. This system turns out to be quite cumbersome during the positioning and extraction processes, when long distances need to be covered by the endoscope to follow the insertion of the trocars. In this phase, voice control proved to be slower than the finger-ring joystick (4:28 vs 6:14, $p < 0.0001$; 3:29 vs 4:11, $p < 0.0001$). On the other hand, the interface, although speaker-independent, proved as safe and reliable as other speaker-dependent interfaces previously tested.

The global time registered by the control group was significantly shorter than with the combinations involving the FIPS and TISKA Endoarms ($p < 0.0001$). This was the result of shorter set-up, positioning, extraction, and breakdown times (each $p < 0.0001$). As regards intervention time, the three groups scored comparable times, with no statistically significant difference.

Discussion

Laparoscopic assistance often demands tiring standing positions and monotonous tasks. The use of mechanical positioning systems can be unsatisfactory. The movement of the retractors is often cumbersome and unsafe, since in most



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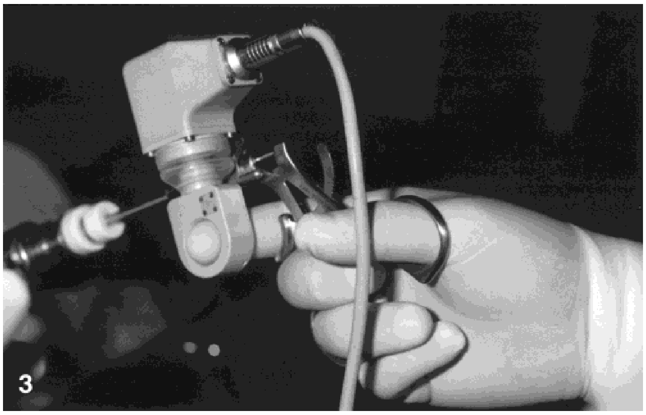

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Fig. 2. Basic design of the FIPS Endoarm.

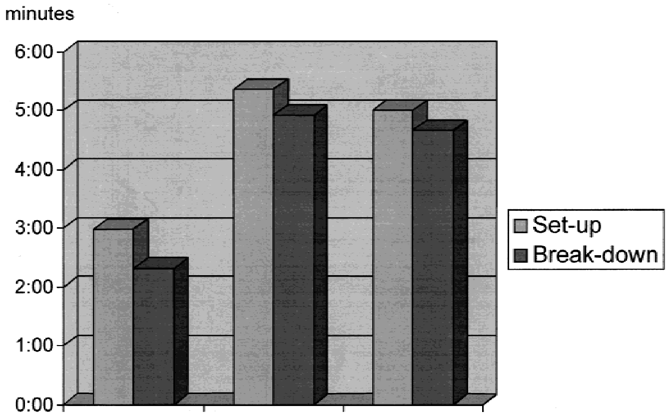
Fig. 3. Finger-ring joystick interface of the FIPS Endoarm.

cases both hands of the surgeon are required for changes in position.

The introduction of robotic technologies seems to be the major step toward the solution of this problem. The use of positioning and holding devices in laparoscopic surgery returns direct control of the whole procedure to the operating surgeons. Solo surgery is meant to allow for an increased precision of action.

Several laparoscopic camera-driving systems have been devised in recent years. Currently, the Endoassist (Armstrong Healthcare) [1] and the AESOP system (Computer Motion) [8] are on the market. The rapid introduction of several different architecture and interface solutions reflects the growing interest in these developments. Since 1994, prototype work has been performed in cooperation with the Research Center in Karlsruhe; it led first to the design of the passive system TISKA Endoarm [6] and later to the remote-controlled FIPS Endoarm presented here. The FIPS Endoarm allows motion in four degrees of freedom, consisting of two spatial axes and translation and rotation about the endoscope longitudinal axis, all of which are electrically driven. The FIPS Endoarm prototype has several basic advantages, which were confirmed during our phantom and animal experiments:

- Negligible force exerted around the trocar puncture site: The system keeps an invariant point of constraint motion.
- Reduction of dangerous interferences with other positioning systems and the surgeon's movements: The system architecture has the shape of an arch, which comes on the operative field from above; this design allows free space around the optic.
- Reduction of space requirement: The arm is attached directly to the trocar, close to the insertion of the instrument into the body; the movement of the optic does not affect the position of the arm.
- Remote control of the rotation of the optic: This is mandatory when angulated optics are used. Without it, the surgeon is forced to rotate the angulated optic by hand; a sudden drop of the light cable would cause involuntary rotation of the optic and consequent dangerous loss of the image of the point of surgical interest.
- Different intuitive interfaces, consisting either of a speaker-independent voice control device or a finger-ring



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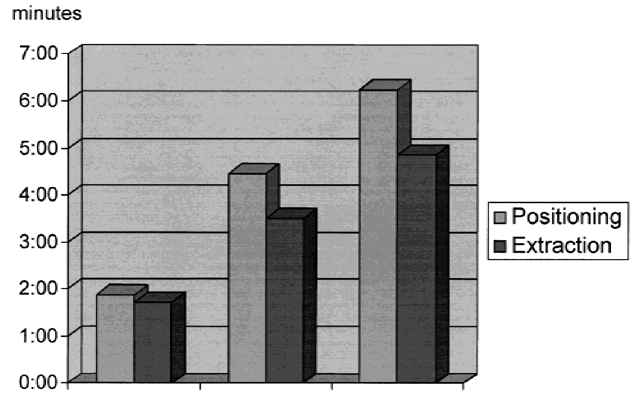

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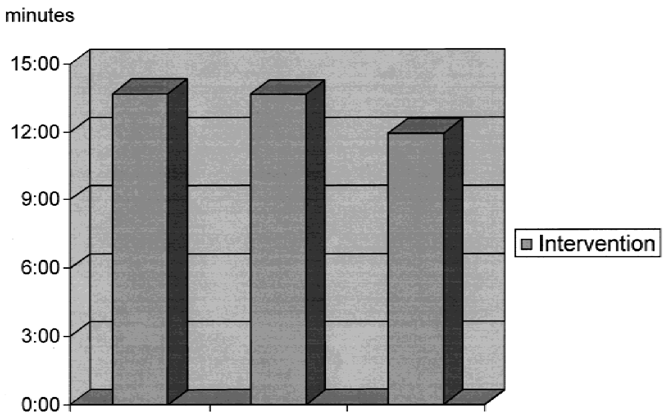

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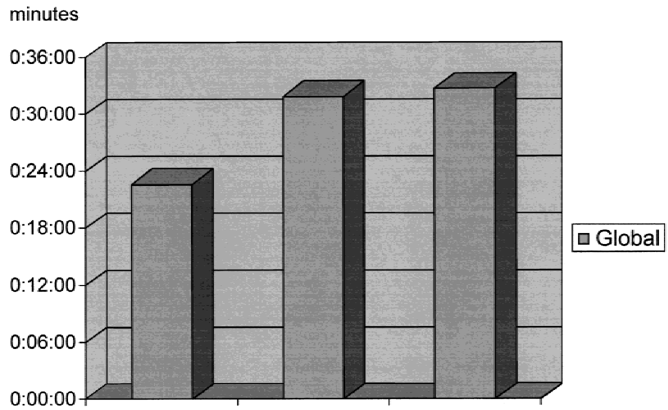

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Fig. 4. Set-up and break-down time requirements with human assistance, FIPS joystick control and FIPS voice control, respectively.

Fig. 5. Positioning and extraction time requirements with human assistance, FIPS joystick control and FIPS voice control, respectively.

Fig. 6. Intervention time requirements with human assistance, FIPS joystick control and FIPS voice control, respectively.

Fig. 7. Global time requirements with human assistance, FIPS joystick control and FIPS voice control, respectively.

joystick clipped close to the handle of the working instrument.

The voice interpreter system developed by DASA proved as reliable as the speaker-dependent systems available today. At the same time, it obviates the need to program the system. A single command generates a motion along the axis of the optic of 10 mm or a motion of 5°. Thus, the surgeon is obliged to repeat the command in sequence to obtain long motions. The joystick controller, on the other hand, is capable of long and combined movements. Although it is still in a prototype version, its ergonomy proved to be sufficient. A safety button placed inside the ring obviates involuntary movements. The speed is set to a reasonably slow rate to avoid abrupt movements and to adapt well to the operator.

Other human-machine interfaces have been designed previously. Hand controls consisting of different buttons for different movements were ergonomically deficient. Foot pedals are more intuitive because they free the hands from the camera guidance task. Because the feet are inherently more clumsy than hands for precise tasks, they have found limited acceptance among surgeons, although there are a number of types of foot-operated switches in use [1, 8]. Voice control systems consisting of a recognition system for synthesized speech have proved to be an extremely useful means of providing information and short instructions to surgeons. On the input side, speech recognition systems are now reliable and fast enough to be useful, but recognition of accuracy and response time are critical to their acceptance, since confusion could result, especially in stressful situations when control is critical [1, 8]. A natural method of indicating the way to an object is simply to point to it. In the act of pointing to the object, the movement is straight rather than being split into different vectors of motion, as is the case with robots, including those guiding the endoscope. This method is not only time-consuming, but often also results in less precision when pointing to the target.

Track visual markers have been suggested as a possible improvement, but according to some authors [7], these devices do not always provide an optimal view in depth. This drawback is due to the difficulty in calculating the depth of the track, which can result in suboptimal magnification of the visual field. Moreover, it is sometimes inconvenient to have to keep the marker always in sight, as it could accidentally be covered by grasped or overlying tissue. Finally, visual track recognition systems require the use of expensive three-dimensional optics.

A different solution proposed for a human-machine interface is the head controller, which consists of a helmet with a light pointer held by the surgeon and a visual detector placed just over the monitor in front of him or her. Thus, the movements of the surgeon's head are picked up by the visual detector and transferred to the robot guiding the optics. Tests with head controllers have shown that compound motion was sometimes confusing to the surgeon. Therefore, the controller was limited to detecting the dominant head gesture and powering only this axis of the manipulator [6].

We believe that the finger-ring joystick solution supplying the FIPS Endoarm is currently the best interface because it does not require any training due to its intuitive construction, and it is supported by a sufficiently safe technology.

As with all other systems, the FIPS Endoarm entails the inconvenience of requiring a considerable amount of time for its set-up and breakdown. More effort needs to be directed toward streamlining this aspect of positioning systems. On the other hand, the longer time required for tasks other than intervention was particularly influenced by the relatively short time required for dissection in phantoms. In real-life clinical situations, the intervention time will account for more than half the procedure; consequently, the longer time needed for other phases will be less influential in the calculation of the overall time required.

In phantom and animal models, the system proved to be safe, compact, user-friendly, and compatible with existing surgical equipment. It does not interfere with the ergonomic work space of the surgeon but, on the contrary, returns to him or her the freedom to determine a personal view, which was lost when laparoscopy replaced the open method.

By replacing the camera assistant, the FIPS system enables solo surgery for standard laparoscopic procedures. The ability to perform solo surgery in community hospitals and private institutions can be expected to alleviate some of the pressure due to limited resources, as well as reducing the need for extra personnel [3]. At the same time, residents in university and teaching hospitals would no longer be asked to perform tiring and boring assistant duties and therefore should be able to pay more attention to the maneuvers performed by the operating surgeon during the operation.

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