

Experimental comparison of kinematics and control interfaces for laparoscope positioners

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Abstract—Ergonomics is known to be poor during laparoscopic surgery because of the minimal access and the manual handling of the laparoscope, which is required to display intra-abdominal images on monitors in the absence of direct vision. Several robots were developed over the last two decades to hold and move the laparoscope, so as to offer better image stability and free the assistant's hands and mind. The purpose of this study is to compare the motion performance of these devices, including the EVOLAP robot designed at UCL, and to assess the influence of two main factors on motion duration: the kinematic architecture and the control capabilities of the human-robot interface (i.e. the number of directions). An experimental bench was set up using a modified version of the EVOLAP robot, capable of generating laparoscope motions identical to the ones induced by the three most common kinematics among existing laparoscope positioners. Results show that the kinematics has a large influence on motion duration. It also appears that performance is increased significantly with a control interface that provides more motion directions than the commercially available ones.

Keywords—medical robotics, laparoscopic surgery, kinematics, human-machine interface

I. INTRODUCTION

SINCE the early nineties, robotic technologies have been proposed by researchers and manufacturers for overcoming ergonomic problems of minimally invasive laparoscopic surgery. Indeed, gestures like suturing or knot tying are more complicated than with the classic open technique, due to the indirect access to tissues in the peritoneal cavity and to the mirroring and scaling effects of the keyhole incisions performed in the abdominal wall. Famous telesurgery robots (e.g. Zeus [1], da Vinci [2], and the recent MiroSurge in development at DLR [3]) were designed to restore some mobility in the abdomen and make hand gestures more intuitive and natural. Besides these large, complex, and pretty expensive systems that will not fit into most operating theaters, smaller robots are dedicated solely to the handling of laparoscope and camera, required to display intra-abdominal images on monitors in the absence of direct vision of organs. These simpler devices allow the surgeon to control the camera displacements via a 'hands-free' interface (e.g. voice recognition, head tracking, miniature joystick). A couple of them reached the market and can be seen working in operating rooms, such as AESOP [4], LapMan [5], EndoAssist [6] and its successor FreeHand [7], and the Lightweight Endoscope Robot marketed as ViKY [8]. Several other prototypes are under development in laboratories, including the VESALIUS [9] robot from KULeuven and the EVOLAP robot [10] designed at UCL. More comprehensive reviews of existing devices can be found in literature (see for example [11]).

A common way to estimate the performance of a laparoscope positioner is to carry out a small clinical study. Most commer-

cially available robots were introduced to the medical community by means of such studies (e.g. [5–8]). Since AESOP was the first available laparoscope positioner, several surgical teams took it as a reference to assess the relative performance of a new robot during comparative clinical trials (e.g. [12]). Most authors report that these devices can actually replace the assistant for holding the camera, thus allowing solo surgery in some cases. Occurrence of peroperative complications do not differ significantly from human-assisted laparoscopy. These systems offer a more stable image, making fine suturing easier. They also reduce the number of lens cleaning actions needed. Furthermore, surgeons feel less fatigue and can concentrate better on their work, since they do not have to guide the assistant. Finally, an assistant who has to hold an instrument spends less energy during surgery and can better focus on his surgical task.

These studies in real conditions are sufficient for a proof of concept. However, they are not very reproducible, since the operation time is affected by many external and uncontrolled factors. A standardized experimental protocol outside the operating room would allow a more accurate and reliable measurement of their performance. For industrial robots, performance metrics and methodologies to measure them are defined by international standards (e.g. ISO 8373, ISO 9283). Unfortunately, no such regulation is established for surgical robots.

Yavuz *et al.* [13] and Nebot *et al.* [14] compared the performance of AESOP and EndoAssist in a more standardized way. In their *ex vivo* study on pelvitrainer, one subject had to repeat a series of basic motions following several linear paths with increasing length and along various directions from horizontal to vertical (directions being relative to the local image frame at the starting point of motion). The experimental setup and protocol are more controllable than in a series of real surgical procedures. This methodology is therefore much less sensitive to external factors and more easily reproducible. The main limitation of these two studies lies in the fact that robots are analyzed as whole devices. It is therefore difficult to find out why a robot performs better than the other in terms of motion duration. It could be thanks to a more intuitive and fast-reacting interface, or just because the preprogrammed angular velocity of the laparoscope is set at a higher level.

Yet, it could be desirable to identify the influence of each characteristic of laparoscope positioners. In particular, as explained below, one can anticipate that two factors have a large influence: the control interface and the kinematics. The purpose of the study reported in this paper is therefore to assess, through a standardized benchtop protocol, the influence of robot kinematics and human-machine interface on the motion performance

of laparoscope positioners. More precisely, we want (1) to compare the EVOLAP kinematics with the other available solutions, and (2) to determine the most suitable number of directions that the surgeon should control. The paper is organized as follows. The next section presents the two characteristics of laparoscope positioners that are studied. Section III describes in details the experimental methodology that was designed to assess the influence of these factors on motion performance. Results of a first campaign are reported in section IV and discussed in section V.

II. CHARACTERISTICS OF LAPAROSCOPE POSITIONERS

Many characteristics of laparoscope positioners have an impact on their overall performance — ease of use, ease of installation, safety, intuitiveness, etc. Size and weight influence both installation duration and ergonomics for the surgical team, as room is scarce around the patient. The need for alignment of a remote axis or center of rotation with the incision also extends the installation procedure. All those elements account for usability; yet, they play only a minor role on the quality of laparoscope (and image) motion.

Several other factors influence motion more directly: stiffness of the robot frame and linkages, quality of actuators and transmissions, presence of passive (free) joints in the kinematic chain, length of the acceleration and deceleration phases, etc. These characteristics can induce vibrations or backlash that are a source of undesired motions during or shortly after teleoperation. However, they are mainly linked to the quality of design and implementation.

Choosing the kinematics has probably a more significant influence on quality and intuitiveness of motion, whatever the quality of implementation. Indeed, the laparoscope should always move in the direction desired by the surgeon. This seems obvious but section II-A will show that it is not always guaranteed. Surprisingly enough, the few kinematics used in laparoscope positioners have not been compared yet in any study. Kinematics is therefore the first factor analyzed in our study.

A wide variety of control interfaces are also used to drive these robots. It seems obvious that not all interfaces provide equal performance and intuitiveness due to many characteristics (detailed in section II-B below). But, again, one in particular should have a major influence: the number of motions in which the laparoscope can move. Indeed, since no particular motion direction is preferred in the abdominal cavity during laparoscopic procedures, a too small number of controllable directions could increase motion duration and reduce intuitiveness. This second factor will also be studied below.

Furthermore, it is not sure whether the same number of controllable directions is required for each kinematics to perform well. As a consequence, these two factors will be studied together. The rest of this section will now describe in details these two factors and the most widespread alternatives for each one.

A. Kinematics

A laparoscope, like any instrument for keyhole surgery, has only 4 degrees of freedom (DOF) since two translations are precluded by the constraint of passing through a small incision in the abdominal wall. It can be moved forward and backward along its longitudinal axis (*zoom* of the images), rotated around it (*self-rotation*), and swiveled around two orthogonal axes of

revolution passing through the entry point (*Left-Right* and *Up-Down* pan motions of the images with respect to the monitor).

The most natural way to drive the laparoscope is to use its intrinsic coordinate system, defined by its longitudinal axis and the two principal directions of the camera chip (corresponding with the horizontal and vertical borders of the monitor). This is what all surgeons and residents do when they hold the laparoscope and camera in hand. For example, in order to shift images to the left, one has to move the laparoscope along the horizontal display border. The motion is regulated by visual feedback from the screen and, to a lesser extent, by haptic feedback of the friction forces in the trocar that can help avoiding an unwanted zoom motion. Doing that, the user revolves the laparoscope around an instantaneous axis located in a plane parallel to the camera chip (and, therefore, normal to the longitudinal axis of the laparoscope) passing through the incision.

The AESOP induces the same laparoscope motions. At a given time step, knowing the relative orientation of the laparoscope with respect to the table (carrying the robot base), the controller determines the instantaneous axis of revolution required for the desired motion and moves the laparoscope around it. At the end of the controller time step, it recomputes the transformation matrix to the new local coordinate frame and continues motion around the refreshed instantaneous axis, and so on until the user stops the motion. Since the instantaneous axis of revolution can have any orientation with respect to the table coordinate system, three independent actuators are required to make the laparoscope swivel. The controller must also perform real-time kinematic computation to get the laparoscope instantaneous configuration and achieve the desired motion.

Most other robots do not move the laparoscope in this intrinsic laparoscope frame. Instead, they use a hybrid combination of fixed and mobile axes of revolution: one for *Left-Right* motion, and a second for *Up-Down* motion. The wide majority of these can be sorted into two groups. Robots of the first group have a fixed *Left-Right* axis that is essentially vertical, and a mobile *Up-Down* axis that remains parallel to the horizontal vector of the laparoscope frame (see Fig. 1a). EndoAssist, FreeHand, ViKY, and the video arm of da Vinci S and Si systems belong to this group. Robots of the second group, on the contrary, have a mobile *Left-Right* axis parallel to the vertical vector of the laparoscope frame and a fixed *Up-Down* axis (see Fig. 1b) that lies parallel to the ground. The second group includes EVOLAP, VESALIUS, and LapMan. VESALIUS can also be operated with switched axes: the fixed axis for *Left-Right* motion and the mobile axis for *Up-Down* motion (with the laparoscope turned by 90 degrees). Note that some robots have actuators placed directly on the axes of revolution, while the others use a remote center-of-motion mechanism (e.g. with parallelograms, timing belts, gears) to achieve the same result. In addition, some use one actuator for each basic motion, whereas others have to combine the motions of both motors. Yet, these considerations are related to the internal robot kinematics and control, and have no influence on the overall laparoscope kinematics (with respect to the table and, most of all, to the patient lying on it). It is therefore out of the scope of the paper. The interested reader can find a more detailed review and discussion of existing kinematics used in minimally invasive surgical robots (not only laparoscope positioners) in [15].

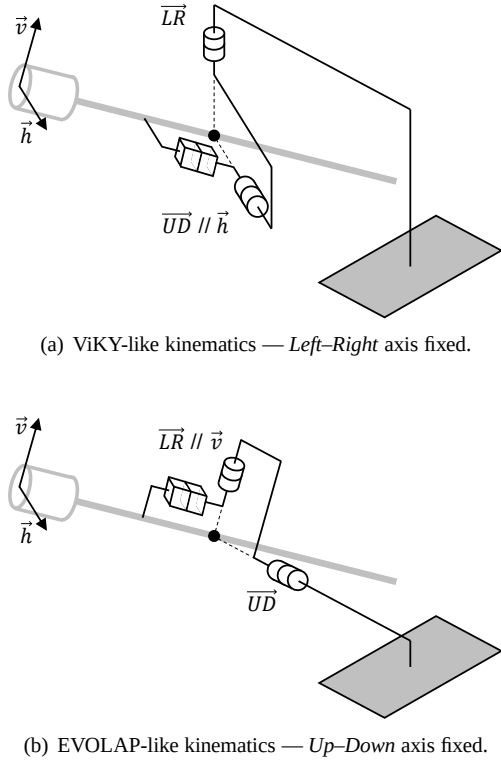


Fig. 1. Laparoscope kinematics with the two most common architectures using one fixed rotation axis.

The main difference between AESOP and robots of these two groups is that the latter have only two actuated axes to make the laparoscope swivel around the entry point. However, the frame in which the laparoscope is moved is not always aligned with its own intrinsic frame. Therefore, in some configurations (which vary between the two groups), the actual laparoscope motion can be different from the one desired by the surgeon. This effect can of course impair the performance. In this paper, we compare the performance obtained by three different kinematics: AESOP-like, ViKY-like and EVOLAP-like.

B. Human-Machine Interfaces

Direct interaction between the robot and its user is a fundamental characteristic of medical applications. It is especially important when the surgeon has to control the robot in real-time during a procedure. During laparoscopy, the surgeon uses both hands to handle instruments. The interface must therefore allow him/her to drive the laparoscope without having to release the instruments.

Footswitches equipped early versions of AESOP and ViKY. It appeared quickly that they cause stability problems for the user. Furthermore, various surgical devices (e.g. electro-surgical instruments) are operated by pedal and confusion might occur. Voice control replaced them conveniently, as surgeons are used to order image motions by talking to the assistant who holds the scope. Tracking of head motions by means of accelerometers or gyroscopes is also used to control robotic camera positioners (e.g. EndoAssist, FreeHand). Many university prototypes work with a miniature finger-operated joystick mounted on the instrument, since it is cheap, reliable and easy to interface with robots. All these control devices are generally designed to nav-

igate the laparoscope in real-time until the surgeon decides to stop motion.

Several characteristics of human-machine interfaces have an impact on motion quality and duration: response time, learning curve to get used to it, accessibility, rate of order recognition error, mental concentration required to avoid an unwanted motion, etc. Again, these characteristics mostly depend on the quality of hardware and software implementation of the interface. The number of controllable motion directions has probably a large influence on motion duration and intuitiveness. Indeed, although the image can be panned in any direction by hand, the wide majority of available robots only allow fully-decoupled *Left, Right, Up, or Down* (Cartesian) image shifts, regardless the technology of interface. Increasing the number of controllable directions is therefore likely to decrease motion duration.

To be comprehensive, it should be mentioned that a second approach could be followed to improve the motion performance. Instead of controlling the camera in real-time, it is possible to give the robot a target, and to let it move autonomously until the desired position is reached. Several teams have developed image processing systems that locate the position of the instrument end-effector and keep it within a prescribed region in the image [16–18]. The surgeons line of sight towards the monitor can also be computed from eye- or face tracking systems [19]. However, these solutions suffer so far from lack of robustness, which is a major safety issue. Moreover, from our experience, surgeons prefer real-time control of the robot to triggered autonomous motions.

Therefore, this study will only focus on the first approach, in which the surgeon controls the motion continuously until he/she decides to stop the camera. Three sets of directions will be compared: Cartesian directions, Cartesian directions with diagonals, and omnidirectionality.

III. EXPERIMENTAL SETUP

As explained above, a single robot should be used for an experimental comparison of these two factors. It permits to exclude all uncontrollable sources of variability between different devices (e.g. maximum laparoscope velocity, acceleration and deceleration duration, reaction time of the interface). The

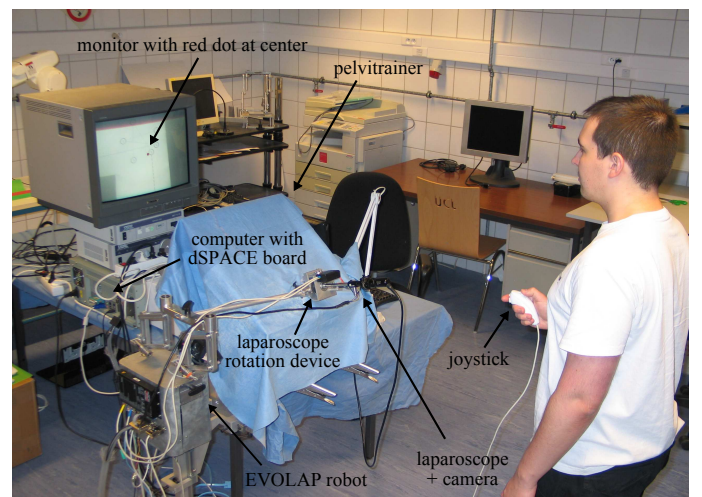


Fig. 2. Experimental setup.

EVOLAP robot was therefore upgraded to become capable of reproducing the three desired kinematics. The experimental setup built around it is depicted on Fig. 2. It comprises a STORZ laparoscopic system (laparoscope, camera, video unit), a monitor, and a pelvitrainer with a specific task placed inside.

After a short introduction to the EVOLAP robot, this section presents its mechatronic upgrade, the proposed task, the performance metrics, the statistical methods used to process the results, and the experimental protocol of the first campaign.

A. The EVOLAP Robot

The EVOLAP laparoscope positioner is a table-mounted robot developed at UCL by researchers from the CEREM and the department of gynecology, in collaboration with the Montpellier Laboratory of Informatics, Robotics and Microelectronics (LIRMM, Université Montpellier 2 – CNRS, Montpellier, France). It consists of three main components (Fig. 3):

- A main 2-DOF *remote manipulator* generates the angular motions of the laparoscope around the incision. Its architecture uses a combination of orthogonal parallelograms to translate the end-effector onto the surface of a half-sphere, producing so-called ‘circular translations’.
- This motion is then transferred to the laparoscope by a *passive lockable arm*, via two orthogonal passive joints. The distal end of the arm reproduces the circular translations above the patient, and the laparoscope swivels passively thanks to the passive joints and the constraint of the incision point. The arm has also several joints that can be unlocked for adjustment during installation, once the main manipulator has been secured on the table in a convenient position.
- A *local zoom device* located at the end of the lockable arm translates the laparoscope inside the trocar without any motion of the arm.

This decoupled architecture is capable of producing large intra-abdominal displacements of the lens with limited robot motions above the patient’s abdomen. The particular (internal)

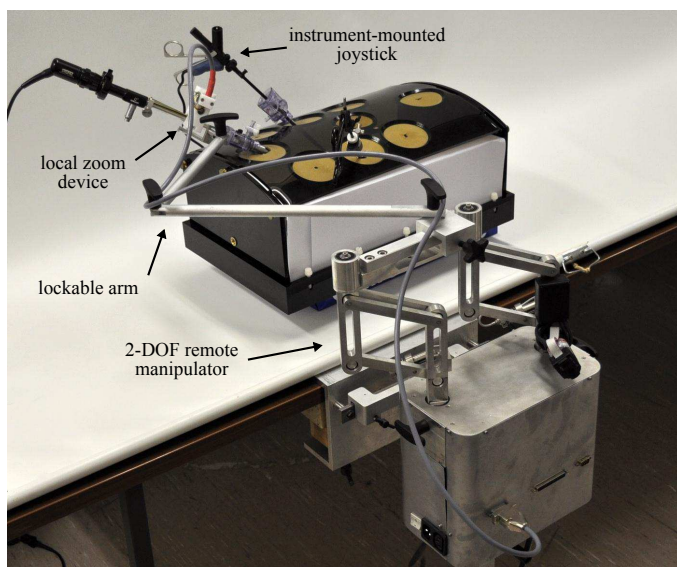


Fig. 3. The original EVOLAP prototype with remote 2-DOF manipulator mounted on table, local zoom device, lockable arm and instrument-mounted joystick.

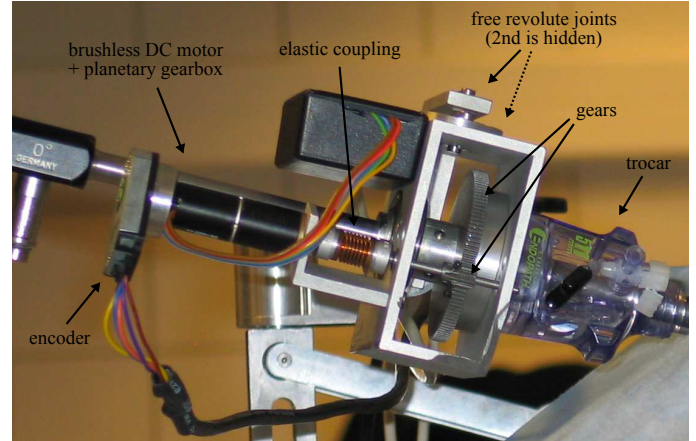


Fig. 4. Local rotation device designed for the study.

kinematics of the main 2-DOF remote manipulator does not require any alignment with the insertion point of the laparoscope. Priority can thus be given to the optimal placement of the surgical team around the patient, the robot being positioned conveniently next to them on the suitable side of the patient, regardless of the insertion point of the laparoscope, or the type of procedure. Table mounting allows a change of table set up during the procedure without requiring any robot adaptation or re-positioning.

The prototype includes an instrument-mounted joystick that allows the surgeon to teleoperate the robot in any direction and with proportional control of the angular velocity. The control algorithm is implemented in a Matlab/Simulink block diagram on a standard Windows-based computer. It runs at 200 Hz on a dSPACE1102 real-time controller board embedded in the computer and equipped with analog and digital I/O's.

B. Mechatronic Upgrade of the EVOLAP Prototype

The current EVOLAP prototype possesses only two actuated revolute DOFs to make the laparoscope swivel around the incision. The laparoscope is fastened to the zoom device in such a way that it can only be translated. Self-rotation is therefore precluded in normal use. Therefore, the mechatronic structure of the prototype had to be adapted so as to be able to reproduce the three kinematic behavior described in section II-A: (1) AESOP-like, (2) ViKY-like, and (3) EVOLAP-like.

Since all kinematics induce the zoom motion by a pure translation of the laparoscope along its longitudinal axis, we decide to exclude this motion from the study. The zoom device was replaced by a local rotation device designed for the purpose of this study (see Fig. 4). It motorizes the self-rotation of the laparoscope by means of a Maxon EC16 brushless motor with a GP16 planetary gearbox (84:1 ratio) and 10:1 gears. This third revolute DOF allows to pivot the laparoscope around any axis of revolution. In this way, the laparoscope motion can be controlled in the three specific coordinate frames that we want to compare.

The two additional kinematic models were computed and implemented in the Simulink control scheme to map the external laparoscope kinematics described in section II-A with the actuated joints of the modified EVOLAP prototype. The control algorithm was also modified to use a single joystick with the three

sets of directions (i.e. Cardinal directions, Cardinal directions with diagonals, and omnidirectionality).

The instrument-mounted joystick was replaced by a Nintendo Wii Nunchuk, whose ergonomic qualities are widely recognized. The goal was to minimize the learning phase that could possibly be longer with the instrument-mounted joystick.

C. Task

The task that was designed to assess the motion performance is inspired by Yavuz *et al.* [13] and Nebot *et al.* [14]. A series of eighteen numbered circular targets linked by straight lines are organized on a sheet of paper (see Fig. 5). The sheet of paper was cut in L-shape and fixed on a spherical support placed inside the pelvitrainer. The radius of the sphere was set to 18 cm and its center coincident with the pivot point of the laparoscope in the pelvitrainer. The laparoscope distal tip was inserted at 10 cm from the center of rotation, and the optical zoom of the camera was set so that no black corners appeared on the screen edges. At the center of the monitor, a red paper dot was glued with a diameter approximately twice smaller than the displayed circular targets.

The goal is to move as fast as possible the laparoscope from one target to the next one, with a very short stop when the red dot is inside a target. The straight lines between the targets only intend to help the subject find quickly the next target, but no trajectory was prescribed between the targets. The angular velocity of the laparoscope was set to 8 degrees per second (reached in 0.2 s from rest), which turned out to be a good balance between speed and accuracy regarding the task difficulty.

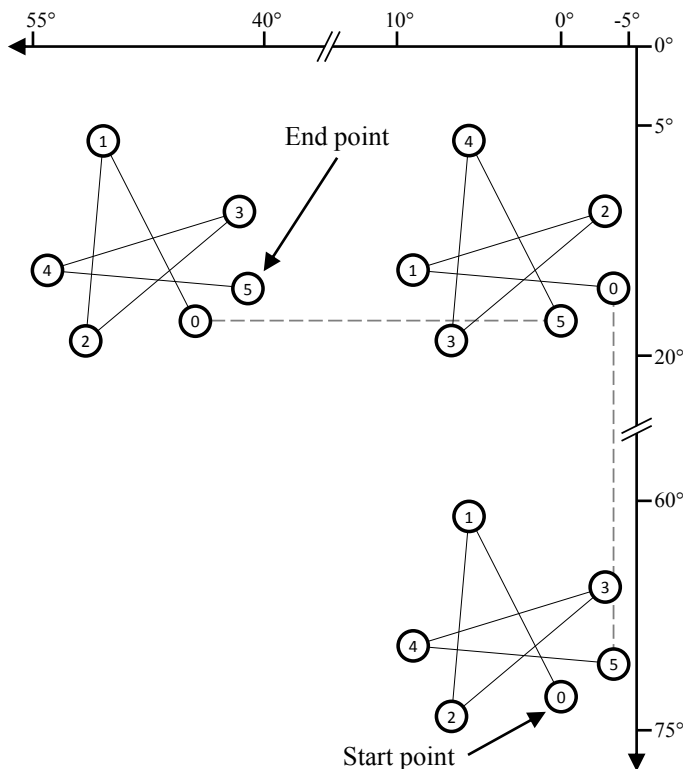


Fig. 5. Trajectory used for the experiments, composed of three groups of equally-spaced circular targets, each group being located at a specific extremity of the workspace.

The circular targets are grouped six by six in sort of stars, each group being located at a specific extremities of the (symmetric) intra-abdominal workspace that can be reached by the compared robots during a surgical procedure (i.e. bottom-center, top-center, and top-left). The three stars are identical, and composed of five straight lines of equal length. Targets are placed in such a way that the lines range from 5 to 95 degrees with respect to the vertical, with angular increments of 22.5 degrees. Vertical, horizontal and diagonal directions were avoided within a group. Although they are representative of what available robots *can* do, they might not be representative of what they *should* do since no direction of motion is privileged inside the abdomen. This is especially true for small adjustment motions between steps of a specific surgical task (e.g. coagulation and cutting, suturing). When performed by hand, large camera displacements to move from one organ to another are more often decomposed of a Cartesian motion followed by a small adjustment in an undefined direction. Therefore, the three groups of targets are aligned horizontally and vertically.

The angular positions in Fig. 5 are relative the world coordinate system. The arrow pointing towards left lies, when curved on the spherical support in the pelvitrainer, in an horizontal plane parallel to the ground, the table, and the robot base. The arrow pointing downwards defines a vertical plane normal to the ground and parallel to the longitudinal side of the robot. The pelvitrainer was only placed in a raised configuration of about 35 degrees with respect to the table to avoid any collision between the rigid pelvitrainer top face and the local rotation device, which is quite bulky.

D. Performance Metrics

The main metric is naturally the amount of time required to complete the task. The recording of the task duration is fully automated, to avoid any variability in reaction time from the user that should start when a light flashes or a sound beeps, or from a supervisor that should synchronize a stopwatch manually when the robot starts moving. The stopwatch integrated in the dSPACE real-time interface starts when the subject uses the joystick for the first time. It stops when the robot stops moving with the image centered on the last target. The task duration is then displayed for manual recording in an Excel table and analysis of the learning curve (see section III-F below).

Besides the task duration, which has a 0.01 s precision, several parameters are recorded at 10 Hz if a further investigation is required: angular position and velocity of each actuated joint, input signals acquired from the joystick, kinematics and joystick mode, task repetition, start time, and several internal variables.

During one preliminary trial, the laparoscopic image was video-recorded, as well as an external view of the setup, to analyze visually the differences in motion between all combinations of factors.

E. Statistical Analysis

The data were analyzed using General Linear Model (GLM) with JMP 9.0.3 and SAS 9.3 statistical softwares. The model contained the following effects: subject, kinematics, joystick mode, and all the two-factors interactions. Kinematics, joystick mode and their interaction were defined as fixed factors for the ANOVA. Subject and its interactions with the fixed factors

TABLE I
SUMMARY OF TASK DURATION [S] DURING THE FIRST EXPERIMENTAL SESSION.

Kinematics		ViKY	EVOLAP	AESOP	All robots		
Joystick mode		Mean (SD)	Mean (SD)	Mean (SD)	Mean ^a	LSq ^b	Log ₁₀ ^c
Cartesian		65.67 (3.54)	56.88 (4.37)	53.64 (5.92)	58.73	58.33	1.7659
Diagonals		55.75 (2.06)	47.85 (2.80)	45.17 (2.87)	49.59	49.32	1.6930
Omnidirectional		53.20 (1.57)	45.17 (2.80)	43.03 (3.70)	47.14	46.85	1.6707
All joysticks	Mean ^d	58.21	49.97	47.28			
	LSq	57.92	49.62	46.90			
	Log ₁₀	1.7628	1.6957	1.6711			

^aMean for one joystick mode with all robots.

^bLeast squares mean computed from the model fitted on data for one joystick mode with all robots.

^cLogarithm of the least squares mean used for the Tukey HSD test.

^dMean for one kinematics with all joystick modes.

were defined as random. In other words, results of all subjects were analyzed together for each kinematics-joystick mode couple. The model was solved using REML (Restricted Maximum Likelihood). The Tukey HSD test of multiple comparisons was used to compare modalities of significant factors.

F. Protocol

For this first experimental campaign, six subjects were recruited. They are all researchers in mechatronics at the CEREM, with no previous experience of laparoscopic surgery or robotic camera holder. All of them had experience in video games, ranging from a few times over the past ten years to several hours a day. The session with the first subject was used for testing and tuning the whole protocol and therefore not analyzed.

Each subject tried the kinematics in random order. For each kinematics, the joystick modes were also selected in random order. Four valid repetitions were required for each kinematics-joystick mode couple. To exclude any learning effect on the statistical analysis, a learning curve for each couple was computed with a Matlab script after each repetition. If a learning effect was detected, trials were repeated until 4 repetitions were performed after learning.

IV. RESULTS

Table I summarizes the results of the experiments. Mean value and standard deviation are presented for each kinematics-joystick mode couple over the whole subjects population. Fig. 6f is a graphical representation of these average results, while Fig. 6a–e depict individual results for each subject.

The ANOVA performed on modeled means value and after log₁₀ transformation (not presented in Table I for clarity) shows that factors kinematics and joystick mode are significant ($p < .0001$) while the interaction between these two factors are non significant ($p = 0.43$). This absence of interaction means that the difference(s) between the kinematics are the same whatever the joystick mode and that the difference(s) between the joystick modes are the same for each kinematics.

As a consequence, the Tukey HSD test could be performed on global modeled mean values (of all kinematics together for each joystick mode, and vice versa) again after log₁₀ transfor-

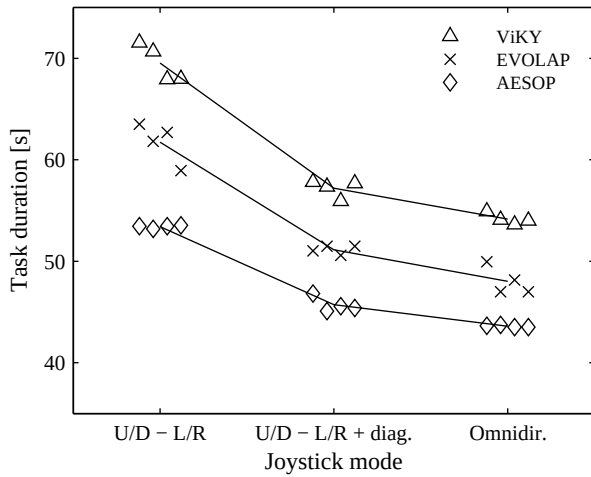
mation, as presented in Table I. The Tukey HSD test showed that the use of ViKY-like kinematics leads to a significant longer task duration than EVOLAP-like and AESOP-like kinematics ($p = .0005$ and $p < .0001$, respectively). EVOLAP presented a longer task duration than AESOP but this difference was not significant ($p = 0.1$). The three joystick modes appear to be significantly different from each other, the Cartesian mode presenting a longer task duration than Cartesian with diagonals ($p < .0001$) and the omnidirectional mode a shorter one ($p = .0025$).

V. DISCUSSION

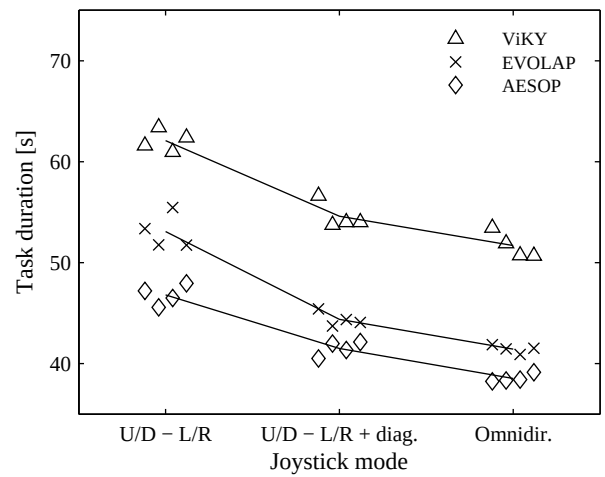
As expected, not all kinematics and joystick modes are equal regarding the motion performance. The increase of time required to complete the task with the slowest kinematics-joystick mode couple is nearly 50% of the average task duration with the fastest couple.

AESOP-like kinematics is the most efficient and also the most intuitive, since it allows the control of the camera motions directly in the image directions whatever the instantaneous laparoscope configuration. The ViKY-, EndoAssist-, and FreeHand-like kinematics, on the contrary, is the slowest. Its behavior is close to the AESOP-like kinematics when the laparoscope remains nearly parallel to the table plane. However, subjects found it pretty difficult to maneuver properly and efficiently when the laparoscope becomes too vertical. In this configuration, it tends to align with the fixed *Left–Right* axis and become close to singularity. A *Left of Right* order will therefore lead to a self-rotation around the laparoscope axis rather than a sideways translation of the images on the monitor. EVOLAP-like kinematics offers performances between the two others and tend to be close to AESOP-like results among 3 subjects (see Fig. 6). The narrowing of angle between the laparoscope axis and the *Up–Down* axis when approaching lateral borders of the workspace seems to penalize less the performance. This kinematics could therefore offer a good balance between mechatronic complexity (without motorization of the laparoscope self-rotation) and performance in terms of motion duration and ease of use.

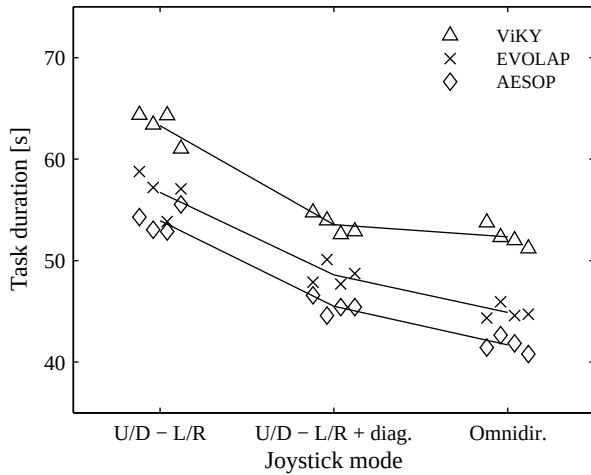
Regarding the number of controllable motion directions, it appears clearly that restricting to Cartesian directions only dete-



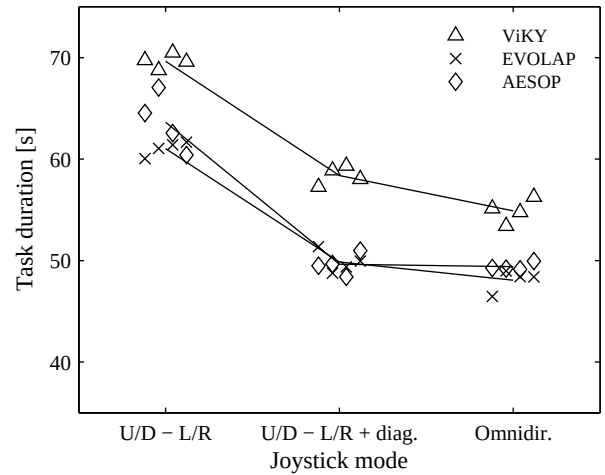
(a) Subject 1.



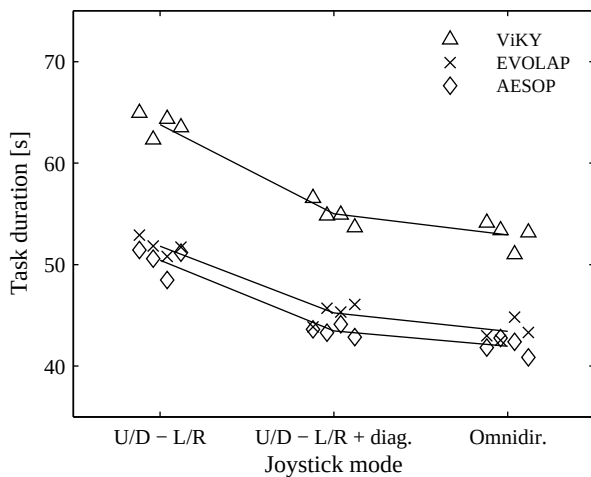
(b) Subject 2.



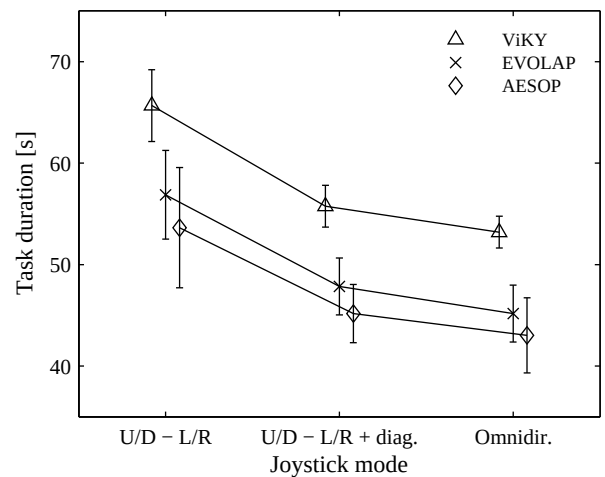
(c) Subject 3.



(d) Subject 4.



(e) Subject 5.



(f) All subjects.

Fig. 6. Results of the trials. Graphs (a)–(e) depict the results for each subject, with each repetition for the same joystick mode in order of occurrence and plain lines joining the mean value for each joystick mode. Graph (f) shows the results for all subjects, with plain lines joining the overall mean value and vertical lines showing the standard deviation.

riorates the motion efficiency. The advantage of adding the diagonals is quite obvious and all subjects agreed with that. However, the increase of performance offered by omnidirectionality, yet statistically significant, might not be that important and the majority of subjects did not feel any advantage with respect to the mode with diagonals. The latter seems therefore to be an interesting solution that could be implemented on several existing modalities: joystick or buttons, voice control, maybe head control although it could become too complicated, or even eye-tracking (since localizing the line of sight in 8 zones might not be too complex or require excessive precision). As for omnidirectionality, it is by far more difficult (not to say impossible) to implement in any other interface than a joystick.

VI. CONCLUSIONS AND FUTURE WORK

The purpose of the study reported in this paper was to assess the influence on robot kinematics and number of controllable directions of laparoscope positioners on motion performance. An *ex vivo* experimental protocol was set up, using an upgraded version of the EVOLAP laparoscope positioner developed at UCL. A group of five subjects performed a simple task made of successive point to point camera motions with the three most widespread kinematics, in combination with three sets of directions that could be controlled with the human-machine interface.

Results of this first campaign show that significant differences exist between kinematics, in terms of time required to complete the task. Furthermore, increasing the number of controllable directions improves the performance for all kinematics.

These preliminary results should be confirmed by a second session with surgeons. During this session, their subjective impressions should also be collected by means of a usability test. The influence of angular velocity on task performance should also be assessed. Indeed, one can postulate that above a certain image velocity, motions become difficult to control precisely. This is of importance since a constant angular velocity of the laparoscope do not lead to a constant image velocity, which depends on the distance between the distal lens and organs, and on the insertion depth of the laparoscope (leverage effect on the distal lens). A manual or automatic adjustment of the laparoscope angular speed might therefore be desirable. Finally, a further study should also assess the influence of kinematics on the realization of complex surgical tasks (e.g. suturing, intracorporeal knot tying). Indeed, a self-rotation of the laparoscope changes the image orientation with respect to the organs and the instruments, and it could increase the difficulty to perform these challenging gestures.

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