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Is the Human Brain Capable of Controlling Seven Degrees of Freedom?

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ABSTRACT

Background: Conventional rigid laparoscopic instruments offer five degrees of freedom (DOF). Robotic instruments add two independent DOFs allowing unconstrained directional steering. Several nonrobotic instruments have been developed with the additional DOFs, but with these devices, surgeon's wrist movements are not intuitively transmitted into tip movements. In this study, a new articulated instrument has been evaluated. The aim of the study was to compare learning curves and performances of conventional laparoscopic instruments, the da Vinci system and Steerable devices in a crossover study.

Materials and methods: A total of 16 medical students without any laparoscopic experience were trained for 27 h to operate all of a rigid, a robotic, and a new Steerable instrument in a random order. Learning curves and ultimate experience scores were determined for each instrument. Strain in wrist and shoulders was assessed with a visual analog score.

Results: Performing the suturing task with rigid and robot instruments required 4 h of training, compared with 6 h to master the Steerable instrument. After 9 h of training with each instrument, completing the complex suturing pattern required 662 ± 308 s with rigid instruments, 279 ± 90 s with the da Vinci system, and 279 ± 53 s with the Steerable instrument. Pain scores were significantly higher after using the rigid instruments compared with the Steerable instruments.

Conclusions: Transmission of torque and the presence of additional two DOFs in combination with reduced crosstalk significantly improved the instrument dexterity where the Steerable platform is concerned. Although the learning curve is longer, once mastered, it provides enhanced surgical freedom.

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Introduction

Since the start of laparoscopic surgery in the late 80s,[1,2] the level of dexterity of manually operated rigid instruments has shown little progress. Although this is no barrier for performing pioneering surgery, the constraints of reduced freedom of movement become apparent during challenging surgery in confined spaces.

A conventional rigid laparoscopic instrument offers only five degrees of freedom (DOF) of movement: instrument rotation, up-down angulations, left-right angulations, in-out movements, and one degree assigned to a gripper at the instrument tip.

A significant step forward in laparoscopy came with the introduction of the da Vinci robot in 1999. Urologists have been at the forefront of exploring and using this new technology. Addition of two independent DOF—up/down and left/right bending of the tip—allows the dexterity of the human hand to be reflected in the tip. Together with several other features such as stereoscopic vision and tremor filtration, performance of laparoscopic tasks dramatically improved, which might explain the rapid acceptance of this technology.

Many attempts have tried to increase the number of DOFs of nonrobotic devices so as to combine the accessibility of manual instruments with the dexterity and aptitude of robotic systems. These solutions have been described and summarized in the literature; their main restriction is a lack of force and intuitiveness.[3,4]

In this study, a new type of articulated surgical instrument platform known as Steerable (Steerable Instruments, Ghent, Belgium; Fig. 1)[5] has been evaluated.

Instruments of the Steerable platform are based on an innovative transmission mechanism, which mechanically transfers directional movement of the surgeon's wrist to bend the instrument tip in any direction (360°) and at an angle of at least 90°, and it stably maintains the tip position against an external force. The mechanism has the ability to rotate the tip itself in the bent position without the need for a separate controller. The four principal features of the Steerable platform are discussed in the following paragraphs.

Stability

Paradoxically, whereas it must permit smooth, low-friction manipulation with excellent tactile feedback, an instrument tip has to be resistant to an opposing external bending or lateral force while it adopts any direction or angle. Existing manually-operated articulated instruments cannot resist large lateral forces–there is either device failure or slippage. Jeong[3] concluded in 2012 that the 1.8 N (N) slippage force of current articulating instruments was not sufficient to meet the usual operative needs of up to 14.5 N. The Steerable platform can maintain the tip at a given direction and angle against an external force of 25 N. An articulating instrument should be manually controlled with ease in all directions up to a bending angle of at least 90° and should be able to maintain its position. In other words, the steering mechanism should be stable so as to resist unwanted flexing. This is accomplished by among other attributes, a stent-like Nitinol steering mechanism in the Steerable platform.[6-8]

Fig. 1 – An instrument of the Steerable platform. (Color version of figure is available online.)

Crosstalk

Crosstalk refers to a change in the direction of the whole shaft, that is, up/down angulation and left/right angulation, caused by the wrist movement of the surgeon when controlling an articulated tip; where there is crosstalk, both shaft and tip direction change when attempting to control only the direction of the tip. In the Steerable platform, unwanted shaft movements are eliminated by locating the center of rotation of the proximal joint close to the surgeon's wrist. The handles are oriented in a reverse orientation, which has been found to reduce or eliminate negative influences of wrist movements of the surgeon on the direction of the shaft.

Transmission of torque

In open surgery, the human wrist is sufficiently jointed so as to bend and rotate simultaneously thereby introducing a needled stitch with relative ease. In most currently available articulated instruments, these actions are temporally separated and follow a time-consuming sequence: manually actuating the instrument to bend the tip, fixing the tip using a locking mechanism, grasping the needle between gripper jaws on the tip and fixing the jaws with a ratchet, and finally rotating the tip (gripper) by turning a wheel with the fingers. In instruments of the Steerable platform, these actions are executed simultaneously and fluently by natural wrist movements in a manner as effective as in open surgery.

Amplification

A velocity ratio >1 between bending movements of the proximal and distal bendable areas allows for more economical and less exhausting wrist movements by the surgeon. For instance, bending the handle by 45° is translated by the mechanism to a 90° bending of the tip. This angular amplification may initially confuse the operator and affect the learning curve.

Realizing the previously mentioned features required a complete redesign of the laparoscopic instrument, resulting in a new transmission mechanism permitting much improved instrument dexterity. It remains unclear, however, how much effort it takes to fully master the instrument compared with conventional laparoscopic (five DOF) instruments and the da Vinci robot. The expanded number of DOF involves several challenges for the human operator for fluent control of the device. In robotic systems, the complexities to assure intuitive manipulation of the distal end of the device is taken care of by sophisticated algorithms that translate intuitive manipulations of the hand controls of the surgeon console to combinations of movements resulting in appropriate movements of the actuator. In a 7-DOF mechanical device, such as the Steerable, the human brain has to adapt to translate a combination of movements of forearm and wrist to the desired response of the distal end. Therefore, the aim of the study was to evaluate the learning curve and performance of this instrument in a crossover study involving 16 medical students without any previous experience with any of the technologies.

Materials and methods

To compare the three different technologies, a randomized crossover study was designed.

Participants

Sixteen medical students (Ghent University Hospital) without any experience in laparoscopic surgery (eight men and eight women; mean ± standard deviation [SD] age 23 ± 1.78 y) were recruited, supplemented by 10 experienced surgeons (five laparoscopic surgeons and five robotic surgeons) with more than 5 y of experience.

At the start of the study, written informed consent was obtained, and all participants completed a questionnaire regarding age, sex, hand dominance, and surgical professional interests. Ambidexterity determination was established through the Edinburgh Handedness Inventory.[9]

Study protocol

Sixteen medical students participated in the study. Each student was trained for 27 h within a 3-wk period, including 9 h of training with a straight laparoscopic needle holder (Karl Storz, Tuttlingen, Germany), 9 h of training with the da Vinci Robot (Intuitive Surgical, CA), and 9 h of training with the Steerable needle holder (Steerable Instruments, Ghent, Belgium). Three different training schedules were devised (Fig. 2) whereby the order of exposure to and training on each instrument was different, and each student was assigned to one of the three schedules.

To avoid a memory effect, the instrument type was switched after each 3-h-long session in such a way that all instrument types were equally trained. Individualized active feedback was provided during the training based on the observed errors by one expert for every four students. During each training session, all subjects undertook 1 h training using direct vision, 1 h using a 0° full HD three-dimensional (3D) endoscope (Karl Storz), and 1 h with 0° full HD two-dimensional endoscope (Karl Storz). Throughout the entire training period, three standardized tasks of increasing difficulty were repeatedly performed and measured in the same order. A prerecorded instruction video of all the exercises was shown at the start of the program. A specific number of task repetitions was not required. To avoid boredom, more advanced procedures such as needle threading through eyelets, knot tying, circular anastomosis, and vesicourethral anastomosis were presented and performed. Training using the rigid instruments was supervised by two general surgeons with more than 15 y of experience each. Robotic training was carried out at the ORSI Academy (Melle, Belgium), and a standard training protocol was followed. The first two authors

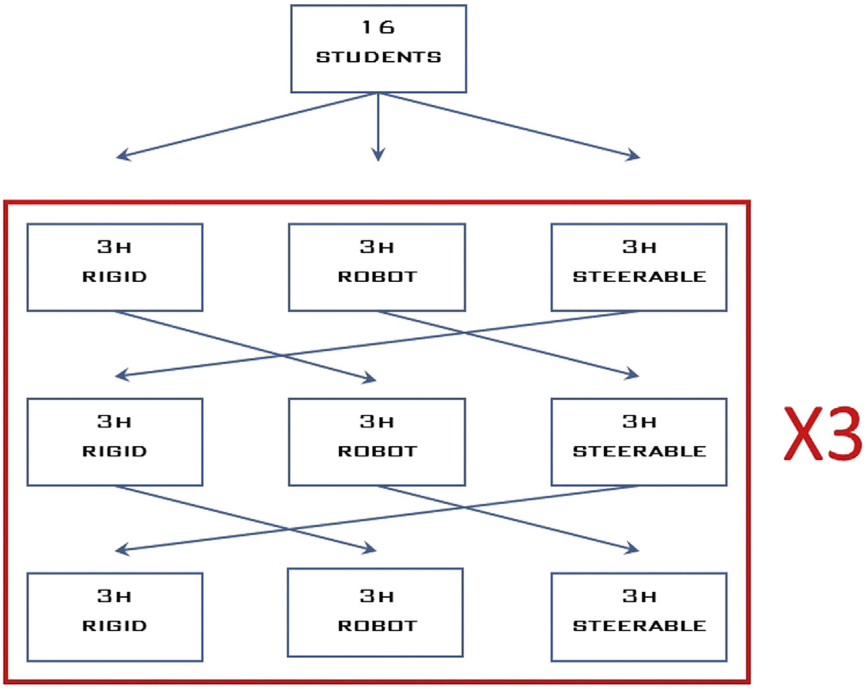

Fig. 2 – Crossover study design: each participant performed three times (×3) a sequence of nine randomized hours totaling 27 h per individual. (Color version of figure is available online.)

trained the students on the Steerable platform. After the extensive training, experience was quantified by means of a complex suturing pattern (Fig. 3).

The training of each participant for the duration of the 27 h and the final evaluation were video recorded using a GoPro Hero4 or a MediCap USB200 Medical Video Recorder (MediCapture Inc, Philadelphia, PA) for post-hoc analysis.

Exercise 1: Peg transfer

Task: transfer two rubber “O-rings” (I.D. 8 mm) placed on a peg one by one to another peg and back to the original position. The pegs were separated by 55 mm. The steps were repeated five times (20 moves) during the exercise. If the participant lost a ring, this step had to be repeated. During this task, only five DOF (instrument rotation, up/down angulation, left/right angulation, instrument in/out translations, and one degree assigned to a gripper at the instrument tip) are required to complete the task successfully.

Exercise 2: Eyelets

Task: insert the tip of the needle holder coaxially into each of seven eyelets placed at different angles. This task was specifically designed to become adept to the seven DOF of the Steerable needle holder. This test is technically impossible to accomplish using the rigid needle holders.

Exercise 3: Around the world

This test is a concise version of an existing module used in the da Vinci simulator training. A soft suturing pad (Eyelabinnovations, Innsbruck, Austria) was provided with a print of five circles using a marker (Staedtler Lumocolor Permanent F 318). The inner diameter is 2.7 mm, and the outer 4.1 mm. Four circles are positioned crosswise at a distance of 10 mm around a central circle. The goal is to enter an outer circle using an Ethicon 3-0 JB 26 mm 1/2c Visi-Black needle and to exit the central circle. To be considered successful, the needle must exit inside the ring or in contact with the black rim of the ring. One test consisted of one needle insertion in each of the four directions. The time limit to perform the test was set at 600 s. Where the Steerable device was used, it operated in a seven DOF mode with tip rotation in a bent position (transmission of torque [TOT]). The tests were evaluated by the first or second author.

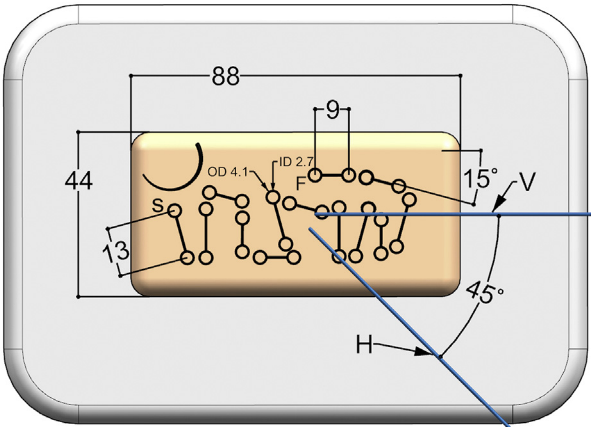

Fig. 3 – The complex needle driving pattern was provided in a left-handed and right-handed version and consisted of 13 needle passes. The circles were arbitrarily positioned at an intercircle distance of 9 or 13 mm. The directions were vertical and horizontal or making an angle of 15°. The inner diameter was 2.7 mm, and the outer 4.1 mm. (Color version of figure is available online.)

Final performance test: complex suturing pattern

All participants were posttested after finishing all their training sessions by completing an intricate needle driving task in two different positions (Figs. 4 and 5). Akin to the “Around the World” test, the participants were requested to drive a needle entering a circle and exiting a connected circle inside or at least in contact with the black rim. Exits outside the black rim of the circle were assessed live by an examiner and required a new correct needle passage or reorientation of the needle in case of errors. Both entering and exiting needed to be performed with the needle holder, not with the assisting instrument. Very superficial suturing was not possible because a minimum angle of insertion was required to perforate the material. Tissue manipulation was not allowed. In case of needle drop, time recording was stopped until the needle was grasped again. The complex needle driving pattern was provided in a left-handed and right-handed version and consisted of 13 needle passes (Fig. 3). The circles were arbitrarily positioned at an intercircle distance of 9 or 13 mm. The directions were vertical and horizontal or making an angle of 15°. The inner diameter was 2.7 mm, and the outer 4.1 mm. The test was performed with the suturing pad in a horizontal position (Fig. 4) and in a more challenging almost vertical (Fig. 5) position (75° to the horizon). As none of the aforementioned errors were allowed, the only parameter was execution time. The blue projection line (Fig. 3) of the shaft of the instrument is 45° degrees to the horizon in case of a horizontal positioning of the suturing pad. In an almost vertical position of the suturing pad, the projection line is parallel to the horizon. In both positions, the angle of the instrument shaft and the plane of the suturing pad was 45°. The test was carried out using a 0° full HD 3D endoscope (Karl Storz), and a Maryland (Endopath; Ethicon, Somerville, NJ) as assistant instrument for the rigid and steerable instruments. For the robotic procedure, a large needle driver and a Maryland bipolar forceps were used. Ethicon 3-0 JB 26 mm 1/2c Visi-Black

Fig. 4 – Complex suturing pattern in horizontal position. (Color version of figure is available online.)

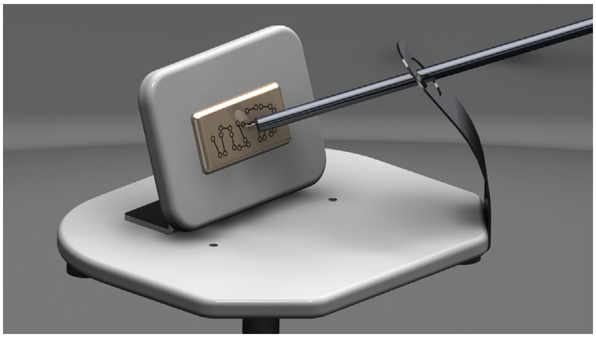

Fig. 5 – Complex suturing pattern in vertical position. (Color version of figure is available online.)

needles were used in each setup. The tests were evaluated by two independent examiners. In addition, a pain rating based on a visual analog scale was used to evaluate strain in wrist and shoulders.

Ethical committee

The study was approved by the Ghent University Hospital ethical committee and registered as B670201628871.

Statistical analysis

A pilot study based on three medical students (Ghent University Hospital) without any experience in laparoscopic surgery was organized. Proficiency levels were reached after 6 h of training. It demonstrated a mean ± SD of 567 ± 310 s to perform the complex suturing task in the rigid group and revealed an SD of 280 s in the steerable group. To detect this difference of 40% with a chance of alpha error of 0.05 and a power of 0.90, a total sample size of 14 was needed. Sixteen volunteers were included in this study.[10] Statistical analysis was performed using *Excel* (Microsoft, Redwood, MS) and SPSS version 24.0 (SPSS Inc, Chicago, IL). The results of the final testing were analyzed using linear mixed-effect models to assess the effect of the instrument type and the position (horizontal/vertical) of the suturing pattern on the final time scores. A natural log transformation of the data was used for significance testing, permitting parametric statistics. The Wilcoxon signed-rank test was used for comparing the pain scores after finishing the final task. $P < 0.05$ was considered significant, and results are reported as mean ± SD.

Results

Demographics

The subject demographics and result of the Edinburgh Handedness Inventory questionnaire are shown in Table.

Learning curves rigid—robot—Steerable

All 16 participants successfully completed the study. A total of 432 training hours and 25 evaluation hours were recorded.

Table – Demographics of study subjects.

Characteristic value	
Number of participants	16
Age (mean ± SD)	23 ± 1.78
Sex (male:female)	8:8
Experience of video games (yes:no)	8:8
Experience of musical instrument (yes:no)	5:11
Edinburgh handedness classification (left: Mixed: Right)	2: 4: 10
Interests in surgery (yes:no)	16:0

The results of the "Around the World" training is visualized in Figure 6. The Steerable platform learning curve[11] was "steeper" than for the other instruments. Some participants could perform the "Around the World" test after <30 min of training. After 9 h of training, the learning curves for the three technologies leveled off at a noteworthy 35 (23-62) s for one "Around the World" circuit. All 16 participants could control the instrument within the given time frame.

Learning curves freedom modalities steerable

The learning curve of the Steerable platform was further investigated using three different modalities of control: using the Steerable device as a five DOF instrument evaluated during the simple peg transfer, using the seven available DOF without TOT during the eyelets exercise, and finally the full use of seven DOF and TOT during the demanding "Around the World" exercise. Based on a pilot study, the three exercises were adapted as such to have similar level-off scores. Figure 7 convincingly demonstrates that only little time is required to use the Steerable needle holder as a five DOF instrument akin to a rigid instrument. To control seven DOF without TOT as in first-generation articulated instruments, only 1 h of training is required. It is the TOT from the surgeon's wrist to the instruments' tip, in other words, the complementary tip rotation in a bent position that is challenging and requires an average (range) of 6 (4-8) h of training.

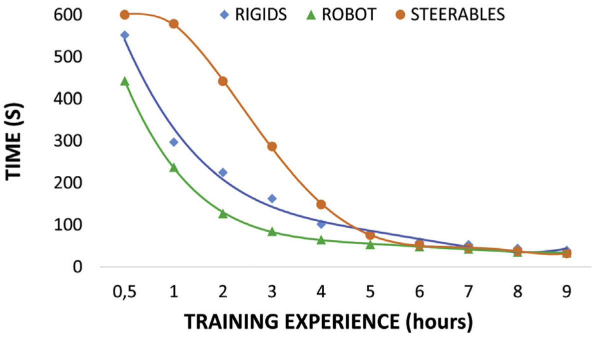

Fig. 6 – Learning curve for the three different technologies. Average time required to finish "Around the World." It takes some more time to fully control the Steerable, but after 6 h of training, proficiency levels were all reached. (Color version of figure is available online.)

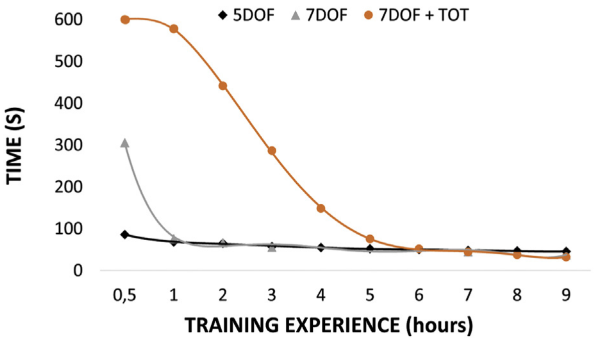

Fig. 7 – Learning curve for the different DOF modalities within the Steerable. Five DOF measured during simple peg transfer, seven DOF during coaxial alignments in eyelet and full seven DOF with TOT during "Around the World" suturing. The full seven DOF with TOT is more demanding for the coordinative capacity of the surgeon and requires more initial training but eventually allows intuitive dexterity. (Color version of figure is available online.)

Final performance testing

The results of the final testing (Fig. 8) demonstrate superiority of the seven DOF technologies. The time to perform the complex suturing pattern with a rigid instrument in a vertical position was 688 s. The 95% confidence intervals are visualized. The mean ± SD time required to perform complex suturing tasks (combined H and V) was 279 ± 90 s with the da Vinci and 279 ± 53 s with the Steerable, which is 2.3 times faster than the 662 ± 308 s with traditional rigid instruments ($P < 0.001$). Whether it is computer processed or human brain processed, both seven DOF technologies arrive at almost the same scores ($P > 0.99$). The seven DOF technologies also demonstrate a smaller spread. The final testing performed by expert surgeons revealed 743 ± 145 s with the rigid instruments and 185 ± 36 s for the robotic surgeons. This indicates that the students had reached an adequate proficiency level for off-axis suturing. It also demonstrates that using the robot can be up to four times faster in executing complex suturing patterns.

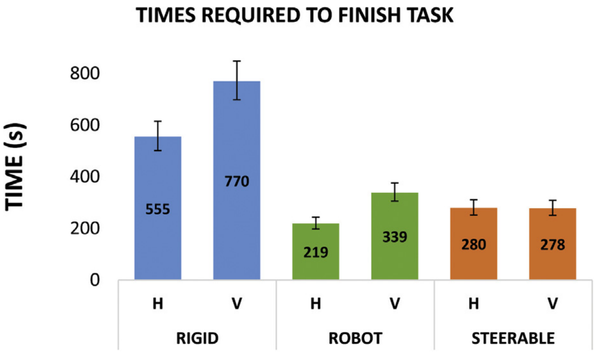

Fig. 8 – Time required to perform the complex suturing pattern. In horizontal (H) position and vertical (V) position. Histogram shows mean values and 95% confidence interval. (Color version of figure is available online.)

Pain scores

Pain rating was based on a visual analog scale using emoticons. The higher the score, the more pain was experienced by the operator (0 = no pain, 100 = worst pain possible). The students noted most strain in shoulders (moderate pain, 40 ± 24) and wrist (mild pain, 15 ± 17) while using the rigid instruments. Although the students had reported pain during the early training phase, the results of the final testing show no wrist complaints after using the robotic system nor after using the Steerable (Fig. 9).

Discussion

Since the shift toward laparoscopy as a viable alternative to open surgery, the quest to restore to the surgeon's hand a high level of dexterity and feedback in relation to motions of an instrument inside of the human body has proved to be challenging. To a large extent, current robotic systems have managed to fulfill most of these demands, albeit through sophisticated human–machine interfaces, real-time data processing, and electromechanical actuators. Simultaneously, there is a pursuit to achieve the same effects without the complexity or expense.

Precise suturing in minimal access surgery has been regarded as an advanced skill.[12] This skill is particularly difficult to master when the suture line and the axis of the needle holder are perpendiculars. The reduced instrument dexterity is mainly because of the absence of wrist-like movements at the tip of the instrument. Awareness of this disadvantage increases in more complex endoscopic procedures, restricted spaces, and single-port surgeries (characterized by "sword fighting" of the instruments).

The Steerable platform manages to significantly augment instrument dexterity by adding two independent DOFs that are exclusively controlled by the surgeon's wrist. *In vivo* testing illuminated that the dexterity facilitated complex procedures such as vesicourethral anastomosis after prostatectomy,[13] partial nephrectomies requiring perpendicular cutting around the tumor and rectopexies in the small pelvis. In distinct "complex" suturing tasks with difficult off-axis approaches such as in ventral or inguinal hernia repair, we may anticipate a particular advantage of the steerable instruments.

Instrument dexterity

Mastering a full seven DOFs articulated instrument requires additional training, ideally stepwise. Initially, the Steerable instrument was used by the trainees as a conventional rigid instrument having five DOF. The most difficult part when using a rigid instrument is to overcome the fulcrum effect. The fulcrum effect is explained by the length of the instrument that pivots at the level of the trocar inserted in the abdomen. A movement of the handle to the left pivots the whole instrument to move the tip end to the right. Novices

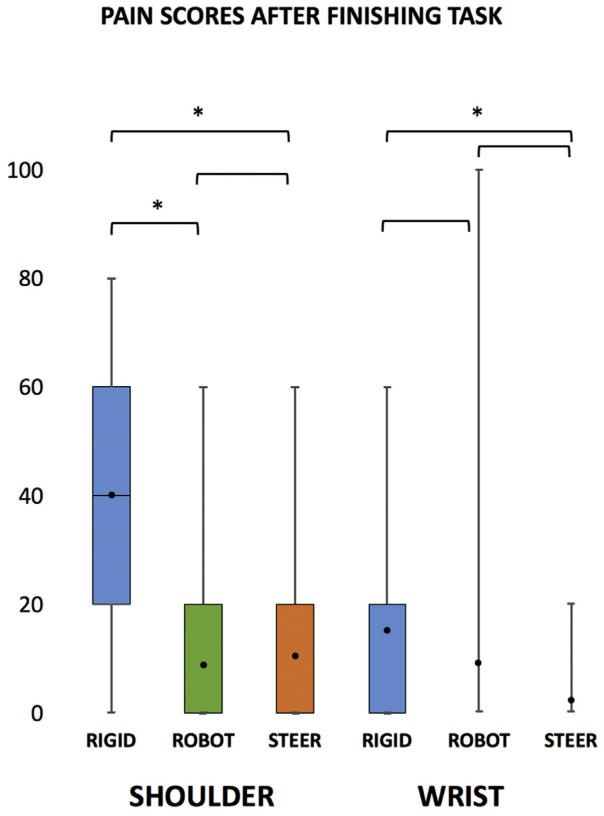

Fig. 9 – Pain scores in the wrist and shoulder after finishing the final complex suturing with different surgical instruments. The higher the score, the more pain experienced. The dot represents the mean. (Color version of figure is available online.)

adapted surprisingly quickly to these inversed movements in a pick and place task and reached proficiency after less than half an hour of training (Fig. 7).

Next, the Steerable device was used by the trainee in a seven DOF mode without tip rotation. This involves a combination of two movements: first, the surgeon's wrist movement that controls the direction of the tip and, second, the arm movements that control the direction of the shaft. By reversing the handles, the Steerable is constructed in such a way that these two movements do not influence each other (no crosstalk), resulting in a fast learning curve of about 1 h to reach proficiency (Fig. 7).

The third and highest level is very demanding for the coordinative capacity of the surgeon: A pronosupination rotation of the surgeon's wrist is added to the other two movements to rotate the tip. Especially during needle insertion for suturing, a TOT from the surgeon's forearm resulting in a rotation of the tip, even in a bent position, is of utmost importance. If this movement needs to be initiated by a finger-controlled rotating knob, as in current articulated instruments, the intuitive character is completely lost. Catherine *et al.*[14] recently concluded that existing articulated instruments indeed lack axial rotation in a fixed bending or the ability to use the two additional DOFs simultaneously like in the da Vinci's decoupled DOFs.

Figure 7 shows it generally takes about 3 h before this complex combination of movements is understood. Once this maximum level of control is reached, the further learning curve is fast, reaching a proficiency level after 6 h. Once this is mastered, an enhanced freedom is available for surgery. Based on the results—similar to those of the robotic solution—it can be stated that the human brain is indeed capable of controlling seven DOF.

Hardware and software algorithms in the da Vinci robot liberate the surgeon from the troublesome fulcrum effect, the complex coordination of wrist movements, and the TOT from the forearm. This results in a rapid adaptation of the controls. Some novices managed to perform the "Around the World" task after only 30 min of training.

Rather surprising is the contrast between the fast learning curve[15] and the poor final testing results observed with the traditional rigid needle holder. This can be explained by an unanticipated effect of the research setting: the participants were educated in how to drive a needle by experienced surgeons. During this manipulation, the axis of the suture line in relation to the needle driver is paramount. When both axes are parallel, driving a needle is easy. Once the angle changes and off-axis suturing is required, fine adjustment of the angle of the needle onto the needle holder becomes essential. During a cross verification maneuver, the angle can be evaluated and checked against the anticipated path that the needle will blindly follow. Once the driving process has started, however, no further control or steering of the needle trajectory is possible. After a few hours of training, the participants had already memorized the needle angle for the four different suture directions in the "Around the World" test. As soon as a slightly different suture line was presented, the participants could not rely on their memorized angles and had to fall back to the cross-verification maneuver, which is time-consuming and requires several "trial movements." A problem in rigid instruments is that once the piercing is initiated, the further trajectory is totally blind and almost impossible to readjust. It is worth noting that also in clinical practice, unless the tissue would be firmly manipulated, a second attempt for correct needle positioning can only be attempted after the initial movement is completed, often resulting in undue tissue damage. This is generally anticipated by good advance planning of the most ergonomic site for the trocar placement.

Our results are consistent with Tuncel *et al.*,[16] who compared rigid and articulating needle drivers. He concluded that in surgically naive medical students, laparoscopic skills were learned more quickly with the conventional needle driver than with the existing articulated instruments. We can only confirm this observation but should add that once mastered, the possibilities of seven DOF + TOT manually operated instruments are substantial. Tuncel advises a locking mechanism to prevent unwanted motions when pressure is applied. The more stable steering mechanism renders such a locking mechanism obsolete. Moreover, because the locking mechanism interferes continuously with the required freedoms of movement, elimination of this requirement improves the dexterity of the instrument and the swiftness of the execution. Also interesting is that Tuncel concludes that changing the angle of the suture by moving the hand in the opposite direction is counterintuitive. This problem is solved in the Steerable platform by reversing the handles.

Many authors[17,18] concluded that thumb-controlled articulated instruments outperform the wrist-controlled articulated instruments. This seems contrary to the observation that a human digit has several times less available force compared with the wrist. The thumb control is mostly supported in their further articles where they advise adding a "locking" feature to avoid uncontrolled movements while maintaining the tip of the instrument at a constant angle. Again, it is our opinion that the intuitiveness is diminished using a locking feature; it downgrades the articulated instrument to a prebent fixed instrument.

Many studies including articulating surgical instruments mostly incorporate only a short training time to allow novices to familiarize themselves with the complex instruments. Martinec *et al.*,[4] for instance, provided only 20 min, whereas Heemskerk *et al.*[19] evaluated after 5 min of training. Because a learning curve of hours is required to reach a sufficient level of proficiency, in our opinion, it does not make sense to perform evaluations without solid training.

The importance of 3D visualization in combination with seven DOF technologies cannot be overstressed. Very early on during training, we observed that a lack of depth of vision affected the fluent 3D movements of the instruments. Further research will be required to quantify the importance of 3D vision in concert with steerable devices.

A known limitation of the da Vinci robot is the lack of haptic feedback. This is partially compensated by an optimal 3D visualization, but notably, out-of-view accidents can cause serious injury. Owing to internal friction and compliant subparts of the wrist technology, the feedback remains difficult to implement. In contrast, the feedback of forces is an inherent trait of manually controlled articulated instruments, which was also confirmed during the training. Although controlling the da Vinci robot came with an initial quick learning curve, the students had to invest additional time to avoid needle jumping and suturing pad ruptures, arguably attributed to the lack of haptic feedback.

Strain

Contrary to our expectations, during the first hours of training, more wrist strain was reported using the da Vinci robot and the Steerable platform. However, once the use of the wrist becomes second nature, the complaints disappeared almost entirely. The lack of instrument dexterity in the rigid devices is compensated by a greater involvement of movements of the surgeon's shoulder. This is reflected in a remarkably higher pain score for the shoulder associated with rigid instruments.

Our results are consistent with those of Santos-Carreras[20] who found that during laparoscopic surgery, the main complaints were at the shoulders (41.9%). None of the surgeons complained about wrist pain while performing robotic surgery, whereas 20.9% complained with rigid instruments.

The present study illustrates the significant ergonomic problems in laparoscopic surgery using rigid instruments. It is remarkable that although the surgeon's wrists are more used in the robotic and Steerable instruments, the 7 DOF available apparently alleviates wrists and shoulder pain. While using a rigid instrument, it is an intuition to move the wrist to effect a movement of the tip, but such wrist movement must be suppressed through learning as it leads to an erroneous movement of the tip.

Study limitation

The goal of this study was to measure the dexterity of one instrument and to compare the results across the three different instruments. It can be anticipated that if the tasks would have been performed using two rigid needle holders, as favored by some surgeons, this would have resulted in quicker times compared with using one rigid needle holder. It is noted that also the da Vinci Robot and the Steerable would have performed better compared with the respective single instrument setup if bimanual dexterity would have been allowed.

The final testing (Fig. 8) shows the striking advantage for the seven DOF instruments offered by the da Vinci Robot and the Steerable platform. However, this final test only reflects a manipulation in a difficult-to-reach area with many off-axis suturing positions in which the tissue cannot be manipulated.

The final performance test, purposely designed to evaluate dexterity in difficult off-axis suturing, was not validated so far. The goal is to test and to compare the technologies, not the surgeons. It might be a basis for benchmarking seven DOF instruments.

Although the students had an intensive 27-h training, there is no comparison with the abilities and comfort that advanced laparoscopic surgeons have developed over a long learning curve.

During the training, the individual video recordings were not used as feedback method. This might have accelerated expertise gain. This may be useful to consider in further research.

Conclusions

TOT or the independent use of the additional two DOFs in combination with reduced crosstalk is probably the most important feature in enhancing instrument dexterity. There is an initial price of a longer learning curve but once mastered, the payoff is an enhanced surgical freedom of movement for a manual instrument.

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Disclosure

F.D. and A.K. report shares in Steerable Instruments, and they are inventors on several steerable-related patents. The Flemish government required a legal entity to receive funds for research and development. The company Steerable Instruments provided the articulated instruments, Karl Storz the rigid instruments and the 3D visualization system, and ORSI organized the robotic training.

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Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jss.2019.01.005.

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