Comparing a Mechanical Analogue With the Da Vinci User Interface: Suturing at Challenging Angles

Patrick L. Anderson, Ray A. Lathrop, S. Duke Herrell, and Robert J. Webster, III

***Abstract*—The da Vinci Surgical System offers a natural user interface and wrist articulation, which enable suturing and other complex surgical actions in confined spaces. However, both the one-time cost of the system and the recurring cost of the limited-use instruments remain high. This has motivated the development of several hand-held alternatives—some partially motorized, some fully mechanical—in recent years. While a few of these have been commercialized, none have yet met with broad commercial success comparable to the da Vinci robot. In this letter, we suggest a user interface-based explanation for this, and describe a new mechanical instrument that provides wrist articulation with a novel user interface. We provide results of a single-user pilot study with an experienced laparoscopic surgeon to compare the new device with a traditional wristless laparoscopic tool, a prior commercial wristed mechanical tool (the RealHand), and the da Vinci robot, in the context of suturing at challenging angles. We observe better targeting of desired suture needle entry and exit points with the new device in comparison to prior wristed and wristless mechanical instruments, with the da Vinci only slightly outperforming the new tool.**

***Index Terms*—Surgical Robotics: Laparoscopy, Medical Robots and Systems.**

I. Introduction

The importance of minimally invasive surgery (MIS), in which straight, rigid surgical instruments are inserted into the body through small incisions, has grown significantly over the past two decades. This trend is expected to continue: the global market for MIS is projected to reach $50 billion in 2019 [1]. The short-term patient benefits of MIS compared to traditional open surgical procedures are well documented, including smaller incisions, less blood loss, less postoperative pain, and shorter hospital stays (e.g., see [2], [3], and [4]).

However, manual laparoscopy is not without significant challenges, many of which involve the instruments themselves. Manual laparoscopic tools are long, rigid, and typically do not have a wrist joint at the end effector. In addition, the pivot point created by the abdominal wall inverts the movements of the handle from those of the end effector. This "fulcrum effect" makes laparoscopic techniques more difficult to learn for the surgeon [5]. For these reasons, intracorporeal suture placement, an essential aspect of MIS, is considered to be an advanced surgical skill and perhaps the most difficult part of reconstructive MIS [6].

Robot-assisted surgery (RAS) provides the desirable patient benefits of manual laparoscopic surgery without the drawbacks of cumbersome, counter-intuitive traditional tools. RAS enables three dimensional visualization of the surgical field, gives the surgeon more degrees of freedom, negates the fulcrum effect, and damps hand tremors [7]. A key feature offered by robotic systems is tiny mechanical wrists. When performing open surgery, surgeons can make full use of their dexterous, specially-trained hands and wrists. This ability is severely hindered during minimally invasive surgery because manual tools do not have articulating wrists. A robot, however, can have miniaturized wrists driven by cables and controlled by software, reducing surgeon fatigue and enabling surgeons to perform intricate surgical techniques in a minimally invasive setting.

The da Vinci Surgical System [8], of Intuitive Surgical, Inc., offers the benefits of RAS discussed above and is projected to be used for 600,000 procedures worldwide in 2015 [9]. However, the benefits of the da Vinci system are associated with substantial financial costs. The initial cost of a da Vinci system ranges from $1.3-$1.7 million [10], [11], with an additional annual service contract of approximately $150,000, and instruments that must be replaced after a small number of uses. It has been estimated that use of the da Vinci robot adds $1,500 to the cost of each surgery [10]. Furthermore, the high up-front costs of purchasing the base system must be amortized over many cases, making the purchase of the da Vinci robot unfeasible for low-volume or economically-disadvantaged centers.

Several efforts have been made to design dexterous laparoscopic tools that address both dexterity (i.e. degrees of freedom offered at the end effector) and the price gap between inexpensive, rigid manual tools and expensive, sophisticated RAS systems. Some tools, like JAiMY by EndoControl [12], are partially motorized; others, such as the RealHand by Novare Surgical Systems, Inc., are completely mechanical devices [13]. Despite a variety of proposed solutions to the dexterous tool problem, none has yet been as widely adopted as the da Vinci or traditional manual laparoscopic tools.

In this letter we suggest without proof a user interface-based explanation for this. We then proceed to the most important contribution of this letter, which is a description of a new design for a manual laparoscopic tool that places handle articulation within the user's grasp, at a location analogous to the da Vinci

Manuscript received August 31, 2015; accepted January 16, 2016. Date of publication February 11, 2016; date of current version March 8, 2016. This paper was recommended for publication by Associate Editor I. I. Iordachita and Editor K. Masamune upon evaluation of the reviewers comments. This work was supported by a maturation grant from Vanderbilt Center for Technology Transfer and Commercialization.

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Digital Object Identifier 10.1109/LRA.2016.2528302

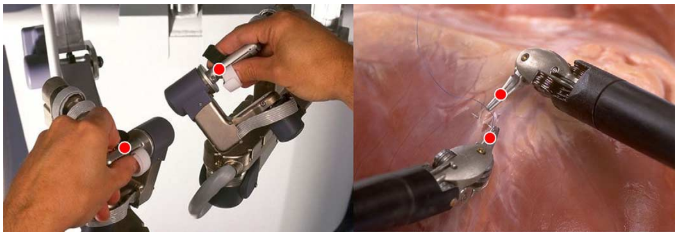

Fig. 1. The da Vinci robot user interface maps motion of control points located between the user's fingers to corresponding control points on the instruments inside the patient. Image source: http://www.intuitivesurgical.com/, control point illustrations added.

robot's user interface. Lastly, we present a single-user comparison of our new device with a traditional laparoscopic tool that lack a wrist, a previously commercialized articulated manual tool (the RealHand from Novare Surgical Systems, Inc.), and the da Vinci robot. The comparison is conducted in the context of throwing sutures at a variety of angles.

II. User Interface Kinematic Mappings

It is generally agreed that the da Vinci provides an intuitive user interface. The master-slave system creates a direct mapping of the surgeon's hand to the robot's end effector. The system provides the surgeon with a "control point" that is directly between the surgeon's fingers (Fig. 1). The surgeon interacts with the robot by applying linear and angular displacements to this control point.

In this letter we suggest that this control point concept can be applied to mechanical laparoscopic tools. The key ideas in doing so are (1) that there exists a point where both linear and angular displacements are applied and (2) that the location of this point should be within the surgeon's grasp as it is in the da Vinci system. It is important to note that we make no attempt to prove these hypotheses in this letter, but rather introduce them as the design guidelines that we used in creating our new tool.

Prior hand-held tools have sought to provide wrist articulation only, without attempting to place the control point within the surgeon's grasp. Examples include the commercially released RealHand from Novare Surgical Systems, Inc. [13] and Radius Surgical System from Tuebingen Scientific Medical GmbH [14], [15], as well as the FlexDex [16] which has not yet been released commercially. Fig. 2 illustrates the location of the control point for each of these devices.

The RealHand (Fig. 2b) has a pistol grip with a control point located where the pistol connects to the tool shaft. This forces sweeping, arc-shaped motions of the surgeon's hand to achieve tip deflection. Ponsky et al. note that the RealHand instruments have a significant learning curve [13]. The Autonomy Laparo-Angle of Cambridge Endoscopic Devices, Inc. is a similar pistol grip-style dexterous laparoscopic tool that also places the control point in front of the user's hand [13], [17].

The Radius (Fig. 2c) [15], [18], [19] has a handle that pivots about a point below the user's hand, which controls unidirectional wrist angulation relative to the tool shaft. The wrist can be spun axially (with respect to the tool shaft) by a thumb knob at the tip of the handle above the user's hand. Waseda et al. acknowledge that manipulation using the Radius is significantly different from traditional manual laparoscopic tools and that tip rotation is less intuitive than robotic systems, and therefore suggest long practice times with the tool.

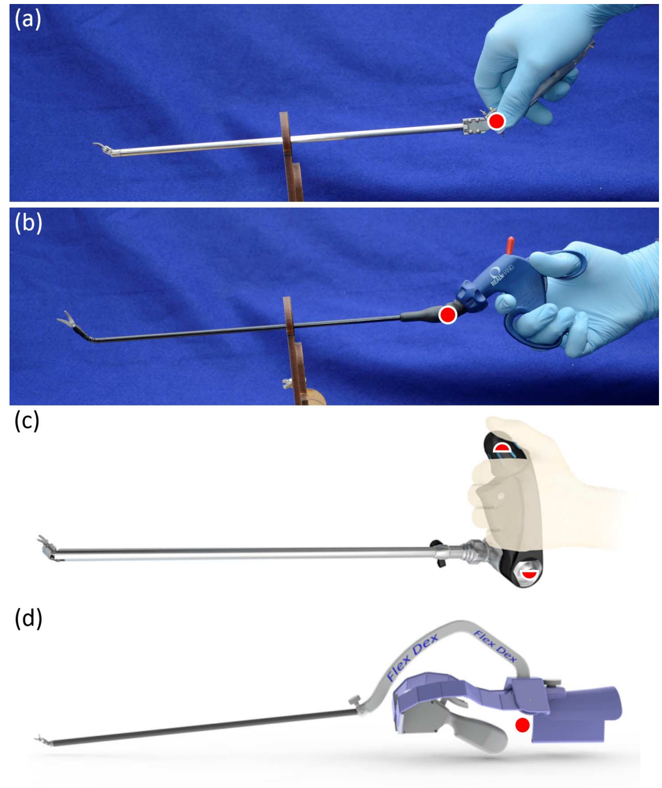

Fig. 2. A comparison of control point location for ⓐ the new tool described in this letter, ⓑ the RealHand, ⓒ the Radius, and ⓓ the FlexDex instrument. The new tool is the only one that places the control point within the user's grasp as the da Vinci robot's user interface does.

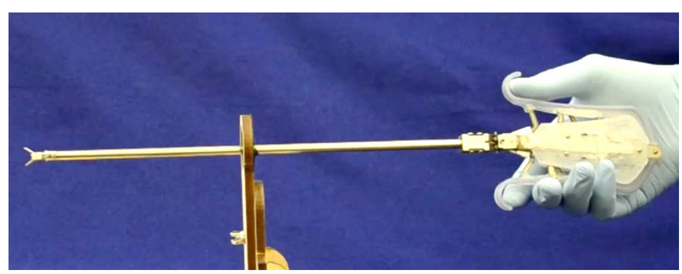

Fig. 3. The dexterous tool, showing distal wrist (left), proximal wrist (right), and handle. The control point (see Fig. 2 for control point illustration) is between the thumb and forefinger, and the end effector grippers are closed by squeezing the handle.

Another control point placement option is seen in the FlexDex (Fig. 2d) [16], which places the control point at the center of the user's wrist. While the wrist-to-wrist mapping is appealing in the sense that the device's tip angle mimics the surgeon's hand angle, the approach imposes some logistical challenges. First, it is not as easy to pick up and put down the FlexDex as it is for the other tools reviewed above, since doing so requires a donning and doffing procedure in which the tool is connected to a frame mounted to the surgeon's forearm. This frame also imposes the requirement that the tool

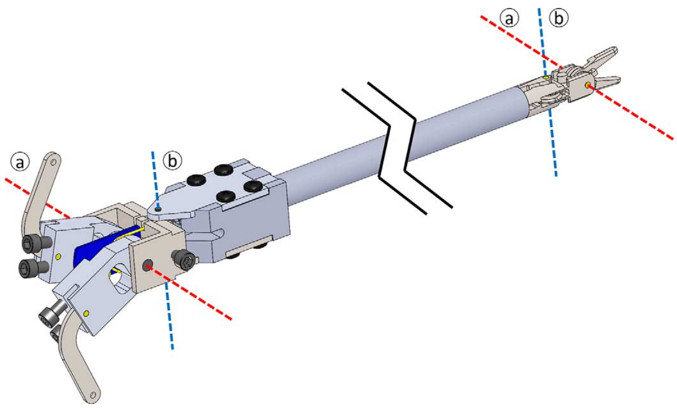

Fig. 4. Control point mapping: axes of rotation in the proximal wrist joint (left) are mapped to the distal wrist joint (right).

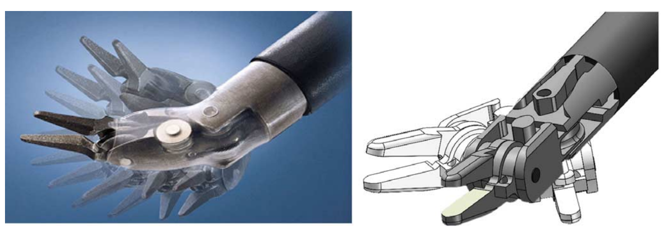

Fig. 5. The distal wrist (right) provides articulation similar the da Vinci EndoWrist (left) [20]. Cables are not shown; routing is illustrated in Fig. 6.

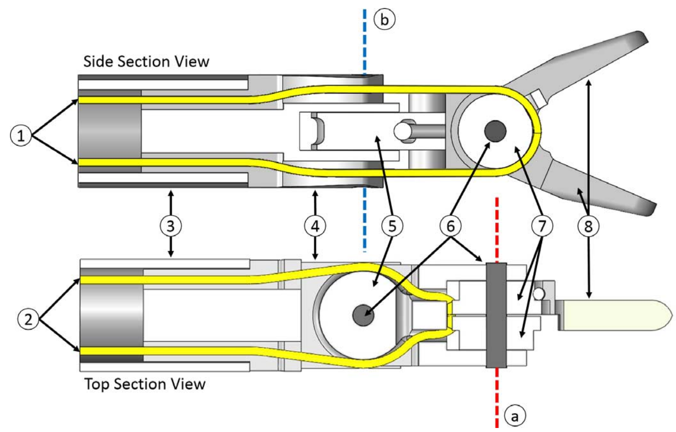

Fig. 6. Side and top section views of the distal wrist mechanism, showing ① one set of end effector gripper cables, ② lateral wrist cables, ③ rod, ④ cable guide, ⑤ lateral wrist pulley, ⑥ pins, ⑦ end effector gripper pulleys, ⑧ end effector grippers, and control axes. Cable management is addressed via the grooves shown in Fig. 5 (right).

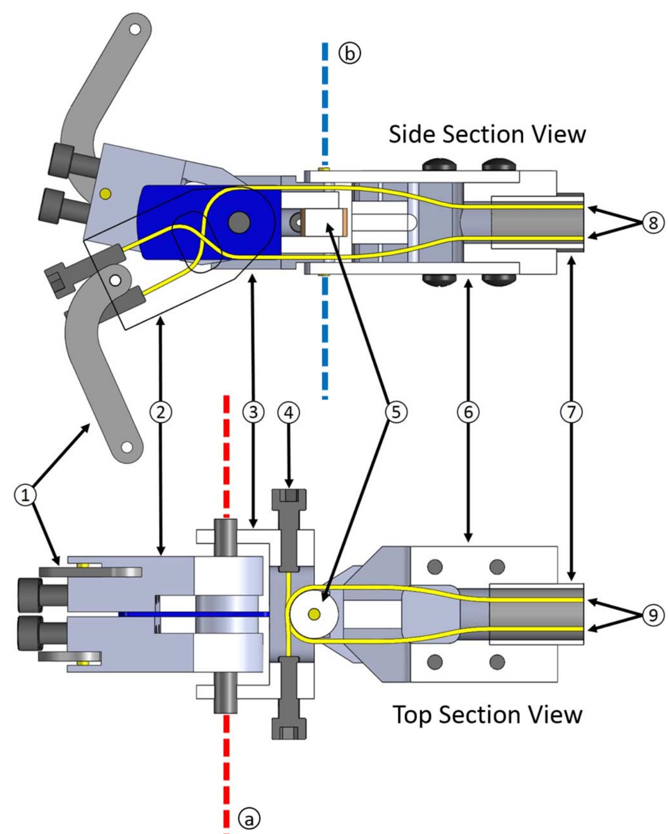

Fig. 7. Side and section views of handle mechanism, showing ① linkage connecting pulley arms to handle, ② pulley arms, ③ proximal wrist, ④ vent screw, ⑤ center pulley, ⑥ cable guide, ⑦ rod, ⑧ cables for one gripper of end effector, ⑨ cables for end effector lateral wrist pulley, and control axes.

shaft remain parallel to the surgeon's forearm, which creates ergonomic challenges in positioning the surgeon and patient in the operating room.

In subsequent sections of this letter, we describe a new design with a handle that places the control point within the user's grasp, as is shown in Fig. 2a. This tool includes a wrist that provides articulation similar to the wrist on the da Vinci robot. The design of the wrist and handle, and the manner in which they are coupled, are described in the following section. We then proceed in Section IV to describe suturing experiments with our new tool in comparison to the RealHand, the da Vinci robot, and a traditional laparoscopic tool without a wrist.

III. Device Design

To place the control point within the surgeon's grasp, our new tool includes two rotational axes in the handle mechanism (we will call these the "proximal wrist" for the remainder of the letter). These axes are perpendicular and mirror the two axes in the end effector mechanism (we will call these two axes the "distal wrist" for the remainder of the letter). Handle movements around the proximal wrist axes are mapped to rotations of the corresponding axes in the distal wrist. The tool's rotational axes can be seen in Fig. 4. These axes correspond to those in Figs. 6 and 7.

A. End Effector Mechanism

A cable-driven distal wrist gives the tool dexterity similar to the Intuitive Surgical EndoWrist (Fig. 5) that is included on standard da Vinci tools. Fig. 6 illustrates how cables are routed through the distal wrist mechanism. The side section view shows the end effector pulley system, and the top section view shows the lateral wrist pulley system. Articulation is achieved with three key components: a lateral wrist pulley ⑤ and two gripper pulleys ⑦. These components are held in place with pins ⑥. Each cable is anchored with crimps at its respective

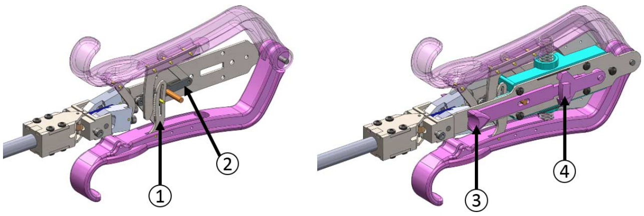

Fig. 8. Dexterous tool handle, showing ① grasp locking mechanism, ② Z-bar mechanism, ③ lock release button, and ④ lock disable switch.

pulley. This effectively creates six cable lengths (two for articulation around axis ⓑ in Fig. 4, and two for each gripper) which are routed through the cable guide ④ into the steel rod ③ and terminate at the handle mechanism. The cables are pulled by the handle mechanism to rotate the end effector about either axis. Cable ① controls gripper rotation around axis ⓐ, and cable ② controls lateral rotation around axis ⓑ. There is an additional cable used to actuate the other gripper, which is not visible in the image and is routed in the same manner as in the side section view, but is on the side of the device facing away from the viewer as shown in the side section view.

B. Handle Mechanism

Fig. 7 illustrates how cables from the wrist are routed through the handle mechanism and anchored. The side section view corresponds to the end effector gripper pulley system, causing rotation around axis ⓐ. The top section view corresponds to the lateral wrist pulley system, causing rotation around axis ⓑ.

In the top section view, a pulley arm ② controls two cables ⑧ that are connected to an end effector gripper. The cables are routed through channels in the cable guide ⑥ and the proximal wrist ③. These cables are then anchored in the pulley arm with crimps and tensioned with vent screws. An identical set of cables controlling the rotation of the other gripper about axis ⓐ are routed in the same manner and anchored in the other pulley arm. The center pulley ⑤ controls lateral proximal wrist rotation and, in turn, distal lateral wrist rotation. These cables are also anchored and tensioned in vent screws ④. For all three pulleys, the cables are crossed to minimize cable slack throughout various angles of rotation.

The proximal wrist mechanism parallels the distal wrist mechanism. Handle movements pull the cables of the corresponding end effector components. The pulley arms correspond to the end effector grippers: when the handle is squeezed and the pulley arms move toward the centerline of the device, the grippers move as the cables are pulled. The pulley arms share an axle pin, as do the gripper pulleys. As seen in the top section views of Figs. 6 and 7, the pulley arms and grippers are mirrored. With this design, the pulley arms control both grasping and gripper rotation.

Fig. 8 shows the remaining handle components. To close the end effector grippers, the handle is squeezed by the operator. This movement is synchronized by a Z-bar mechanism ② to ensure that each half of the handle moves the same distance. An additional linkage (Fig. 7, component ①) moves each pulley arm towards the center axis of the tool. Pulley arm movement

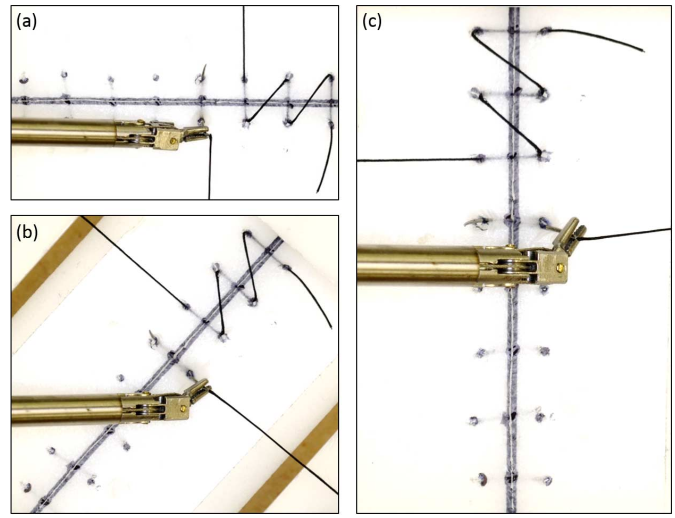

Fig. 9. Surgical tool angles for suturing experiment, showing the dexterous tool throwing sutures at ⓐ 0°, ⓑ 45°, and ⓒ 90° angles.

pulls the corresponding cables which in turn moves the wrist. Because of the symmetric design of the handle, it can be held in a variety of ways without compromising tool performance, and also rolled axially in the user's hand to create an axial rotation at the end effector within the patient, without translating it.

Importantly for suturing tasks, there is also a ratcheting locking mechanism ① included so that a needle can be grasped tightly without requiring the surgeon to constantly squeeze the handle, reducing surgeon fatigue (Fig. 8). The locking mechanism is released by pulling either of the lock release buttons ③ located on both sides of the handle. The locking mechanism can also be disabled with a switch ④ at the base of the handle for when frequent grasping is required. The entire handle is covered with a plate, allowing the tool to fit comfortably along the contours of the surgeon's palm.

IV. SUTURING EXPERIMENTS

An often-cited advantage of the da Vinci compared to traditional laparoscopic tools is the ability to throw sutures in a wide variety of directions. In particular, with manual tools that lack wrists, it is straightforward to throw sutures when the axis of the incision being closed is roughly aligned with the laparoscopic tool shaft. In contrast, it is immensely challenging to throw sutures to close an incision that is perpendicular to the tool shaft. Yet suturing perpendicular to the instrument shaft is often required in surgical procedures. One example among many is transanal endoscopic microsurgery (TEMS), where the intestine must be closed in a direction perpendicular to the intestine axis [21].

To compare the performance of several tools in suturing at various angles, a test stand was constructed to provide a mock surgical scenario. A rubber port simulated the passage of the tool through the body wall to a suturing site. The suturing site could be rotated to change the angle of the suture line relative to the instrument shaft (Fig. 9). A suturing phantom was created by covering a block of foam (Mr. Clean Magic Eraser, Procter &

Gamble, Inc.) with a flexible membrane (OPSITE FLEXIFIX, Smith & Nephew plc). In what follows, we defined the 0° angle as when the incision to be closed was parallel to the instrument shaft.

We conducted an experiment with one participant (the third author of this letter, an experienced manual laparoscopic and da Vinci surgeon) and four instruments. The subject performed suturing at a variety of angles with each of four tools: a standard laparoscopic tool without a wrist (the ENDOPATH E 705R Needle Holder from Ethicon), the new tool described in Sec. III, the da Vinci robot, and the RealHand.

In each experiment, eight targets (dots of approximately 1-2 mm diameter) were marked on the phantom with 1 cm between the targets and 1 cm between each pair. The participant was instructed to throw a running suture, aiming for each pair of two targets as the needle entered and exited the phantom. This was done by passing an Ethicon Taper SH 26 mm suture needle with NUROLON nylon suture (Ethicon, Inc.) through the phantom in a plane perpendicular to the incision. Each experiment consisted of attempting to throw four passes of the needle, while hitting the targets on both entry and exit. The surgeon was right-handed, and was instructed to insert the needle each time on the side of the incision toward his dominant hand. In the case of the 90° angle, he inserted the needle on the side of the incision furthest from him. The completed sutures had a diagonal thread pattern on the surface of the phantom. No knots were attempted as part of this experiment; rather, it focused on each tool's ability to complete the suture throwing motions and hit desired targets with the suture needle.

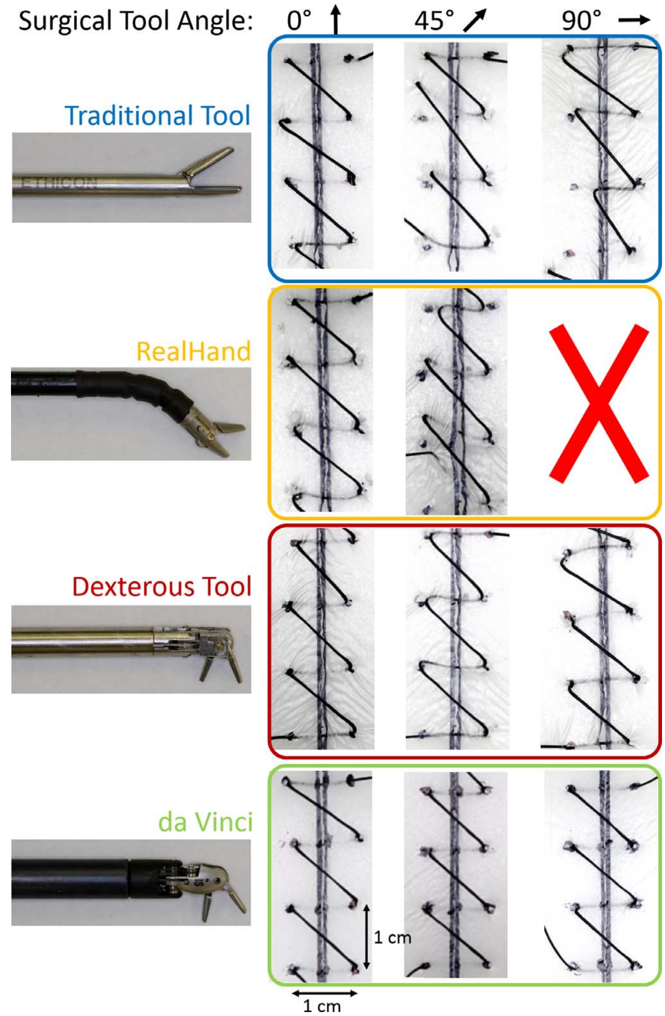

Fig. 10. Results of suturing experiment at three tool angles for, from top to bottom, the traditional laparoscopic tool, the RealHand, the dexterous tool, and the da Vinci robot. The subject was unable to complete the 90° suture with the RealHand.

V. Results

The results of the suturing experiment are shown in Fig. 10. There is one set of sutures for each tool, and each set has sutures thrown at tool angles of 0°, 45°, and 90° (except for the RealHand, which only completed the 0° and 45° cases). When the tool shaft was parallel to the incision (0°), all four tools performed well. The surgeon was able to hit all eight entry and exit targets for each tool. However, the traditional tool and RealHand performed significantly worse at other angles than both the dexterous tool and the da Vinci.

The disparity was most obvious at the 90° tool angle (incision axis perpendicular to the tool shaft): the surgeon missed all four exit targets with the traditional tool. Because the tool does not have a wrist joint, the surgeon could only throw these sutures by aligning the suture needle in parallel with the tool shaft with the tip and gradually pushing the needle backwards through the phantom. This required many regrasps of the needle on both entry and exit to force the needle into a curved path and it was impossible to use the typical rotating suturing motion. As such, suturing at a 90° angle with a traditional tool took much longer than with the dexterous tool or the da Vinci. The subject was unable to complete the sutures with the RealHand during the 90° case. During the 45° case, the surgeon performed better with each of the other tools than he did with the RealHand.

In contrast, the da Vinci demonstrated the "naturalness" of its user interface. All three tool angles produced identical results, as the surgeon was able to hit all eight targets in each case. The dexterous tool, while not as accurate as the da Vinci, was an improvement over the traditional tool and the RealHand. At the 90° tool angle, the surgeon still hit all eight targets. However, this did take longer to accomplish than with the da Vinci. These results suggest that, in the case of this surgeon, the dexterous tool produced results more like the da Vinci than like a traditional wristless tool.

VI. Discussion

It is important to note in interpreting the results in the previous section that the surgeon had thousands of hours of experience with both traditional manual laparoscopic tools and the da Vinci robot. With both the RealHand and our new tool, he had limited experience, amounting to no more than a few hours, cumulatively. He had never used either of the latter two devices in a human surgical case. Thus, these results are by no means definitive statements on what is possible with any of the various tools, since learning curves are not accounted for, and this is also only a single subject pilot study. It is also worth noting that the surgeon in question is a co-inventor of our new tool and co-author of this letter, so the potential for unintended bias does exist, and future studies will be needed with surgeons without a vested interest in any of the devices before firm conclusions can be drawn. However, the surgeon's good performance with our new tool motivates future studies on the learning curve and the control point concept we have introduced in this letter.

Another potentially important aspect of articulating laparoscopic instruments that our results do not shed light on are the effects of the kinematics of the distal wrist. The RealHand has an endoscope-like circular bending section that connects the tool shaft to the instrument tip. The FlexDex has a similar wrist design. The Radius features a wrist that bends about a single axis, but in one direction only. Our new device uses a da Vinci-like configuration with perpendicular axes that articulate in both directions. It is unclear at present if there are inherent advantages or disadvantages in particular distal wrist kinematic architectures.

It is also worth noting that dexterous laparoscopic tools can have either a "parallel" or "anti-parallel" kinematic mapping. In the parallel case, the mapping of the control handle and end effector is such that the central axis of the two remain approximately parallel during articulation. The anti-parallel case is the reverse of this mapping. In the case of the new tool described in this letter, we have constructed prototypes with both mappings. The only difference between them is that in the anti-parallel mapping, the control cables pass through low friction helical guide channels that twist them 180° as they pass through the instrument shaft, whereas the control cables run straight from one end of the device to the other to create the parallel mapping. The design used in the suturing experiment in this letter was anti-parallel. We expect both mappings to be useful, and which is preferred will depend on both surgeon preference and the ergonomics of particular procedures. For example, the parallel mapping tilts the surgeon's hands away from one another when tool tips touch inside the patient, and may thus be useful when tool shafts must remain near one another along their entire lengths, as in TEMS or throat surgery. In contrast, when wide triangulation is possible, as in some abdominal procedures, the anti-parallel mapping will likely be more comfortable, since it will put the surgeons hands nearer to one another when tool tips touch within the patient.

VII. Conclusion

We have presented the design of a novel articulated manual laparoscopic tool that offers wrist dexterity within the patient. We introduced the idea as a topic for future study that placing the user interface control point within the surgeon's grasp, in a location analogous to the control point of the da Vinci Surgical System, is beneficial for making articulated tools easier to use. We performed a single-user pilot study exploring suturing at challenging angles, observing better user performance in hitting desired targets with the new tool design than with the RealHand or traditional wristless manual laparoscopic tools. Indeed, the results with the da Vinci robot were only slightly better than the new tool.

This initial pilot study motivates future studies with more users to explore learning curves, the effects of wrist kinematics, parallel vs. anti-parallel mappings, and the effects of various control point locations. However, the fact that the surgeon was able to throw the sutures needed to close an incision perpendicular to the tool shaft entry axis with our new tool is a promising result. It illustrates that mechanical tools with the right user interfaces may one day be able to encode benefits traditionally associated solely with robotic systems into lower-cost surgical instruments. This may one day bring the advantages of surgical robotic systems to hospitals that today simply cannot afford the high price tag of modern surgical robotic systems.

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