Expert Review of Medical Devices

ISSN: 1743-4440 (Print) 1745-2422 (Online) Journal homepage: http://www.tandfonline.com/loi/ierd20

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Patrick L. Anderson, Ray A. Lathrop & Robert J. Webster III

EXPERT REVIEW OF MEDICAL DEVICES, 2016
VOL. 13, NO. 7, 661–672
http://dx.doi.org/10.1586/17434440.2016.1146585

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REVIEW

# Robot-like dexterity without computers and motors: a review of hand-held laparoscopic instruments with wrist-like tip articulation

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

Mechanical Engineering, Vanderbilt University, Nashville, USA

**ABSTRACT**

**Introduction:** Conventional manual laparoscopic instruments for minimally invasive surgery have limited dexterity within the patient, making procedures challenging. Surgical robotic systems offer enhanced articulation, but at substantial financial costs. This has motivated the development of high-dexterity, low-cost laparoscopic instruments.

**Areas covered:** This article reviews both commercial and academic results on creating fully mechanical (i.e. non-robotic) laparoscopic instruments that provide wrists or wrist-like dexterity within the patient. We review the state of the art in the development of these mechanical instruments, focusing on the surgeon interface, wrist mechanism, and the kinematic mapping between the two.

**Expert commentary:** Current articulated mechanical laparoscopic instruments exhibit a wide range of designs, with no clear consensus on what makes such devices easy to use. As these technologies mature, user studies are needed to determine surgeon preferences. Articulated, low-cost instruments have the potential to impact the minimally invasive surgery market if they provide compelling benefits to surgeons.

**ARTICLE HISTORY**
Received 23 November 2015
Accepted 22 January 2016
Published online 1 July 2016

**KEYWORDS**
Surgical robotics; manual instruments; laparoscopic; minimally invasive surgery; surgical dexterity; wrist; abdominal procedures

## Introduction

Minimally invasive surgery, in which surgical instruments are inserted into the body through small ports, has been widely adopted because of its well-documented patient benefits compared to traditional open surgical procedures. These benefits include smaller incisions that result in smaller scars, less blood loss, less postoperative pain, and shorter hospital stays [1–3]. The minimally invasive surgery market is projected to grow to $50 billion in 2019 [4]. The current landscape of minimally invasive surgical instruments is divided into two primary categories: conventional manual instruments and robotic systems.

Conventional manual laparoscopic instruments are long, straight, rigid, and typically have jaws rigidly attached at their tips that can open and close. These instruments are inserted into the body through ports in the body wall. The port creates a ‘fulcrum point’ along the instrument shaft, inverting the movements of the handle and the instrument tip, making laparoscopic surgery challenging [5]. Making laparoscopic surgery easier was a major motivation for the development of robotic systems for laparoscopic surgery, such as the da Vinci Surgical System by Intuitive Surgical, Inc. [6]. The da Vinci system enables three-dimensional visualization of the surgical field, gives the surgeon more degrees of freedom, negates the fulcrum effect, and dampens hand tremors [7]. A key feature offered by robotic systems is the tiny mechanical wrists robotic instruments provide, which make dexterous surgical motions (e.g. those used in suturing) much easier to accomplish. Over the past few years, robotic surgery has been employed increasingly frequently, with 600,000 procedures worldwide projected for 2015 [8]. However, the advantages of the da Vinci system are associated with substantial financial costs. The initial cost of a da Vinci system ranges from $1.3 to $1.7 million [9,10], 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 $1500–3000 to the cost of each surgery [9,10].

Over the past several years, there has been substantial interest in both academic and commercial laboratories in creating devices that can provide some of the advantages of surgical robots, but at a lower cost. Much effort has been focused on providing articulated (i.e. ‘wrist-like’) dexterity at the tip of an instrument that is more like a traditional laparoscopic instrument and less like a robot. Such instruments are also beneficial for single-port laparoscopic surgery, which seeks to further reduce invasiveness and trauma to the patient. Articulating instruments are listed as an important method for reducing instrument crowding and providing instrument triangulation at the surgical site, two important challenges for single-port procedures [11]. The purpose of this paper is to review the state of the art in manual laparoscopic instruments that provide wrist-like dexterity within the patient in a purely mechanical manner (i.e. without requiring computers and motors) and to provide a perspective on the future of these instruments.

### Important ideas and terms

A conventional laparoscopic instrument (Figure 1, top) consists of a handle, a long, straight, rigid shaft that passes through a port in the abdominal wall, and an end effector.

**CONTACT** Robert J. Webster III robert.webster@vanderbilt.edu

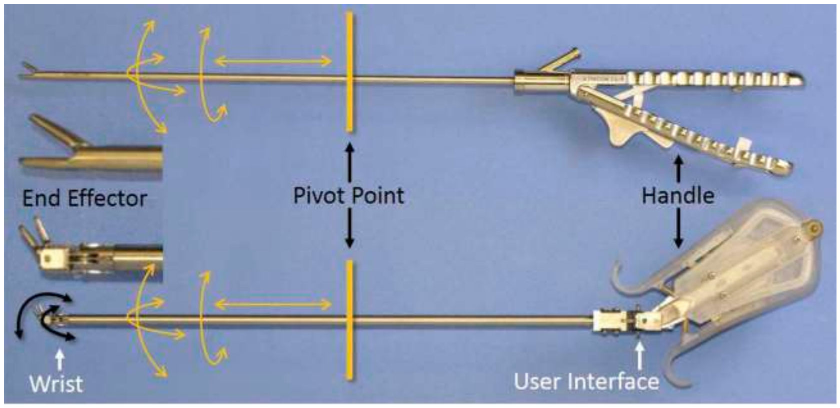


Figure 1. Comparison of a conventional laparoscopic instrument (top) to a laparoscopic instrument with a wrist (bottom). The instrument used in this example is the Vanderbilt Maestro. A variety of options are available for user interfaces and wrist designs, as reviewed in Section II.

The surgeon can open and close the handle that operates the jaws of the end effector. Due to the pivot point that is created at the port in the body wall, conventional laparoscopic instruments are limited to four degrees of freedom as illustrated in Figure 1, plus the opening and closing of the jaws.

The distinction between conventional laparoscopic instruments and the articulated instruments described in this review is the wrist-like joints located within the patient near the end effector. They typically provide two additional degrees of freedom (see example instrument, Figure 1, bottom). This wrist mechanism and the user interface for controlling the wrist with the handle are key aspects of dexterous instruments.

This wrist joint can be created with a variety of mechanisms. For a thorough review of wrist joints for steerable minimally invasive surgical instruments, see Jelínek et al. [12]. There are two basic types of wrist-like mechanism that are particularly relevant to the mechanical instruments reviewed in this paper: those that have zero bend radius when deflected and those that bend into a curved arc when deflected (see Figure 2). In the former, the jaws are typically integrated into the wrist mechanism itself, while in the latter the jaws are typically distal to the wrist and the two act as a separate mechanism.

The surgeon interface is located on the instrument handle. For a review of many control methods for all types of manual

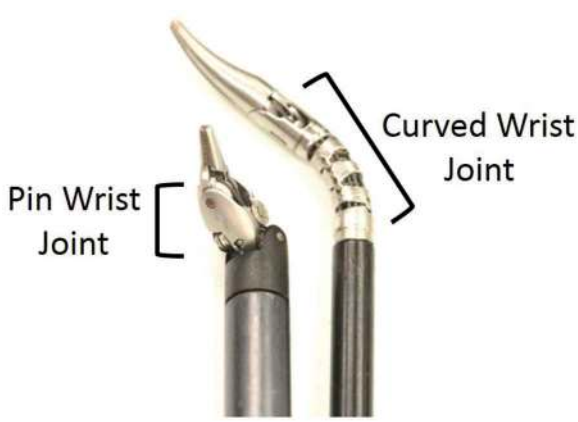


Figure 2. Examples of the two primary types of wrist articulation mechanisms used in the instruments reviewed in this paper. Wrists can be implemented as pin joints or as mechanisms that approximate an arc when deflected.

maneuverable instruments (e.g. endoscopes, laparoscopic instruments), see Fan et al. [13]. Only a subset of these apply to the instruments of interest in this paper. In particular, we identify three different ways the surgeon's hand motions can be mapped to wrist motions, which we refer to as handle control, thumb control, and mixed control (Figure 3). The handle control approach enables the handle to articulate relative to the shaft of the instrument to deflect the wrist (Figure 3a). The thumb control method has a handle that is rigidly attached to the shaft and a joystick or ball manipulated by the user's thumb controls wrist articulation (Figure 3b). In the mixed control method, each wrist degree of freedom is controlled with a separate knob or lever on the handle (Figure 3c). We term it the mixed method because it combines elements of the other two control methods.

Articulating instruments can also be classified by the direction of wrist movement when mapped to the user control interface. We describe these mappings as 'parallel' and 'reverse' (see Figure 4). In the parallel case, the mapping of the control handle (or thumb control) to the end effector is such that the central axes of the two remain approximately parallel during articulation.

## *Scope of review*

In this paper, we review manual laparoscopic tools that feature wrist-like articulation. There are several related categories of medical devices that share some similarities to the devices we review, but for various reasons fall outside of the scope of this review. Furthermore, this review addresses only those devices where we can find clear evidence of substantial development and the existence of a functional prototype. There are a variety concept sketches in the patent literature that are thus excluded because there is no evidence that a prototype was created or that development was pursued beyond the filing of the patent.

Also outside the scope of this review are the many minimally invasive surgical tools that have a pre-bent shape that does not change during use. An example of this are tools with rigid, curved shafts like those sometimes utilized in single-port surgery (Figure 5) [14]. Another group of tools has joint(s) near the tip, but these are designed to be set and then locked during active use in surgery. An example of this is the SERPENT instrument designed for sinus surgery (Figure 6) [15]. Since both of these classes of tools do not actively

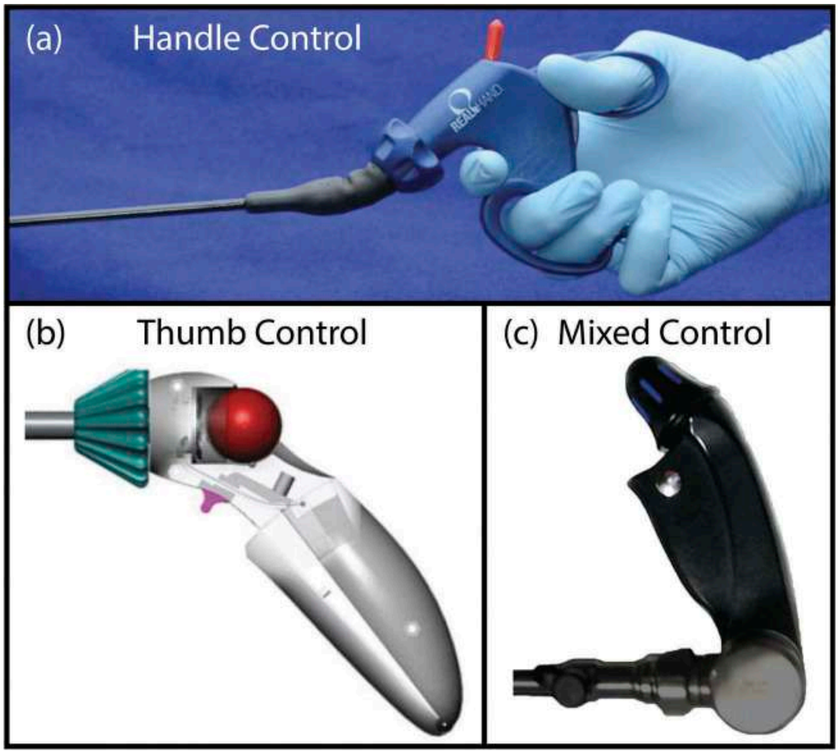


Figure 3. Control interfaces for articulated mechanical instruments: (a) handle control in which the handle can articulate relative to the instrument shaft, (b) thumb control where the handle is rigidly connected to the shaft and a thumb interface deflects the wrist, and (c) mixed control in which independent knobs and levers control various wrist degrees of freedom.

Figure 4. Kinematic mappings for laparoscopic tools with wrists: parallel (top) and reverse (bottom). The instrument used in this example is the Vanderbilt Maestro.


Figure 5. An example of a laparoscopic tool with a curved, but rigid, shaft: the KARL STORZ ROTATIP (© 2016 Photo Courtesy of KARL STORZ Endoscopy-America, Inc.).

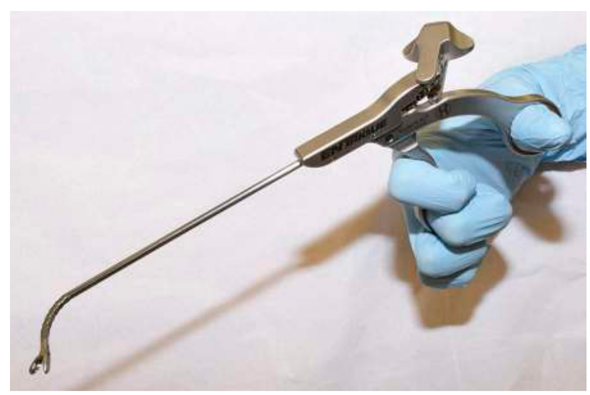

Figure 6. An example of an instrument that can be articulated, but that is designed to be locked during use: the SERPENT from Smith & Nephew [15].

articulate joints within the patient during normal surgical use, they are outside the scope of this review.

Third, there are a number of dexterous instruments that are partially motorized. For example, JAiMY by ENDOCONTROL uses motors within the device handle to actuate the wrist [16]. A number of other handheld partially motorized and robotic devices for laparoscopic surgery have been developed (e.g. see [17–19]). While incorporating motors in the handle provides additional flexibility in the mapping from the user interface to the wrist, these devices require motors and software, placing them at a cost disadvantage compared to fully mechanical instruments. These devices are outside the scope of the current review.

Lastly, we focus on only handheld devices in this review. We know of only one nonrobotic articulated device for

Table 1. Summary of articulating laparoscopic instruments.

| Device | Kinematic mapping | Wrist type | Handle design | Reusable | Entity producing or developing | Status |
|---|---|---|---|---|---|---|
| RealHand | Reverse | Curved | Pistol | No | Novare Surgical Systems, Inc. | Was commercially available, but no longer sold |
| Autonomy Laparo-Angle | Reverse | Curved | Pistol | No | Cambridge Endoscopic Devices, Inc. | Commercially available. Company filed bankruptcy, Sept. 2015 |
| SILS Hand Instrument | Reverse | Curved | Pistol | No | Medtronic (previously Covidien) | Commercially available |
| MiFlex | Reverse | Curved | Pistol/ joystick | Handle: yes End effector: no | DEAM B.V. | Unknown |
| Radius Surgical System | Neither | Pinned | Lever/knob | Yes | Tuebingen Scientific, GmbH | Commercially available |
| Maestro | Either | Pinned | Symmetric- reverse hemostat | Unknown | Vanderbilt University | Seeking commercial partners |
| FlexDex | Parallel | Pinned | Forearm mounted | Unknown | University of Michigan | Under development by FlexDex Surgical Inc. Commercial release planned for 2016 |
| DragonFlex | Parallel | Pinned | Symmetric-hemostat | No | Delft University of Technology | Unknown |
| Easy Grasp | Parallel | Pinned | Hemostat/ shaft grip | Unknown | Tianjin University | Unknown |
| Intuitool | Reverse | Pinned | Pistol/ trackball | Unknown | University of Nebraska | Seeking commercial partners |

laparoscopic surgery that is not handheld: Jaspers and Diks et al. developed a mechanical manipulator that utilizes a pantograph mechanism to control two surgical bed-mounted endoscopic arms, each with seven degrees of freedom [20,21]. While this device provides many of the advantages of the da Vinci robot in a purely mechanical form, reconfigurability is limited by the need to mount it to the surgical bed.

## Devices

In the following subsections, we review each of the basic types of mechanical surgical instruments with wrist-like dexterity. The key characteristics of each instrument are summarized in Table 1. When applicable, instruments that have several similar design aspects, such as control method and handle or wrist mechanisms, are grouped together.

### *Pistol-grip, handle-controlled devices with curved wrists*

There are at least three examples of instruments with pistol-grip handles that are handle-controlled and have curved wrist mechanisms. These are the RealHand by Novare Surgical Systems, Inc. [22]. (Figure 7a), the Autonomy Laparo-Angle Articulating Instruments by Cambridge Endoscopic Devices, Inc. [22–25] (Figure 7b), and the Medtronic-Covidien SILS Hand Instruments [26] (Figure 7c). While the user interface

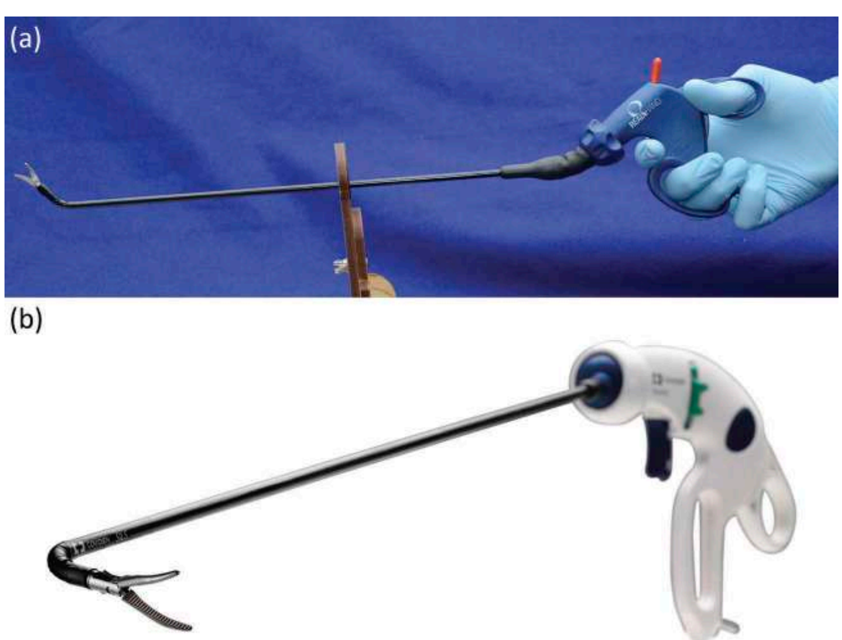


Figure 7. Articulating laparoscopic instruments with pistol grip, handle control method, and curved wrist: (a) RealHand and (b) SILS Hand Instrument. (All rights reserved. Used with the Permission of Medtronic.)

varies slightly among these instruments, the overall design of each instrument is similar. All three have a reverse kinematic mapping with a handle that articulates relative to the instrument shaft in order to control the wrist. For all three, the wrist is a curved device driven by tendons.

These instruments have several other similar features. All three of these instruments have some form of knob to enable axial rotation of the end effector independent from angulations of the instrument handle itself. The RealHand has a collar that slides over the handle joint, preventing wrist articulation for cases when the surgeon wishes to use the instrument like a conventional laparoscopic instrument. The Laparo-Angle and SILS have a wrist-locking mechanism integrated into the handle. In additional, the end effector jaws of all of these instruments can be locked, which is particularly useful for grasping a needle firmly without applying constant handle pressure when suturing. All of these instruments are single-use, disposable devices, and all have 5-mm-diameter shafts.

Currently, the pistol-grip, handle-controlled, curved-wrist instruments are at different stages of development. The RealHand and the Laparo-Angle are commercial products. Novare Surgical Systems, Inc. no longer has products on the market. Cambridge Endoscopic Devices, Inc. filed for Chapter 11 bankruptcy in September 2015 [23]. The SILS Instruments are currently available commercial devices offered by Medtronic.

Noteworthy features and advantages of these pistol-grip, hand-controlled devices include the fact that they are the most commercially mature of any of the categories that follow, with several examples already having been brought to market. The fact that they can be made as single-use disposable devices may also be noteworthy. These devices work under the hypothesis that the handle design (i.e. pistol grip) should be changed as little as possible from the interface of many standard laparoscopic devices when one wishes to create an articulating device. This is a hypothesis that the designers of several of the other devices described below dispute and believe to be one of the reasons that these pistol-grip devices are not more widely used. They argue that the need to sweep the user's hand through a large arc simply to deflect the wrist causes these instruments to be challenging to learn to use (this was also noted by Ponksy et al. [22]) and also causes them to apply undesirable forces to the body wall where the device shaft enters the patient.

### *Tuebingen Scientific Radius Surgical System*

The Radius Surgical System by Tuebingen Scientific GmbH is a reusable instrument that uses the mixed control method [27] (see Figure 8). The wrist deflects unidirectionally with respect to the shaft as the handle is articulated relative to the shaft of the device, and axial rotation of the shaft is achieved via a thumb knob. A large, multifinger trigger on the handle operates the jaws of the end effector. The end effector cannot be locked [28]. The operating mechanism does not use cables, but rather uses a system of gears to deflect and rotate the end effector. The instrument shaft diameter is 10 mm, which is larger than the commercial pistol-grip, handle-controlled devices, which are typically 5 mm in diameter. Several authors argue shaft diameter as a disadvantage for the Radius [29–31]. The Radius Surgical System is sterilizable and can be disassembled for cleaning [27]. Due to its unique handle mechanism that decouples the wrist degrees of freedom, the Radius cannot be categorized as having either a parallel or reverse kinematic mapping.

The Radius has been the subject of a number of user studies and in vivo trials [29–37]. As of 2013, the Radius had been used in 260 clinical procedures worldwide [33]. Reports on the instrument's learning curve vary. DiLorenzo et al. noted differences between experienced surgeons and novices and stated that the learning curve 'is not so complex' [32]. Frede et al. state that 'compared to our experimental experiences with conventional reconstructive laparoscopic surgery the learning curve of the [Radius] is significantly shorter', and that even complex tasks such as complete urethro-vesical anastomoses 'require less than 10 trials to maintain a good quality of performance' [29]. However, when performing colorectal anastomosis in a phantom model, Torres Bermudez et al. found a learning curve of 21 procedures before no reduction in completion time was observed [36]. Waseda et al. acknowledge that manipulation using the Radius is significantly different from traditional manual laparoscopic instruments and that tip rotation is less intuitive than robotic systems, and therefore, suggest long practice times with the instrument [37].

Regardless of the learning curve required to achieve proficiency with the Radius, all of these studies found that the instrument provided improved dexterity at the surgical site for a variety of procedures, including perpendicular suturing during transabdominal preperitoneal hernioplasty, closure of the common bile duct opening during single-site stone removal, and mesh fixation in animal organs to repair inguinal hernia. The studies also noted improved ergonomics in comparison to conventional laparoscopic instruments. It has also been noted that the Radius avoids forced wrist flexion and exaggerated shoulder and elbow angles that occur with conventional instruments [36].

It is also worth noting that Tuebingen Scientific has developed other dexterous handheld laparoscopic instruments that are not as well documented in the literature as the Radius. The r2 DRIVE has a handle design similar to the Radius, but with a

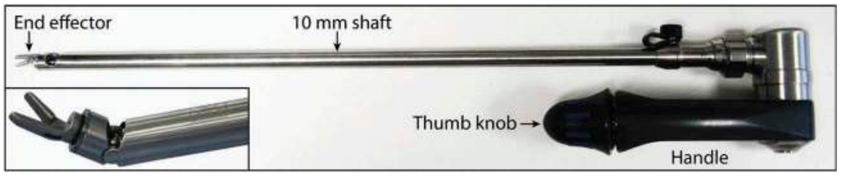


Figure 8. Tuebingen Scientific Radius Surgical System (inset figure: copyright © TransEnterix, Inc. 2015. All rights reserved).

5 mm shaft and slightly different end effector mechanism. Unlike the Radius, the r2 DRIVE is a disposable, single-use instrument [27].

Noteworthy features and advantages of the Radius concept include its physical robustness, and hence ability to last through multiple procedures and autoclave sterilization cycles. The device is designed to be cleanable and uses metal rods and gears to transmit handle motions to wrist motions, enabling it to be a reusable surgical instrument rather than a disposable one. Potential drawbacks of the design are the need to use a thumb knob to control one of the degrees of freedom and the unidirectional nature of wrist articulation. There is debate in the literature about how easy this device is to use and how steep the learning curve is. It is the opinion of the authors of this review that this device is more challenging to use than many of the other devices reviewed in this section due to the manner in which the degrees of freedom are decoupled (e.g. the surgeon must learn to mentally map thumb motions to shaft rotation, a mapping that is not present in other medical devices).

## Maestro

The Maestro is a device developed by a team of engineers and surgeons at Vanderbilt University (Figure 9). It uses the handle control method and places the axes that articulate the handle relative to the instrument shaft (which map to wrist axes inside the patient) within the user's grasp, at a location similar to that of the da Vinci Surgical System's user interface (see 'Expert commentary' for more information). The Maestro has been built with both parallel and reverse kinematic mappings. The only difference between the two is that the tendons that connect the wrist to the handle twist 180° around the shaft axis as they transit from the handle to the wrist in the reverse mapping. The Maestro features a unique symmetric handle design that can be rotated within the user's hand to generate axial shaft rotation.

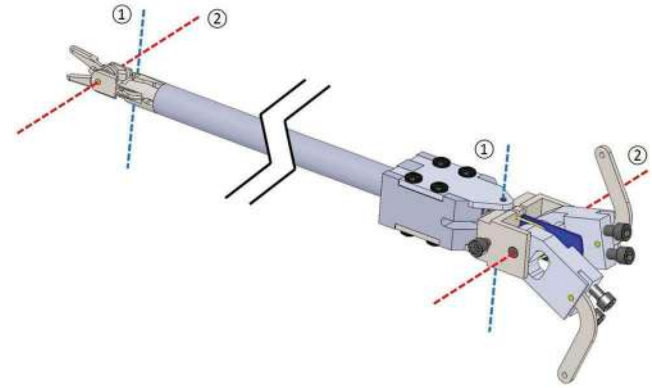


Figure 10. CAD drawing of the Maestro wrist and handle articulation axes. Two rotational axes in the handle are mapped to corresponding axes in the wrist.

The Maestro has two rotational axes in the handle that are perpendicular to one another and mirror the axes in the wrist (Figure 10). The end effector is tendon-driven via three pulley revolute joints. There are three tendons made of steel cable used in this instrument. Each cable is anchored with crimps at its respective pulley. This effectively creates six cable lengths (two for articulation around axis 1 in Figure 10 and two for each end effector jaw), which are routed through a cable guide into the steel rod and terminate at the handle mechanism. In the handle, one pulley (axis 1 in Figure 10) achieves lateral rotation, while two finger pulleys open, close, and also angle the jaws of the end effector about axis 2 in Figure 10. These axes are placed close together enabling pin-based deflection in two directions, without requiring large sweeping motions of the jaws during articulation. The surgeon can open and close the jaws on the end effector by squeezing the two handle arms toward one another. In addition, the handle has a ratcheting locking mechanism to lock the grip of the end effector jaws. The ratcheting mechanism can be disabled with a switch on the handle.

Noteworthy features and advantages of the Maestro design include the fact that the handle design places a pivot point

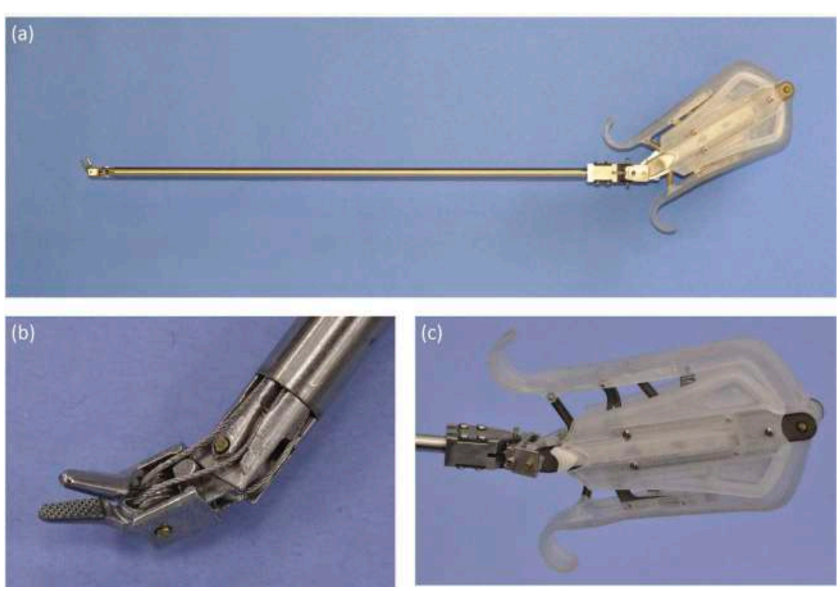


Figure 9. The Maestro articulating laparoscopic instrument: (a) entire instrument, (b) wrist, and (c) handle control interface.

between the user's finger and thumb, making it the design that most closely matches the interface of the da Vinci robot. Future experiments will be needed to evaluate whether this makes the device easy to use in surgery, as we hypothesize. The device also includes a jaw lock that clamps the jaws down (e.g. on a suture needle) with a ratcheting mechanism, while still allowing the wrist to articulate. Lastly, the handle is designed to be symmetric so that it can be rolled in the user's grasp to generate axial instrument shaft and wrist rotation.

### FlexDex

The FlexDex instrument is based on the work of Awtar et al. at the University of Michigan [38–41], and FlexDex Surgical Inc. is currently developing it as a commercial product. The FlexDex has a unique user interface in which the shaft of the device is connected by a frame to the user's forearm and the wrist articulation axes are placed at the center of the surgeon's wrist (Figure 11). The surgeon's wrist deflections are mapped to wrist deflections inside the patient by two transmission strips, yielding a parallel mapping. Movements of transmission strips are connected to pulleys in the frame mechanism, which in turn operate cables running through the frame to the end effector wrist inside the patient. Each transmission strip is stiff about one axis (the desired input axis) and highly compliant about the other axis, which helps to decouple rotations about each axis. By placing the wrist articulation axes at the center of the surgeon's wrist, the FlexDex enables wrist degrees of freedom to be decoupled from the conventional four degrees of freedom of standard laparoscopic instruments. The surgeon controls the standard four degrees of freedom with his or her forearm, and the wrist deflections with his or her wrist. One advantage the developers of FlexDex argue that their device has with respect to pistol-grip, handle-controlled devices like the RealHand is that FlexDex does not require body wall reaction forces to stabilize the instrument shaft. The FlexDex has a pin wrist joint and the jaws of the end effector are opened and closed with a thumb lever in the handle. This instrument will have a multi-segment curved wrist joint [42].

Noteworthy features of this device include the appealing concept of 1:1 mapping of surgeon wrist to instrument wrist inside the patient (this mapping can also be scaled if desired to optimize the input to output ratio). A potential challenge is the forearm attachment, which would make picking up and putting down the device more complex than it is for traditional laparoscopic instruments. Another potential challenge is that the forearm mount keeps the instrument shaft parallel to the surgeon's forearm, which may limit the surgeon's options in terms of patient and port positioning in the operating room.

Figure 11. The FlexDex articulating laparoscopic instrument (used with permission).

### DragonFlex

The DragonFlex developed by Jelínek et al. at Delft University of Technology [43–47] is motivated by the desire to provide the surgeon with da Vinci EndoWrist-like capabilities in a low-cost device. The authors seek to reduce manufacturing complexity and mitigate the drawbacks (cable fatigue, etc.) associated with running cables around small diameter pulleys. The DragonFlex (Figure 12) consists of a pair of orthogonal, offset, rolling joints that form the wrist. The joints utilize a pair of rolling gears, each with two driving cables that follow asymmetric arced guides. The rolling joints are also designed to equalize the length and forces on the cables during rotation. The joints offer a near-zero bend radius similar to that of a pinned joint. The end effector jaws are located beyond the wrist axes and are not directly integrated into them. The cables are looped around the end effector to enable jaw opening and closing. The user interface uses the handle control method and the handle is coupled to the instrument shaft using offset, orthogonal rolling joints similar to those of the wrist. The joints are mechanically similar to pin wrist joints, but the distance between the wrist and the end effector is comparable to curved wrist joints. Jelínek et al. note that future prototypes will examine joint element shortening to reduce tip displacement.

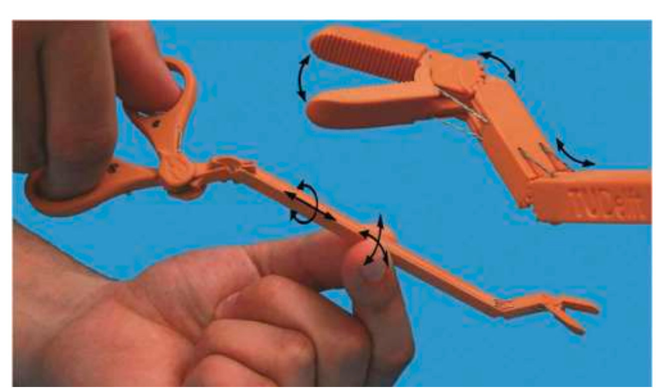

Figure 12. The DragonFlex articulating laparoscopic instrument (used with permission) [43].

The DragonFlex uses the handle control method to achieve parallel mapping. Rolling the end effector is done by rolling the instrument in the hand as was described in the Maestro section above. The published prototypes do not illustrate a locking mechanism. Two other goals of the design are to reduce joint play and cable slack [46] and to achieve high joint stiffness to external loads compared to underactuated curved wrist designs, which flex under load [47].

Noteworthy features of this device include the backlash and stiffness advantages referenced above. In addition, the DragonFlex was intentionally developed with a minimalistic design: only seven structural components and four cables comprise the entire device. This is made possible by additive manufacturing [45]. This could enable the instrument to be made in an inexpensive, disposable fashion, which the authors state is advantageous because the design would be challenging to sterilize.

### Thumb-controlled devices

There are two examples of instruments where the handle is rigidly connected to the instrument shaft and wrist articulation is activated by a thumb interface. Known as the MiFlex and the Intuitool, these both have pistol-grip handles and thumb interfaces that are connected to the wrist inside the patient using tendons or rods. They are also both designed with a reverse mapping.

The MiFlex was developed by DEAM B.V., a company started by researchers at the Delft University of Technology [48]. The handle and ergonomics were designed by Indes B.V [49]. It has pistol-grip handle, a curved wrist design, and a 5-mm-diameter shaft. The wrist is articulated using a thumb joystick mounted on the handle. The wrist angle can be locked, and there is also a ratcheting mechanism to lock the end effector jaws. Axial rotation is achieved with a knob in the handle. The handle is reusable, but the end effector is single use.

The Intuitool developed by Hallbeck et al. at the University of Nebraska [50,51] (Figure 13) uses a thumb trackball positioned in the same way that the MiFlex joystick is positioned. The trackball is held in place by spherical rings. A ball-and-socket joint in the handle transmits trackball movements to rods within the instrument shaft, which in turn articulate the wrist using a second ball-in-socket joint. The trackball enables ±60° wrist articulation. The end effector jaws are operated by a trigger in the pistol-grip handle and they can be locked with a button on the handle. There is also a knob for axial shaft rotation. UNeMed is currently seeking investors to commercially develop the Intuitool [52]. The design of the Intuitool has focused on ergonomics and human factors, following five user-centered design principles (ease of learning and use, efficiency of use, error minimization, subjective satisfaction, and accommodation), using surgeon questionnaires, and performing user studies with the goal of creating a comfortable, effective instrument [53–55].

Figure 13. The Intuitool, an example of a thumb control method articulating instrument (used with permission).

Noteworthy features of these instruments are their thumb control methods, utilizing a joystick and a trackball. Some research has been performed to compare thumb control to handle control. Zahrahee et al. suggested that a finger-operated joystick control handle is easier to use and less fatiguing than an articulated handle such as the RealHand [28]. In a comparison study of the MiFlex and Laparo-Angle, Fan et al. found no difference between thumb control and wrist control in terms of task performance, but noted that 'thumb control was strongly preferred by the participants due to the perceptive feeling in performance' [56]. Future studies are needed to compare thumb-controlled devices to other types of handle control and mixed control besides the pistol-grip, curved wrist variety. Another interesting aspect of the Intuitool is its emphasis on ergonomic analysis.

### Easy Grasp

The Easy Grasp by Wang et al. uses a rod-actuated mechanism for the same robustness reasons as the previously described Radius instrument [57,58] (Figure 14). The end effector jaws are push-pull rod-actuated and located beyond the pin wrist joint, rather than integrated into the wrist. The instrument uses the handle control method with a parallel kinematic mapping and offers ±30° articulation about two axes. Axial rotation of the instrument tip is accomplished by rolling the hemostat handle; the instrument shaft itself does not rotate, but the wrist and end effector jaws rotate within it. One feature that differentiates the Easy Grasp from other designs is that it can be used in a two-handed manner, with an optional secondary handle available to directly manipulate the instrument shaft.

Noteworthy features of this instrument include it being the only one to suggest two handed use, and the design intent of it being a reusable device. The tip articulation of ±30° is lower than many of the other devices reviewed in this section, which may be a drawback.

## Expert commentary

The articulated manual laparoscopic instruments featured in this review illustrate a variety of approaches to providing wrist-like dexterity to surgeons in a handheld, nonrobotic

Figure 14. The Easy Grasp articulating instrument (used with permission) [57].

device. The goal is to bring some of the dexterity benefits of currently associated with robotic surgery to patients and surgeons without the large financial costs of current surgical robots. Perhaps the most important factor in achieving this is providing a surgeon interface and wrist control mapping that is natural and easy to use. However, there is currently no consensus in the research community in terms of which factors make articulated devices easy to use.

For example, the best direction of kinematic mapping is currently debated. Many of the instruments presented in the previous section, including the RealHand, Laparo-Angle, and Medtronic SILS instrument, feature reverse kinematic mappings. The inventors of FlexDex, however, argue that reverse mappings are counterintuitive. It may be that neither mapping is intrinsically better than the other, but that each is best for particular surgical contexts. For procedures in deep narrow anatomical corridors (e.g. transoral throat surgery), where instrument shafts must be near parallel and close to one another, it is likely that a parallel mapping will reduce the risk of the surgeon's hands colliding. In contrast, for procedures where wide triangulation is desirable (e.g. abdominal surgery), it is likely that the reverse mapping will place the surgeon's hands in a location that is more comfortable. It is also possible that the best mapping may be a matter of surgeon preference. Much more experimentation will be needed to isolate the mapping from other elements of the various designs in order to determine the conditions under which each mapping provides better results. With many designs – particularly those using tendons – it may be possible to produce devices with both mappings and let market forces decide which is preferred.

There is similarly no consensus on the best wrist designs to employ in these devices. Many of the products that have reached the commercial market use curved wrists, while many under development employ pin joints in their wrists. An advantage of the curved wrists is that they are conceptually similar to endoscope tips, which are well-known elements in medical device design. A potential disadvantage is that the large radius of curvature requires a correspondingly large volume of space inside the patient for wrist articulation, which has motivated the development of pin joints in recent years. In addition, these wrist joints are underactuated and can produce unintended deflection under applied loads [47]. Pin joints also offer the potential of integrating the jaws into the wrist itself, which also reduces the workspace required inside the patient for wrist articulation.

Another open question in articulated instrument design is how best to transmit axial shaft rotation to the end effector. Options include a dedicated knob in various positions (e.g. Radius, Laparo-Angle) or rotation of the handle itself within the surgeon's grasp (e.g. Maestro, DragonFlex). Furthermore, some instruments rotate the shaft itself, while others rotate the end effector using mechanisms internal to the shaft without outer shaft rotation. As with other design aspects, there is no conclusive study concerning how best to achieve end effector axial rotation.

Similarly, it is unclear whether a locking mechanism for the jaws or the wrist is required or optional features. Both the Laparo-Angle and SILS Hand Instrument provide wrist locks to make the device function as a curved, rigid instrument when the surgeon desires it to do so. However, many other devices have not incorporated this feature. The same is true of jaw closure locks, which have only been implemented on a few instruments (e.g. Maestro and the pistol-grip, handle-controlled devices). Jaw closure locks are standard in traditional laparoscopic instruments designed for needle driving to enable the surgeon to firmly grasp the needle without applying constant pressure on the handle. It remains to be seen whether this feature will be required by many surgeons in order to adopt an articulated instrument in place of a traditional laparoscopic instrument.

Future work concerning articulated laparoscopic instruments should also evaluate quantifiable aspects of each instrument's performance. For example, it would be beneficial to measure and compare the range of motion about each wrist axis, the force that must be applied by the user to grasp tissue or perform suturing, the bending stiffness of the end effector, and other such quantities. One study by Jelínek et al. compared the bending stiffness of three instruments [47], but more comprehensive studies are needed for this metric and others.

Lastly, one concept that the authors of this review have found helpful in evaluating control mappings and designs for articulated laparoscopic instruments is the idea of a 'control point', which has not to our knowledge been previously discussed in the context of articulated manual instruments. One can perhaps most easily understand the control point concept in reference to master-slave robotic systems such as the da Vinci robot as shown in Figure 15. It is the point about which linear and angular motions of the surgeon's hands are

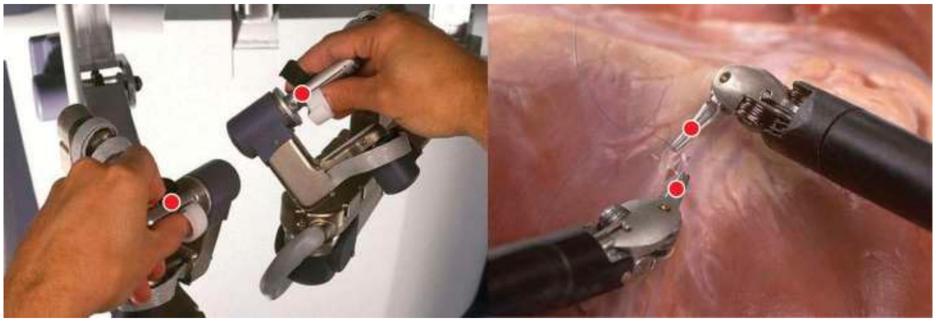

Figure 15. Demonstration of control point concept in robotic master-slave: the da Vinci robot user interface maps motion of control points located between the user's fingers to corresponding control points on the instruments inside the patient. Image source: [59], © 2016 Intuitive Surgical, Inc., control point illustrations added.

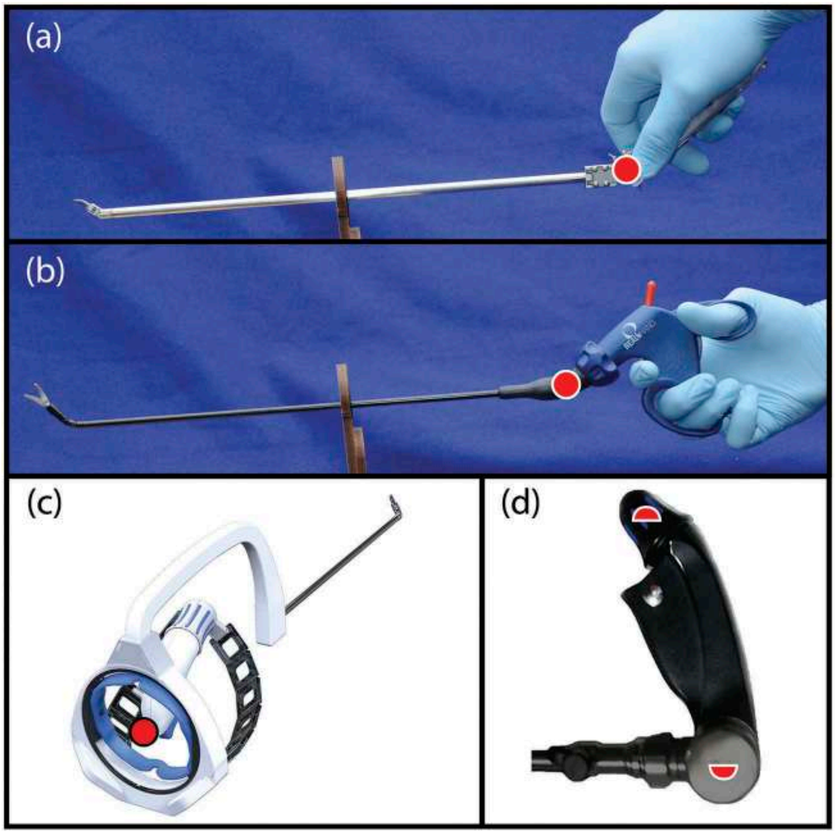


Figure 16. Comparison of control point location for the Maestro, RealHand, FlexDex (control point located at center of frame ring), and Radius.

inputted, and it is the corresponding point on the end effector where those motions are applied. The same concept can be applied to some (though not all) of the articulated mechanical instruments reviewed in this paper, as illustrated in Figure 16. These instruments place the control point in many different locations, including along the instrument shaft in front of a pistol grip (all of the pistol-grip, handle-controlled devices) or at the center of the surgeon's own wrist (e.g. the FlexDex). The Maestro seeks to replicate the location of the control point on the da Vinci system in a mechanical device by placing it between the user's finger and thumb. While future experiments will be needed to determine whether the location of the control point significantly contributes to ease of use in nonrobotic instruments, it is a topic worthy of future study, given the success of the da Vinci Surgical System.

In summary, many groups around the world have begun to pursue articulated manual laparoscopic instruments over the past several years in view of their potential to provide some of the dexterity benefits of robotic surgery at a substantially lower cost. However, many of these instrument designs are still in early stages of development. Many opinions exist on how these instruments ought to function and on what elements to prioritize in design. To sort through these issues rigorously, new results are needed in terms of both the psychophysics of how surgeons interact with these instruments and in surgeon preferences and use cases. Ultimately, it is the surgeon end users and the commercial marketplace that will determine which devices provide the most compelling benefits to surgeons and their patients.

## Five-year view

It is an exciting time in the development history of articulated mechanical instruments. Several devices are already on the market, including the Radius instruments and the several devices in the pistol-grip, handle-control category. Equally exciting are the new devices coming out of research laboratories and at various stages of the commercialization process, including the several designs from Delft, the FlexDex from Michigan, and the Maestro from Vanderbilt. In the next five years, it is likely that some of these devices will come to market.

It is also likely that some general design principles will emerge in the same time period. For example, the control point idea introduced in the prior section will be studied. Similarly, ideas like thumb control may be compared rigorously with other interface choices to evaluate their utility from an ergonomic and psychophysics perspective. And lastly, it is likely that we will have a better idea five years from now on whether certain features such as wrist and jaw locks are required or optional in articulated mechanical surgical instruments.

It is also likely that designers will find ways to add additional degrees of freedom to articulated mechanical instruments, for example, incorporating both a 'wrist' and an 'elbow'. At least two groups are already pursuing research toward this. The DuoFlex, developed in the BITE Group at Delft University of Technology [60,13] uses cable-ring mechanisms to create both a wrist and an elbow in the same instrument. The other example, from Vanderbilt University [61], uses multiple push-pull elastic rods to create a stiff elbow and incorporates an elastic compensator on the handle to enable the surgeon to easily deflect what would otherwise be a stiff elbow joint in addition to a cable-driven wrist joint.

In summary, we foresee advancements during the next five years in terms of both new commercial products, new designs with even more dexterity, and new understandings of how to judge the naturalness of a user interface, mapping, and wrist combination. As these advancements take place and more surgeons are exposed to articulated instruments, we predict a steady increase on the utilization of these devices over the next five years and beyond.

## Key issues

- Robotic surgery is much easier to perform than traditional laparoscopic surgery, yet much more expensive.
- A variety of nonrobotic articulated mechanical devices with wrist-like dexterity have been developed recently to provide end effector articulation at a lower financial cost.
- Current articulated mechanical surgical instruments exhibit a wide range of user interfaces, wrist mechanisms, and mappings between the two.
- There is currently no clear consensus on what makes an articulated mechanical instrument easy to use.
- Some articulated mechanical instruments have reached the commercial market and others are under development and soon will be released commercially.
- As articulated mechanical surgical instruments mature, they have the potential to impact the minimally invasive surgery market by providing some of the capabilities currently only found in robotic systems at a lower cost.

## Declaration of interest

The authors were supported by internal funding through Vanderbilt University. R.J. Webster III and R.A. Lathrop hold a patent on the Maestro technology (US20120277762A1). The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

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•• of considerable interest

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