Surg Endosc (2015) 29:1281–1296
DOI 10.1007/s00464-014-3816-z

REVIEW

A state of the art review and categorization of multi-branched instruments for NOTES and SILS

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Received: 27 January 2014 / Accepted: 12 August 2014 / Published online: 24 September 2014

Abstract
Background Since the advent of Natural Orifice Translumenal Endoscopic Surgery (NOTES) and single incision laparoscopic surgery (SILS), a variety of multitasking platforms have been under development with the objective to allow for bimanual surgical tasks to be performed. These instruments show large differences in construction, enabled degrees of freedom (DOF), and control aspects.
Methods Through a literature review, the absence of an in-depth analysis and structural comparison of these instruments in the literature is addressed. All the designed and prototyped multitasking platforms are identified and categorized with respect to their actively controlled DOF in their shafts and branches. Additionally, a graphical overview of patents, bench test experiments, and animal and/or human trials performed with each instrument is provided.
Results The large range of instruments, various actuation strategies, and different direct and indirect control methods implemented in the instruments show that an optimal instrument configuration has not been found yet. Moreover, several questions remain unanswered with respect to which DOF are essential for bimanual tasks and which control methods are best suited for the control of these DOF.
Conclusions Considering the complexity of the currently prototyped and tested instruments, future NOTES and SILS instrument development will potentially necessitate a reduction of the available DOF to minimize the control complexity, thereby allowing for single surgeon bimanual task execution.

Keywords General · Instruments · Human/robotics · General · Technical

Natural Orifice Translumenal Endoscopic Surgery (NOTES) is a hybrid procedure which uses flexible endoscopic technology to perform laparoscopic surgical procedures beyond the confines of the gastrointestinal tract. Single incision laparoscopic surgery (SILS[1]), which is the execution of surgery through one single incision, is comparable to NOTES as it is associated with equal challenges with respect to bimanual task performance and surgical limitations. These surgical approaches, which can both be categorized as single access surgery, have potential patient advantages which include faster recovery, less adhesions, and reduced risk of infections [1, 2]. Both NOTES and SILS necessitate the development of dexterous endoscopic and laparoscopic instruments for the surgeon. For this reason, in 2006, the Natural Orifice Surgery Consortium for Assessment and Research (NOSCAR) identified the barriers that needed to be surmounted specifically for the development of NOTES [3], and set up a list of steps and guidelines to aid the research of

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[1] Synonyms to SILS are Single-Port Access (SPA) surgery, Single-Site Laparoscopy (SSL), Single-Port Laparoscopic Surgery (SPLS), Single-Port Laparoscopy (SPL), and Laparo Endoscopic Single-Site (LESS) surgery.

multi-branched instruments, also known as multitasking platforms. According to NOSCAR, several ideal characteristics can be defined for multi-branched instruments, among which adequate maneuverability, independent camera articulation, triangulation, and intuitive control are the most critical for the performance of complex bimanual surgical tasks such as knot-tying and suturing. Other characteristics of importance include adequate stability, sufficiently small instrument dimensions and the incorporation of inflation and irrigation channels.

To provide the surgeon with a stable operating platform, new instruments that attempt to address the aforementioned ideal characteristics have been developed for both NOTES and SILS. While handheld single-branched instruments used for standard minimally invasive surgery (MIS) have been extensively described in the literature [4], very few articles compare surgical task performance, characteristics, and capabilities of prototype multi-branched instruments [5–7]. Moreover, no complete overview of the current state of the art or an in-depth analysis into advantages and disadvantages of the various systems is provided. As such, the goal of this paper is to provide a structured overview of all currently developed multi-branched instruments for NOTES and SILS and to analyze them to help define future obstacles and challenges. As there are inherent differences between instruments intended for NOTES as compared to SILS, this article principally compares them based on their construction, maneuverability, working space, actuation methods, and control strategies.

Methods

A literature study was performed using the Web of Knowledge and PubMed databases to identify literature relating to flexible endoscopic multitasking platforms from January 2004 till October 2013. The following keywords, subdivided into three categories, were used:

(1) *Anatomical area* Gastrointestin* *OR* abdomen* *OR* *luminal* *OR* *lumenal*;
(2) *Surgical access site* ((Insert* *OR* through) *AND* ("natural orifice" *OR* oral *OR* endonasal* *OR* anal *OR* vagina*)) *OR* SILS *OR* SPS *OR* "single-site";
(3) *Endoscopic instrumentation* Instrument* *OR* device* *OR* prototype* *OR* flexible *OR* "multitasking platform" *OR* robo* *OR* branch*.

A separate search action was performed for each group, and the results were combined to identify articles containing one or more keywords present in each group. Through this method, the most relevant multi-branched instruments pertaining to NOTES and SILS were identified. Separate search actions for each identified instrument supplemented this survey. All identified instruments were subsequently analyzed with respect to their actively controlled degrees of freedom (DOF; excluding gripper or tool actuation) and their ability to allow for effective bi-manual task performance.

Results

A total of 31 different multi-branched instrument systems have been identified in the literature (also counting significantly different generations of the same instrument). Because they all display and provide various types of articulating segments, control interfaces, and multitasking capabilities, a categorization is necessary as a basis for comparison. This categorization, based on their mechanical construction, will be developed in the following subsections.

All identified instruments have a common rigid or steerable shaft from which a minimum of two separate branches originate, as schematically depicted in Fig. 1. These branches have a number of DOF incorporated in them to provide multitasking platform functionality. The sequence or order in which these DOF are placed, and their locations along the branches, are relevant with respect to the working space and the intrinsic control methods provided to the surgeon. In order to categorize the branch DOF sequence, two different kinds of segments are distinguished: a segment providing axial DOF, i.e., axial rotation and/or axial translation, and a segment providing deflection DOF, i.e., sideways bending or deflection in one or two separate (orthogonal) planes. These segments are defined as straight and deflecting segments, respectively, and are also schematically shown in Fig. 1. On the basis of these segments, one can define and analyze the construction of all existing instrument branches.

As a frame of reference, one can first look at a standard rigid (single-branched) laparoscopic grasper. When inserted through a trocar, this instrument has 4 DOF; i.e., two deflections, axial translation, and rotation, where the two deflections act around the incision point. As such, the instrument can be seen to have a deflecting segment near the incision, and a straight segment for the remainder of its length. In an identical fashion, all MIS instrumentation for tissue manipulation can be analyzed. In the following sections, firstly single and double-segmented branches are presented, later followed by instruments with branches with more than two segments, i.e., multi-segmented branches. At this point, it should be noted that all multi-branched instruments have a minimum of two branches which are usually alike. Hence, for the purpose of this review, the focus is placed on the construction, control, and multitasking functionality of two branches operating simultaneously.

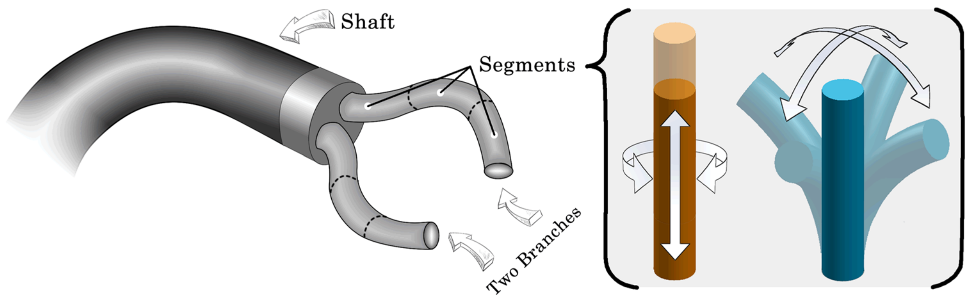

Fig. 1 *Left* schematic depiction of a multi-branched instrument with branches consisting of various segments. *Right* straight segment with axial rotation and/or axial translation and deflecting segment with bending in one or two separate planes

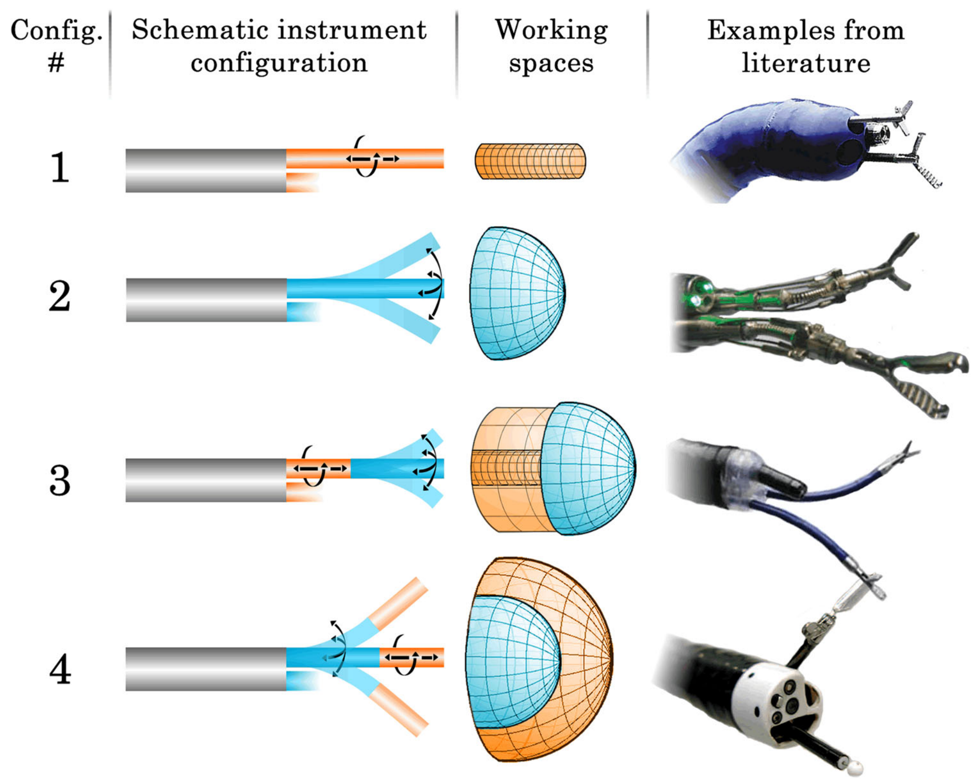

Fig. 2 Schematic multi-branched instruments with single- and double-segmented branches displayed with their respective working spaces and instrument examples identified from the literature. For ease of demonstration, only one branch is shown each time. From *top* to *bottom*, the example instruments are Transport [8], Scorpion-shaped endosurgical robot [9], DDES [10], and R-scope [11]. Note that no double-segmented branches with twice the same type of segment, nor double-branched instruments with two different branch segment sequences, have been identified in literature. Hence all the identified instruments, as far as the literature is concerned, with single- and double-segmented branches can be categorized into these schematically shown configurations

Single and double-segmented branches

Branches with one or two segments have a maximum of 4 DOF and are thus to a certain extent limited in their maneuverability. However, an instrument that has two branches with 4 DOF each, adding up to a total of 8 DOF, may already provide sufficient multitasking functionality. Figure 2 displays four instruments with identical shafts (gray), but with varying branch configurations consisting of one or two segments (straight segment = orange; deflecting segment = blue, see Fig. 1). Figure 2 shows all identified segment combinations for instruments with single- and double-segmented branches. Double-segmented branches with two identical segments in series as well as instruments with dissimilar branch constructions are excluded in Fig. 2, because no such instruments have been found in the literature. Figure 2 additionally shows the working spaces of the various branches, providing an indication of their reachable points in 3D space, as well as instrument examples belonging to the respective branch categories.

Configuration #1 in Fig. 2 consists of two branches with a single straight segment that can only be translated forward and backward and/or rotated around its axis, restricting the working space to a cylinder as wide as the branch itself. Examples of such instruments are the standard dual channel endoscope (DCE; Olympus) [12] and Transport (USGI Medical, San Capistrano, CA, USA) [8] which is a part of incisionless operating platform (USGI Medical) [13]. These instruments all consist of a common 2 DOF steerable flexible shaft with passive instrument delivery channels for the insertion of various surgical tools (e.g., graspers). The tools themselves are not steerable and can only be manipulated coaxially with the common steerable shaft. A point in 3D space can still be reached by the instrument as a whole, however, coaxial steering makes bimanual tasks highly challenging.

Configuration #2 consists of two branches with a single deflecting segment, allowing each branch to bend or deflect in one or two perpendicular planes. The accompanying working space of such a branch is a partial sphere, ranging in size from a partial cone to more than a full hemisphere depending on instrument construction and dimensions. With two such branches, bimanual tasks are in principle possible because, depending on the thickness of the shaft defining the distance between the branches, the branches can be deflected slightly inward to reach a common point. An example of an instrument with this construction is Scorpion-shaped endosurgical robot, Suzuki et al. [9], which is an electromechanical master–slave (MS) system.

The branches in Configuration #3 contain a straight segment followed by a deflecting segment, which entails that the branch can translate forward and deflect at the tip. Approaching a surgical target is accomplished by first translating the branch forward, after which small and precise adjustments can be made through tip deflection. The only instrument found with this construction is direct drive endoscopic system (DDES; Boston Scientific, Natick, MA, USA) [10], which has a relatively large bending radius and translation range, making shaft actuation unnecessary for most surgical tasks within a confined space.

Finally, the branches in Configuration #4 contain a deflecting segment followed by a straight segment. When navigating toward a surgical target, first the branch is aligned with the target through branch deflection, followed by branch extension towards it. As compared to Configuration #3, a drawback of Configuration #4 is that correcting the forward motion by extra bending actions, results in large motions of the tip as the straight segments amplify the deflection of the preceding bending segments. This makes small adjustments in principle less precise and prone to overshooting the surgical target. However, an advantage over Configuration #3 is that Configuration #4 has a larger working space. The only identified example of Configuration #4 is R-scope (XGIF-2TQ160R; Olympus, Center Valley, PA, USA) [11]. Here it should be noted that this is also the only identified instrument with non-identical branches because the deflecting segments (both having 1 DOF) function in planes perpendicular to each other. R-scope is able to stretch tissue with a grasper in one direction and subsequently slice or cut the tissue in a plane perpendicular to this direction (for example: vertical lift and horizontal cut).

Single and double-segmented branches with passive triangulation

The principle of triangulation has often been described in literature, and is defined as 'the ability to apply adequate tissue traction and countertraction with independently controlled instrument branches' [14–16]. For the purpose of this article, this definition is refined in that triangulating branches originating from a common shaft, first need to deflect outwards and then back inwards before engaging tissue. This leads to an enhanced working space allowing for bi-manual tasks like suturing and knot tying [5]. In many systems triangulation is accomplished through a mechanism at the base of the branches which predeflects the branches and sometimes allows them to be locked in a parallel position at some distance from each other. According to literature, this triangulating base should be preferably stationary and stable [3]. If the surgeon can only secure the triangulating base in one outward position without being able to control the outward motion over more angles, this will further be referred to as passive triangulation. In the example in Fig. 3, triangulation is schematically displayed as a fork-shaped extension of the instrument shaft. If the surgeon can control the outward motion over more angles, this will further be referred to as active triangulation. Although active triangulation can be found in instruments with branches having more than two segments, the single- and double-segmented branched triangulating instruments identified from the literature all rely on passive triangulation. These instruments can again be subdivided according to the categorization in Fig. 2, with the difference that each branch is preceded by a passive triangulating segment.

Configuration #1, i.e., a passively triangulating multi-branched instrument with single-segmented branches composed of one straight segment, has not been found in literature. This is logical because it is not possible to achieve triangulation with parallel branches that are unable deflect inwards.

Configuration #2 entails a passively triangulating instrument with branches consisting of a single deflecting segment. The only instrument with this construction is Cobra (USGI Medical, San Clemente, CA, USA) [19, 20]. Although this instrument provides a larger working space as compared to the non-triangulating instruments with the same configuration, the space wherein the branches can reach a common point in space is still very limited due to the absence of straight segments.

Configurations #3 and #4 represent passively triangulating multi-branched instruments with double-segmented branches. Many examples of these configurations have been found. Two examples of Configuration #3 are the experimental flexible endoscopic surgical system described by Kobayashi et al. [17], and ANUBIScope (Karl Storz, Tuttlingen, Germany) [18], see Fig. 3. The first consists of a flexible endoscope with two passive working channels through which two thin flexible endoscopes are inserted, functioning as branches. Both the main endoscope (i.e., the

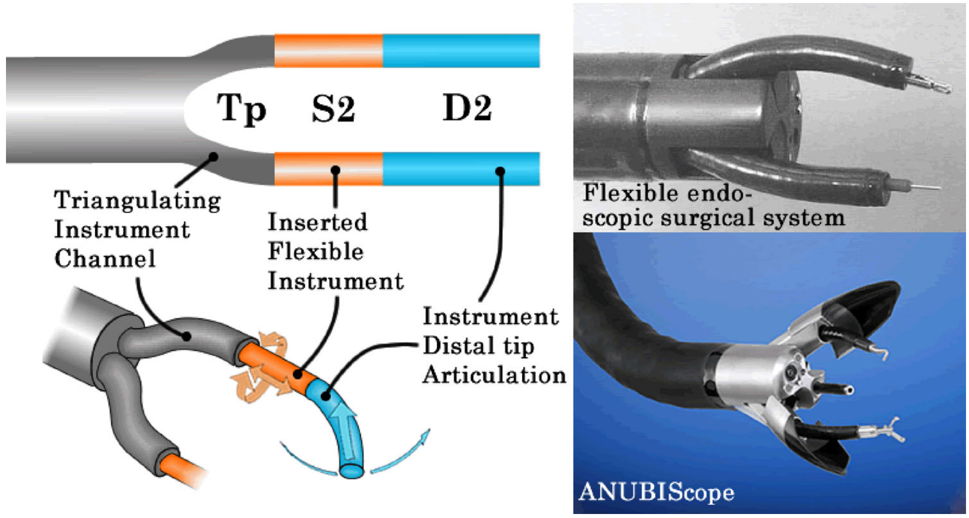

Fig. 3 Schematic representation of a double-segmented instrument with a straight segment followed by a deflecting segment with all instruments identified from literature. *Top* experimental flexible endoscopic surgical system [17], *bottom* ANUBIScope [18]. *Tp* passive triangulation, *S2* 2 DOF straight segment, *D2* 2 DOF deflecting segment

shaft) and the two smaller inserted endoscopes (i.e., the branches) have 2 DOF steerable tips. The triangulation is passive because the branches slide through precurved outward pointing guide channels. The ANUBIScope is similar in construction but more limited in its DOF, as the deflecting segments each have just 1 DOF and can only be bent in one plane. Although this limitation makes the instrument easier to control compared to the system described by Kobayashi et al. [17], it also changes its manipulation capabilities.

Finally, with respect to Configuration #4, four different triangulating instruments have been found, of which three are shown in Fig. 4. These instruments are SPIDER (TransEnterix, Durham, North Carolina, USA) [21], EndoSAMURAI (Olympus, Tokyo, Japan) [22], robotized flexible endoscope described by Bardou et al. [23, 24], and the first generation in vivo dexterous miniature robot build at the University of Nebraska-Lincoln, described by Lehman et al. [25]. The branches of the first three systems are in essence deflectable instrument guide channels through which passive flexible tools are inserted that can axially rotate within the channels and extend axially beyond the channels. These systems thus allow for the inserted tools to be interchanged during surgery, which is advantageous for procedures requiring a broad range of tools. Although SPIDER and EndoSAMURAI are, respectively, designed for SILS and NOTES, they are remarkably similar in terms of construction and control. Robotized flexible endoscope [23, 24] and in vivo dexterous miniature robot [25] are both electromechanically controlled MS systems. Although robotized flexible endoscope is considerably similar to SPIDER and EndoSAMURAI, in vivo dexterous miniature robot makes use of locally actuated joints controlled by small electromotors allowing 1 DOF deflection and axial translation of the instrument tips.

Multi-segmented branches and MS instruments

Besides the instruments with single- and double-segmented branches discussed so far, the literature also revealed instruments with multi-segmented branches incorporating more than two segments. These instruments have potentially improved maneuverability in terms of branch positioning and orientation, however, at the expense of an increase in control complexity. There is a limit to the amount of DOF that one or two surgeons can actively and simultaneously control, and as such multi-segmented branched instruments often heavily rely on computer-controlled DOF actuation and MS interfacing [4]. Defining and classifying instruments with multi-segmented branches by extending the categorization in Fig. 2 quickly becomes complex. In the multi-segmented branched instrument category, many multi-segmented branch configurations are possible, including configurations where twice the same segments are placed in series. Since instruments have been found with up to six segments in series (e.g., Single-Port lapaRoscopy bImaNual roboT, SPRINT by Piccigallo et al. [26, 27]), discussing every instrument configuration is not feasible.

From the literature, sixteen multi-segmented branched instruments have been identified, of which one fully mechanical and the others electromechanical MS systems. All instruments with multi-segmented branches include active or passive triangulation, where active triangulation entails that the outward deflection of the branches is actively controlled to improve instrument maneuverability. The most notable differences between the instruments with multi-segmented branches are the methods of actuation. Although most instruments with single- or double-segmented branches rely on remote actuation, local actuation strategies are seen as well in the multi-segmented

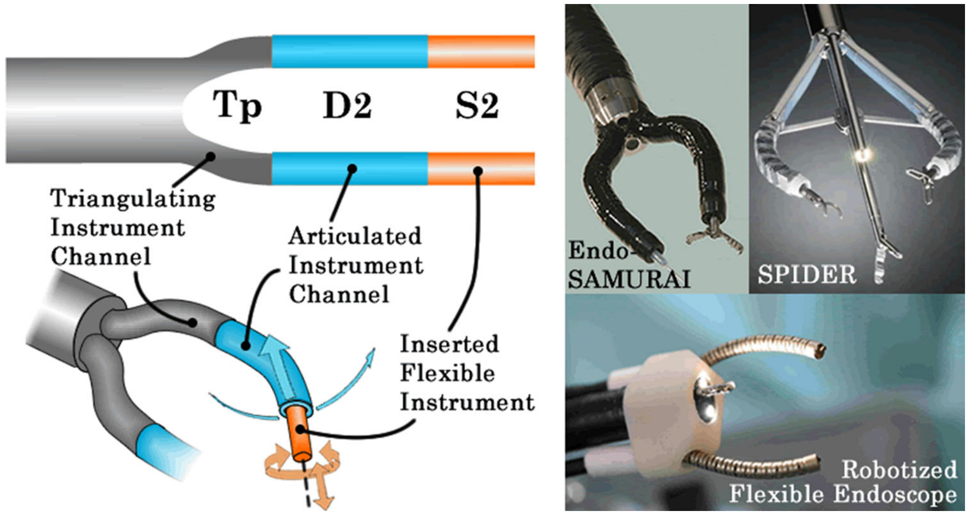

Fig. 4 Schematic representation of a double-segmented instrument with a deflecting segment followed by a straight segment with all instruments identified from the literature. *Top left* EndoSAMURAI [22], *top right* SPIDER [21], *bottom* robotized flexible endoscope [23, 24]. *Tp* passive triangulation, *D2* 2 DOF deflecting segment, *S2* 2 DOF straight segment

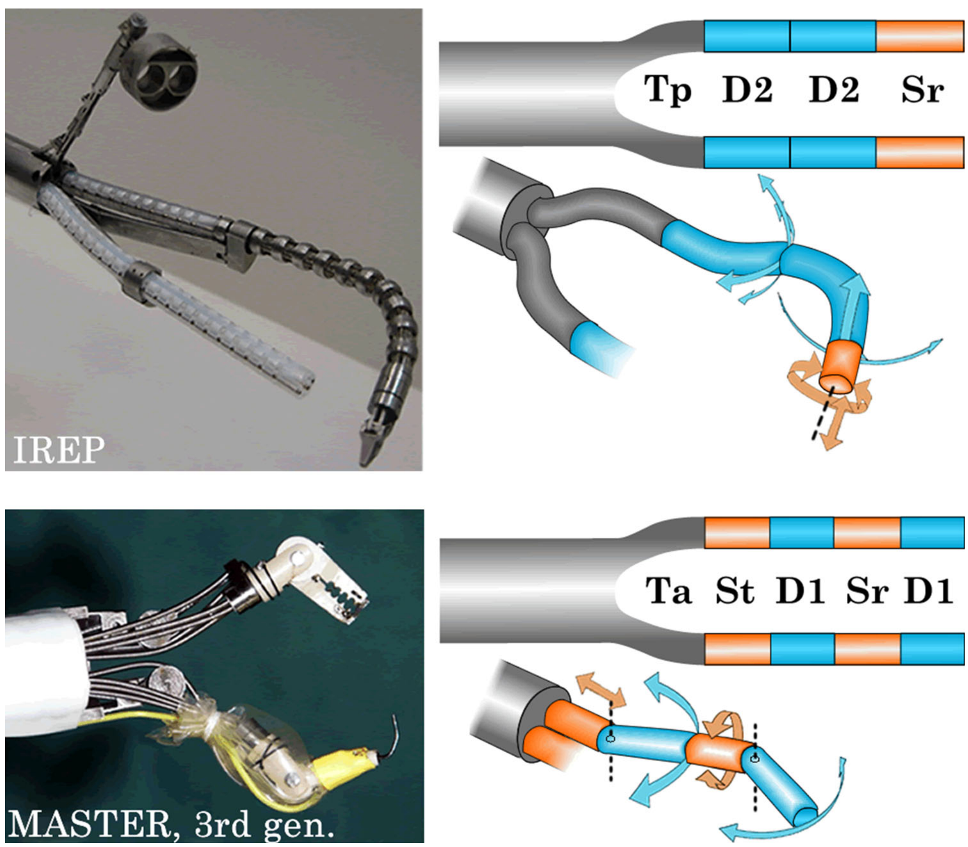

Fig. 5 Schematic and 3D representation of IREP (*top*) [25] and MASTER (*bottom*) [30] with their respective segments visualized and DOF abbreviations. *Tp* passive triangulation, *Ta* active triangulation, *D1* 1 DOF Deflecting segment, *D2* 2 DOF Deflecting segment, *Sr* straight segment allowing for only axial rotation, *St* straight segment allowing for only axial translation

instrument category. Local actuation indicates that the power and motion required for actuation of a joint are created within or near the joint itself. In remotely actuated mechanisms, this power is generated outside of the joint and transferred to the joint through for example cables or tendons [28]. Looking at all multi-segmented branched instruments found in the literature, the systems with remote actuation are Highly Versatile Single Port System (HVSPS) by Can [29], ViaCath (EndoVia, Norwood, MA) by Abbott et al. [30], and Master And Slave Translumenal Endoscopic Robot (MASTER) by Phee et al. [31], see Fig. 5. The systems with local actuation are in vivo dexterous robot second and third generation by Wortman et al. [32, 33] and SPRINT by Niccolini et al. [26, 27]. Lastly, IREP by Xu et al. [34, 35], as seen in Fig. 5, makes use of multiple super-elastic nickel titanium, also known as nitinol, backbones which are remotely push–pull actuated in combination with a cable-actuated axially rotatable tip.

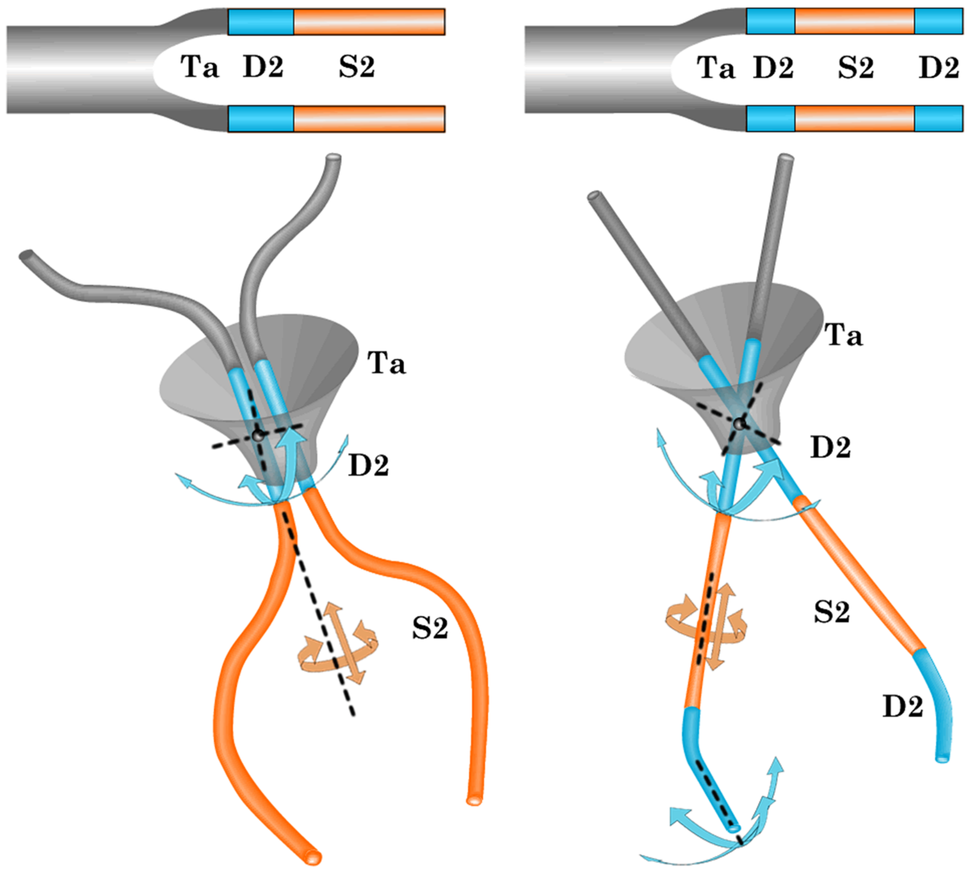

Fig. 6 Schematic representation of SILS instrumentation placed through a SILS port. *Left* straight pre-bent instruments, *right* straight articulating instruments. *Ta* active triangulation, *D2* 2 DOF deflecting segment, *S2* 2 DOF straight segment. The *dotted lines* represent the rotation axes of the respective segments

Interesting to note is that IREP is the only multi-branched system found to combine two different remote actuation methods. Multi-branched systems with hybrid actuation methods, however, i.e., the combined use of both remote and local actuation to control the DOF of a branch or shaft, have not been found, even though such single-branched mechanisms do exist [28, 36, 37].

SILS ports and instruments

Identical to the segment breakdown as performed for mechanical and MS systems in the previous sections and as depicted in Figs. 3, 4, and 5, one can also analyze SILS instrumentation operated through a tri- or quad-port [2, 38]. The instruments inserted through such a SILS-port function as individual branches and the port itself can be seen as the working platform (analogous to the shaft). The pivoting fulcrum effect associated with the insertion of straight pre-bent instruments through the port can then be broken down into the same segments as used previously. Rigid pre-bent instruments for SILS can be seen as double-segmented branches in which the deflection segment is near the SILS port (functioning as the instrument pivoting point), and in which the straight segment is the remainder of the instrument. In an identical fashion, straight articulating instruments for SILS with an added deflecting segment at the distal tip can be considered as a branch with three segments [39]. In Fig. 6, a schematic representation of SILS instrumentation is provided.

In order to create triangulation with straight articulating instruments through a SILS port, the instruments need to be crossed in the port, as shown in Fig. 6. This allows a better range of motion, but the resulting reversal of handedness introduces a major mental challenge for the surgeon [40]. In order to solve this issue, Intuitive Surgical (CA, USA) developed a set of instruments and accessories specifically dedicated to SILS for use with the Da Vinci MS system. In this setup, curved steerable cannulas, actuated with robotic arms, are placed crosswise through a SILS port, and a set of semi-rigid, non-wristed instruments are inserted down the cannulas. These cannulas thus function as double-segmented rigid branches, where the deflection segment is located near the incision. Because of the MS system capabilities, the change in handedness is compensated through software [40, 41].

Discussion

All identified multi-branched instruments with single-, double-, or multi-segmented branches are presented in

Table 1 All multi-branched instruments identified from the literature categorized to branch segment configuration and subdivided into single-, double-, and multi-segmented branch groups

			NOTES/ SILS	Triangu- lation	Degrees of Freedom (DOF) Shaft	Branch						Camera	Channel	Total
Single	Mech	Dual Channel Endoscope (DCE) [12]	NOTES		4	S2						0	0	8
		Transport – USGI [8]	NOTES		4	S2						2	2	12
		Cobra – USGI [19, 20]	NOTES		3	D2						4	0	11
	MS	Scorpion shaped endosurgical robot [9]	NOTES	Tp	3	D2						0	2	9
Double segmented	Mech	R-scope 1st gen. – Olympus [11]	NOTES		5	D1	S2					0	0	11
		R-scope 2nd gen. – Olympus [11]	NOTES		4	D1	S2					0	0	10
		DDES – Boston Scientific [10]	NOTES		3	S2	D2					4	0	15
		SILS-port with rigid pre-bent instr. [2]	SILS	Ta	0	D2	S2					4	2	14
		SPIDER – TransEnterix [21]	SILS	Tp	4	D2	S2					2	2	14
		EndoSAMURAI – Olympus [22]	NOTES	Tp	3+2o[a]	D2	S2					0	2	17
		ANUBIScope – IRCAD & Karl Storz [18]	NOTES	Tp	3	St	D1					0	2	11
		Flexible endoscopic surgical system [17]	NOTES	Tp	3	S2	D2					(12)[b]	2	13
	MS	Robotized flexible endoscope [23, 42]	NOTES	Tp	3	D2	S2					0	4	15
		In-vivo dexterous miniature robot 1st gen. [25]	NOTES	Tp	4	D1	St					0	0	8
		Da Vinci SILS config. – unwristed instr. [43]	SILS	Ta	0	D2	S2					4	0	12
Multi segmented	Mech	SILS-port with articulating instr.[2]	SILS	Ta	0	D2	S2	D2				4	2	18
	MS	Da Vinci SILS configuration – wristed instr. [43]	SILS	Ta	0	D2	S2	D2				4	0	16
		IREP [34]	SILS	Tp	4	D2	D2	Sr				3	0	21
		In-vivo dexterous miniature robot 2nd gen. [44]	NOTES	Tp	4	D1	Sr	St				0	0	10
		ViaCath 1st gen. [30]	NOTES	Ta	1[c]	S2	D2	D2				4	4	21
		ViaCath 2nd gen. [30]	NOTES	Ta	4	S2	D2	D2	D2			4	4	28
		MASTER, 1st gen. [45]	NOTES	Ta	3	D2	D1	Sr	D1			0	0	13
		MASTER, 2nd gen. [46]	NOTES	Ta	3	Sr	D1	Sr	D1			0	0	12
		MASTER, 3rd gen. [31]	NOTES	Ta	3	St	D1	Sr	D1			0	0	12
		In-vivo dexterous miniature robot 3rd gen. [47]	SILS	Tp	4	Sr	D1	Sr	St			0	0	12
		Multi-funct. miniature in vivo robot (NB2.1) [32]	SILS	Tp	4	Sr	D1	D1	Sr			0	0	12
		Miniature in-vivo robot (TB1) [48]	SILS	Ta	0	Sr	D1	D1	Sr			0	0	8
		In-vivo surgical robot (TB2) [33]	SILS	Ta	0	Sr	D1	D1	Sr			0	0	8
		HVSPS [29]	SILS	Ta	4	S2	D1	D2	Sr			5	0	21
		Miniature surgical robot [49]	SILS	Ta	0	D1	Sr	D1	D1	D1	Sr	4	0	16
		SPRINT [26, 27]	SILS	Tp	4	Sr	D1	D1	Sr	D1	Sr	2	2	20

The DOF are obtained from the literature and total number of DOF calculated through summation of the DOF associated with the instrument branches, camera articulation, and passive instrument guide channels

DDES direct drive endoscopic system; *SPIDER* single-port instrument delivery extended research; *SPRINT* Single-Port lapaRoscopy bImaNual roboT; *IREP* insertable robotic effector platform; *HVSPS* highly versatile single port system; *NB* Nate-Bot series; *TB* Tyler-Robot series

[a] 2o = 2DOF overtube control

[b] Special case in which both the main shaft as well as both branches have visualisation incorporated; thus 3 video signals provided

[c] Passive 3-channel overtube, which only allows for axial translation. Steering is accomplished with the 4DoF colonoscope (camera) internally disposed

Table 1. Additional information is provided with respect to their (electro)mechanical construction from shaft to branches, field of application (NOTES/SILS), presence of additional instrument channels (for suction, irrigation, an additional grasper, etc.), passive or active triangulation capabilities and independent camera DOF. The information in Table 1 provides a framework for the comparison of new multi-branched instruments with respect to the current state of the art. Additionally, Table 2 provides an overview of most relevant references pertaining to these instruments with respect to patents, bench top experiments, animal and human trials.

As can be deduced from Table 1, no two instruments are the same when comparing their sequence of branch segments and the presence of additional features. The explanation behind this wide diversity may be that there is no proven optimal branch construction and a large list of surgical procedure requirements. With respect to branch maneuverability, several questions remain unanswered, such as which sequence of segments will provide the surgeon with the most intuitive control, how many DOF can be controlled by one surgeon, what are the effects on the learning curve with respect to basic and complex task performance, which DOF are 'ideally' needed to perform bimanual tasks versus which DOF are 'minimally' required, and what control interface is best suited for these DOF? Especially with respect to the two last posed questions, it may be that providing the surgeon with the 'ideal' set of DOF does not outweigh the increased instrument design and control complexity. Conversely, providing more than the minimum required DOF, but less than what is 'ideal,' may prove more cost-effective. Taking as an

Table 2 Overview of references pertaining to patents, bench top experiments, animal and human trials for all categorized multi-branched instruments identified from the literature

	References			
	Patents	Bench test	Animal trials	Human trials
Single				
Mech				
Dual channel endoscope, DCE [12]	[50, 51]	[22, 52]	[53, 54]	[55, 56]
Transport: USGI Medical [8]	[57, 58]	[20]	[20, 59–62]	[13]
Cobra: USGI Medical [19, 20]	[57, 58]	[63]	[19, 63]	–
MS				
Scorpion shaped endosurgical robot [9]	–	–	[9, 64, 65]	–
Double segmented				
Mech				
R-scope first generation: Olympus [11]	–	–	[66–68]	[69]
R-scope second generation: Olympus [11]	–	[70]	[11, 71, 72]	–
DDES: Boston Scientific [10]	[73, 74]	[10, 75, 76]	[10, 77]	–
SILS port with rigid pre-bent instrument [2]	[78, 79]	[80]	[80]	[81–87]
SPIDER: TransEnterix [21]	[88, 89]	[21, 90]	[21, 90–92]	[21, 93]
EndoSAMURAI: Olympus [22]	[94]	[22, 95, 96]	[95]	–
ANUBIScope: IRCAD and Karl Storz [18]	[97, 98]	[18]	[18]	[99]
Flexible endoscopic surgical system [17]	–	[17]	[17]	–
MS				
Robotized flexible endoscope [23, 42]	–	[23, 24]	–	–
In vivo dexterous miniature robot first generation [25]	[100, 101]	[25]	[25]	–
Da Vinci SILS config.: unwristed instrument [43]	[102]	–	–	[103–108]
Multi segmented				
Mech				
SILS port with articulating instrument [2]	[78, 109]	[80]	[80, 110]	[110, 111]
MS				
Da Vinci SILS configuration: wristed instrument [43]	[112, 113]	–	[114, 115]	[116, 117]
IREP [34]	[118]	[34, 35, 119–121]	–	–
In vivo dexterous miniature robot second generation [44]	[100, 101]	[122]	[44, 123–125]	–
ViaCath first generation [30]	[126, 127]	[30]	[128]	–
ViaCath second generation [30]	[126, 127]	–	–	–
MASTER, first generation [45]	[129]	[45, 46, 130]	–	–
MASTER, second generation [46]	[130]	[46]	[46]	–
MASTER, third generation [31]	[129]	[31, 131–133]	[31, 131–137]	–
In vivo dexterous miniature robot third generation [47]	[100, 101]	–	[47, 138, 139]	–
Multi-function miniature in vivo robot (NB2.1) [32]	–	–	[32, 33]	–
Miniature in vivo robot (TB1) [48]	–	–	[48]	–
In vivo surgical robot (TB2) [33]	–	[33]	–	–
HVSPS [29]	–	[140, 141]	[29, 140]	–
Miniature surgical robot [49]	–	–	[49]	–
SPRINT [26, 27]	–	[26, 142, 143]	–	–

example the basic tasks of knot tying and suturing; these can already be performed sufficiently well with a standard flexible endoscope (like the DCE) but at the cost of significant learning curves [144, 145]. In comparison, the DDES can be used to perform complex bimanual tasks more easily, however, this instrument needs to be secured to its surroundings and an assistant needs to be present during surgery to control the shaft and additional instruments inserted through passive instrument channels [22]. Which system is the better choice is dependent on many aspects, including the type of surgical procedure to be performed, surgeon experience and preference, hospital facilities, and patient characteristics. Further research is thus required to find answers to the raised questions.

Mechanical limitations

The current designs for multi-branched instruments suffer from considerable complexity, especially when intended for NOTES. The presence of a long flexible shaft, as opposed to SILS where the shaft can be relatively short and straight, influences both the design complexity with respect to the used actuation methods and the maximum allowable dimensions of the instruments. Moreover, as most NOTES instruments are not fixated to the abdominal wall, they are associated with a lower shaft stability as compared to SILS instruments which are often rigidly connected to the outside world. As such, NOSCAR has already stated the need for instrument fixation and stiffening to ensure adequate stability [3]. It is also for this reason that many potential future NOTES instruments are constructed as SILS instruments as an in-between stage to allow for testing under the condition of adequate platform stability.

Currently, all multi-branched instruments with single- or double-segmented branches make use of cable actuation to control the tip deflection of the shaft and the deflecting segments of the branches. Depending on the diameter of the used cables however, cable actuation has inherent limitations, such as a limited stiffness due to elasticity of the cables, minimum bending radii and friction forces between the cables and adjacent surfaces [146]. The stiffness issue is even more important when two branches are operated simultaneously. Should the shaft be insufficiently stiff, the force application of one branch can deflect the tip of the shaft, shifting the camera image, influencing task precision, and requiring active correction of the shaft displacement. Research by Swanstrom et al. [20], however, has shown that through the active compression of titanium links incorporated within the shaft, the shaft stiffness can be increased when required. The exact force levels which are required for NOTES and SILS systems have not been defined in the literature because they are dependent on their respective intended surgical application fields. However, the minimum force requirements can be assumed to be approximately equal to those of standard laparoscopic instruments. Forces reported in the literature for laparoscopic instruments used in a range of surgical tasks vary between 0.4 and 10.5 N [147–151]. The current literature on multi-branched instruments does not reveal whether these force requirements are fulfilled.

Dimensional constraints imposed by the anatomical surroundings of the intended surgical application fields greatly influence the design of NOTES and SILS instruments. Therefore, one key design aspect in the development of these systems is the choice of actuation method. Although most instruments make use of remote cable actuation as it places the power generation outside the patient, a locally placed motorized joint having a rigid transmission allows for a higher joint stiffness and the possibility of exerting higher torques [26]. However, incorporation of miniature motorized joints is often at the expense of larger dimensions, cost-effectiveness, and sterilization demands, and the power output of miniature electromotors is limited. Aside from the number and sequence of segments incorporated in the branches, there is thus a trade-off between actuation methods, force requirements, and anatomical constraints. As evidenced by Table 2, the only MS system that has been tested in human trials is Da Vinci which has not been developed specifically for NOTES or SILS. However, using Da Vinci in SILS configuration has been made possible at the expense of several limitations, including a limited range of motion, compared to its usage in standard MIS [117, 152]. The worldwide activities in the design and animal validation of multi-branched instrumentation for NOTES and SILS are a testament to the advancements in this field. However, the absence of human trials at most instruments with multi-segmented branches illustrates the high level of complexity and challenges associated with this field.

Control

Bimanual manipulation is essential to the successful performance of complex NOTES and SILS because it permits traction and countertraction, precise and efficient tissue separation, and approximation [8]. During the standard MIS approach, the surgeon uses surgical instruments while assistants provide visualization and apply traction with an additional tool. This is reversed in the traditional endoscopic setting where the endoscopist, using the control wheels on a gastroscope or colonoscope handle, controls navigation, insufflation, and visualization, as well as specific aspects of tissue manipulation. The assistant is responsible for tissue grasping, exchanging instruments, and helping to clearly visualize the operative field. These duties vary at times, and interactions can become complex and inefficient with more technically demanding procedures [10]. This is for example the case with the DCE, where a single operator has significant difficulties performing these tasks. Multiple operators are required to control the device as a team, through a relatively non-ergonomic user interface [56, 153].

The need for cooperation between multiple surgeons is present in almost all the developed multitasking platforms where in most cases one surgeon controls the branches and another surgeon controls the shaft. A number of systems provide a stable control platform secured to the operating room surroundings (SPIDER [21], EndoSAMURAI [22], ANUBIScope [18], DDES [10]). Since the shaft and branches have separate control interfaces, this stable platform allows for control by a single surgeon who can switch between these interfaces in a modular fashion. However, a single surgeon is not able to simultaneously perform scope stabilization and tissue manipulation, which is often required during interventional endoscopy. Because the tip of the endoscope is rarely stable for a long time [15], a second surgeon is often needed to actively counteract unintended shaft deviations as well as aid with the control of additional instruments passed through passive guide channels. For more insights into the ergonomic properties and control surfaces of the individual systems, the reader is referred to the instrument references provided in Table 1, and the comparison articles by Yeung and Gourlay [5], Karimyan et al. [6], and Zhou et al. [7]. MS systems also require the aid of a second surgeon or an assistant in all cases. For example, MASTER [31] requires one surgeon at the patient's side, manually controlling the instrument shaft, and another surgeon controlling the branches through the master interface. Da Vinci requires a bedside assistant for the introduction and steering of additional instruments which allow for suction and tissue retraction [116].

Important to address at this point is the differing ability in visualization of anatomical structures at the SILS instruments as compared to NOTES. In most of the discussed SILS setups the scope can be moved considerable relative to the branches. This is much less the case in NOTES instruments, where the scope usually has a much smaller range of motion and is more directly influenced by the movements of the shaft. As a result, allowing for scope control similar to standard MIS will likely pose a challenging aspect alongside the branch design and control complexity in the future development of NOTES.

Focusing on the control methods used for the various DOF incorporated in the multi-branched systems, the coupling between handle and steering motions of the shaft and branches is of importance with respect to both the level of operational difficulty (e.g., level of intuitiveness) as well as the precision in control. Both direct and indirect control methods have been developed for single-branched instruments [4]. Direct control entails that the instrument's tip motion is in the same plane and same direction as the surgeon's wrist or finger motion, as opposed to indirect control, where the tip motion occurs in another plane than the surgeon's wrist or finger motion. In multi-branched instruments the focus appears to be mainly on the incorporation of the more intuitive direct control methods by attempting to simulate the standard two-handed MIS approach. Furthermore, there has also been a shift identified in the literature toward integrated control or shape memory control. This refers to a control concept in which only the first segment of the instrument tip is actively steered, followed passively by the rest of the segments as the instrument is advanced [4]. An example of a system with shape memory control is NeoGuide (NeoGuide Systems, Inc., San Jose, California, USA [6]). The influence of these various control methods in NOTES and SILS systems on the learning curve and task precision has not been investigated thoroughly yet. Moreover, the influence on multitasking efficiency of two surgeons operating one instrument combined with these control methods is unknown.

Spaun et al. [22] stated, after they had analyzed and tested the R-scope [11], that a multi-branched instrument design should include independent branch motions, separation of vision and branch end-effectors, and a stable control platform. However, considering the accompanying complexity of such an instrument design, it can be speculated that the advantages of having separately controlled double- or multi-segmented branches, theoretically allowing for a large range of complex bimanual tasks to be performed, do not outweigh the added complexity of these devices [22]. Having two separately controlled branches permitting triangulation at the end of a shaft could even increase procedural instability instead of achieving effective countertraction, enhanced tissue cutting, or the ability to suture [15]. Hence every added feature to a design needs to be weighed for its benefit versus the added complexity in terms of construction and control.

Future

As stated by von Renteln et al. [15]"A single operator with two hands is only able to control a limited number of buttons and wheels. Any functions added to the flexible endoscope that allow for more angles of movement freedom, more capabilities, more control wheels, buttons, and levers will lead to practical limitations due to increased complexity. Consequently, every additional function achieving enhanced triangulation has to be reviewed for its trade-offs in robustness, stability, and practicality."

Due to the complexity of the currently existing multi-branched instruments, no instrument has yet proven to be cost-efficient and functional enough for implementation in general medical practice. Moreover, no multi-branched instrument yet exists which can be controlled by a single surgeon. It is the belief of the authors that smart instrument design and a reduction of the amount of DOF incorporated in the multi-branched systems to only those DOF which are the most essential for specific bimanual tasks will provide the solution to this challenge. In this respect, three questions require answers: (1) which DOF or segments are required for which surgical tasks, (2) in which sequence should the various segments be arranged, and (3) what is the most intuitive method to control the selected DOF? Hence proper task identification, accurate definition of task performance requirements and a focus on control methods are key to surmount the challenges in future NOTES and SILS instrument design.

Conclusions

A state of the art overview was provided of all the developed multi-branched instruments for SILS and NOTES. The instruments were categorized based on the branch segmentation. It was recognized that so far no systems have found their way into clinical practice yet, or proved superior in bimanual task performance with respect to their conventional counterpart minimally invasive procedures. While non-triangulating instruments do not provide sufficient maneuverability for complex tasks such as suturing or knot tying, triangulating instruments quickly become too complex both in terms of design and control. Currently, controlling multi-branched instruments requires a minimum of two surgeons actively working together or the incorporation of a complex MS system. Several fundamental questions remain unanswered: (1) how many and which DOF are minimally needed to perform certain bimanual tasks, (2) which branch segment sequence is optimal for these tasks, and (3) what are the most efficient control methods relating to these DOF and these tasks?

In order to bring NOTES and SILS systems into clinical practice, a reduction of the amount of actively controlled DOF is deemed necessary. Although the design of multi-branched instruments is challenging with respect to anatomical constraints, maneuverability requirements, and actuation of the branches, the optimization of the control aspects is of equal importance. Allowing for a single surgeon to perform bimanual tasks without the aid of a second surgeon is of more value than increasing the multi-branched instrument complexity.

Acknowledgments The research of Ewout A. Arkenbout and Paul Henselmans is supported by the Dutch Technology Foundation STW, which is a part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by Ministry of Economic Affairs, Agriculture and Innovation (STW Project 12137). The research of Filip Jelínek was performed within the framework of CTMM, the Center for Translational Molecular Medicine, Project MUSIS (Grant 030-202).

Disclosures Ir. E. A. Arkenbout, Ir. Paul Henselmans, Ir. Filip Jelínek, and Prof. Dr. Ir. Paul Breedveld have no conflicts of interest or financial ties to disclose.

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