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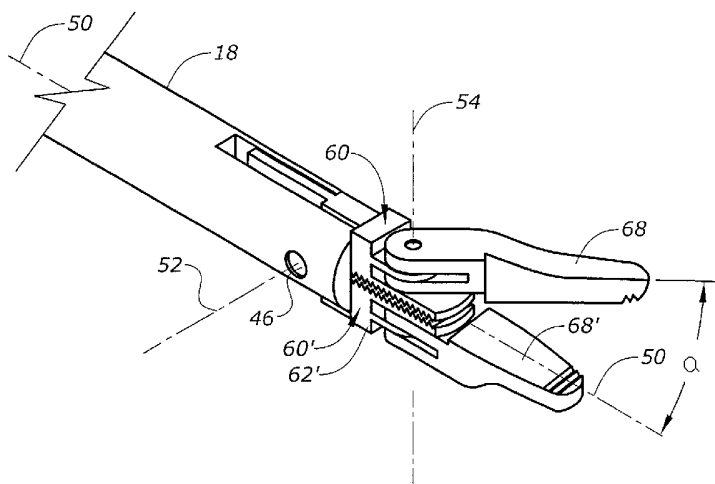
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[Continued on next page]

(54) Title: MULTIFUNCTIONAL TOOL AND METHOD FOR MINIMALLY INVASIVE SURGERY



(57) Abstract: An apparatus and method for minimally invasive surgery. The apparatus can comprise a tool which includes a multi-functioning end effector for insertion into a patient, a user control adapted for use by the surgeon external of the patient, and an intermediate section between the end effector and the user control to translate control instructions from the user control through an actuating mechanism to operate the end effector in one of at least two different functioning states. No instrument exchange is necessary to change between states. The actuation mechanism could be a manually operated mechanical mechanism. Alternatively, it could be partially or fully electromechanical or electrical or electronic. According to one aspect, the end effector is a rigid link mechanism. According to another aspect, the end effector could be a compliant mechanism, at least in part. Another aspect of the invention includes the ability of the end effector to have at least some articulation in addition to grasping and cutting functions.



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**TITLE: MULTIFUNCTIONAL TOOL AND METHOD FOR
MINIMALLY INVASIVE SURGERY**

REFERENCE TO RELATED APPLICATIONS

This application is based upon U.S. Provisional Application Ser. No. 60/310,314, filed August 6, 2001, and Ser. No. 60/310,315, filed August 6, 2001.

INCORPORATION BY REFERENCE

The entire contents of U.S. Provisional Applications Ser. Nos. 60/310,314, and 60/310,315, both filed August 6, 2001, are incorporated by reference herein.

I. BACKGROUND OF THE INVENTION

A. Field of the Invention

This invention relates to Minimally Invasive Surgery tools and methods, and in particular, to multifunction tools and methods.

B. Problems in the Art

Recent advances in the medical sciences have lead to the continued acceptance of Minimally Invasive Surgery ("MIS"). Originally envisioned as far back as about 1900, MIS is today being considered as a replacement to traditional "open" surgeries throughout the body including the chest, spine, abdomen, and pelvis. The major difference between MIS and traditional surgery is the surgeon's access to the patient. During MIS, the surgeon makes several small incisions (under one centimeter) in the patient's skin to gain access to the patient's body. Through one of these incisions is placed the endoscope – a narrow cylindrical scope attached to a camera. The remaining ports allow a variety of specially designed surgical instruments to enter the operating area.

MIS offers many significant advantages to conventional surgery. Traditionally, most postoperative problems have been a result of the large wounds left from open surgery. This leads to long hospital stays, lengthy aberration from normal life, high health care costs, and great personal pain and discomfort. MIS has the potential to reduce recovery time from weeks to days. Furthermore, MIS reduces bowel handling and serosal drying – the two major causes of recovery irritation (Cuschieri, Alfred, 1992. Laparoscopic Biliary Surgery. Oxford: Blackwell Scientific, 1992, pp. 26-98.)

1 While MIS offers many potential benefits to the patient, there are a number of
2 obstacles standing in the way of more widespread use. First, the surgeon cannot view the
3 operating area in three dimensions. This is a result of the endoscope's image being
4 displayed on a television monitor. Second, the perception of distances within the body is a
5 function of their orientation with respect to the endoscope. Objects that are closer to the
6 endoscope will appear much larger than objects that are further away (Cuschieri, 1992.
7 *Id.*). Finally, the surgical instruments themselves continue to be a limiting factor in the
8 advancement of MIS because of limited mobility and lack of multifunctionality. While the
9 first two of these obstacles can be overcome with practice and proficiency on the surgeon's
10 part, the third suggests the need for the development of new and innovative tools for MIS.

11 There is a need in the art for more versatile tools for MIS that have the potential to
12 expand the capability of MIS surgical instruments currently commercially available. To
13 meet this goal, a number of current limitations have been identified.

14 First, most conventional tools possess only four degrees of freedom. These include
15 translation along the longitudinal axis of the instrument, rotation around the longitudinal
16 axis of the instrument, relative rotation around the entry point of the instrument to the
17 body, and the opening and closing of the gripper's jaws (Melzer, AQ., G. Buess, and A.
18 Cuschieri, 1992. *Operative Manual of Endoscopic Surgery*. Berlin: Springer Verlag,
19 1992, pp. 14-36.) Due to the kinetic qualities of the human hand and arm, during open
20 surgery the surgeon can perform movements of approximately twenty degrees of freedom
21 (Melzer, 1996. "Endoscopic Instruments -- Conventional and Intelligent.", *Endosurgery*,
22 New York: Churchill Livingstone, 1996, pp. 69-95.) Because the conventional surgeon's
23 motion is virtually unimpeded by external constraints, the minimally invasive surgeon
24 loses a significant amount of control due to limited degrees of freedom.

25 Second, there is a need for multifunctional MIS tools. Multifunctional tools could
26 provide several advantages over standard single function tools. Studies have shown that
27 10-30% of total operating time is used for changing between tools with single functions
28 (Metzler 1996, *Id.*). Multifunctional tools have the potential to reduce tool changeover
29 time by having the ability to perform two or more previously distinct functions in one.
30 Besides increasing operative time, tool changeover can lead to uncontrollable bleeding.
31 During a tool switch the tissue being worked on needs to be subsequently grasped,
32 coagulated and transected before a new tool can be inserted. Bleeding may occur at any

1 point during this process immediately impeding the view of the surgeon (Melzer 1996, *Id.*).
2 Studies have shown that the primary reason for converting from a minimally invasive
3 technique to open surgery is uncontrollable bleeding (Cuschieri, A., F. Dubois, J. Mouiel,
4 P. Mouret, H. Becker, G. Buess, M. Trede, H. Troild, 1991. "The European Experience
5 with Laparoscopic Cholecystectomy." *American Journal of Surgery*, Vol. 161, pp. 385-
6 387.) Exchange time, disruption of process flow for the surgical procedure, risk of tissue
7 injury, and other issues regarding tool utilization in MIS are discussed in more detail at
8 Mehta, N., Haluck R., Frecker M., Snyder, A. (2002) *Sequence and Task Analysis of*
9 *Instrument Use in Common Laparoscopic Procedures*. *Surgical Endoscopy*, **16**, 280-285.

10 Third, minimally invasive surgical tools are only mobile around the fixed access
11 point of entry into the operating area. Once an initial insertion is made into a patient, a
12 fixed trocar sleeve is put in place through which tools can then be slid in and out. The
13 trocar sleeve defines a conical section in the operative cavity that will be accessible with
14 the surgical instrument. The limitations of this conical section require significant manual
15 dexterity on the part of the operating surgeon (Cuschieri, 1992, *supra*).

16 Fourth, conventional tools lack the ability to reach behind obstructions. There are a
17 number of instances during surgery that the surgeon needs to access a point behind a vessel
18 or tissue. Presently available tools make this motion impossible and require the surgeon to
19 find a different, less optimal, line of approach.

20 There are a number of issues that must be dealt with when developing a new
21 minimally invasive tool. The first of these issues is reusability. A reusable instrument is
22 one that can be re-used. If an instrument is to be reusable then it must have the ability to
23 be completely sterilized. In order to be sterilized, the instrument must have the ability to
24 withstand autoclave temperature of 15 to 120°C or gas sterilization temperature of 127°F
25 with 100% humidity (Cappelleri, D., M. Frecker, T. Simpson, and A. Snyder. 1999. "A
26 Metamodel-Based Approach for Optimal Design of a PZT Bimorph Actuator for
27 Minimally Invasive Surgery." *ASME Journal of Mechanical Design*, **24**, 2, pp. 354-357.)
28 Alternatives to reusable instruments are disposable instruments. Disposable instruments
29 greatly reduce preparation time by eliminating the need for sterilization. However, using
30 disposable instruments is approximately ten times most costly than using reusable
31 instruments. Furthermore, disposable instruments tend to be less precise than reusable
32 ones and raise ecological concerns (Melzer, 1996, *Id.*).

1 Another issue is the ergonomics of the instrument. It has been suggested that an
2 MIS instrument handle has to function independently of the rotation of the instrument tip.
3 Expanding this axiom to a multi-degree of freedom design, preferably all degrees of
4 freedom must function independently of one and other. Additionally, all functions of the
5 instrument preferably must be capable of being carried out with one hand.

6 There are a number of present design preferences for a MIS grasping tool including
7 but not limited to opening width of jaws, length of jaws, response time of jaws, and force
8 required to clamp a suture needle.

9 The maximum diameter of the tool is limited by the inner diameter of the trocar
10 sleeve being used in surgery. Presently trocar sleeve inner diameters of twelve, nine,
11 seven, five, and three millimeters are in common use. The trend in MIS is towards
12 instruments of smaller and smaller diameters. This trend places more emphasis on the
13 development of instruments at the smallest end of the available spectrum.

14 Therefore, a need in the art has been identified, namely the need for a new tool for
15 MIS that responds to the current limitations and the general requirements of minimally
16 invasive instruments.

17 There have been several attempts at creating a multi-degree of freedom gripper
18 prior to this paper. An example of a commercially available multi-degree of freedom
19 gripper is called the Roticulator™ available from USSC, Norwalk, CT, USA. The
20 Roticulator achieves its fifth degree of freedom with the addition of a semi-rigid link
21 between the handle and the jaws of the instrument. As the link is extended beyond the
22 confinement of the handle, the stresses caused by the handle are released allowing the link
23 to return to its naturally curved shape. When the link is fully extended, the gripper is at
24 approximately a 63.5-degree angle with the centerline of the instrument. One issue is the
25 Roticulator's inability to resist a force perpendicular to its jaws when extended. To combat
26 this problem, surgeons have taken to placing a clamp on the instrument such that the tool
27 cannot rotate along the long axis of the instrument. This allows the tool to resist a
28 perpendicular force however it also eliminates a degree of freedom from the instrument.
29 This returns the tool's capabilities to the standard three degrees of freedom.

30 Furthermore, as the instrument is rotated around its long axis, the tip sweeps out a
31 circle. This is substantially different from the traditional gripper which exhibits simple
32 rotation about its axis during the same action. As a result, the axial orientation of the tip

1 cannot be changed in the extended position without considerable experience on the part of
2 the surgeon (Melzer, 1996, *supra.*).

3 A. Melzer et. al. have proposed meeting the need for instruments with increased
4 degrees of freedom by introducing a controllable ball-and-socket joint into the shaft of a
5 gripper (Melzer, 1992, *supra.*). Every movement of the handle at the outer joint would be
6 translated to a similar movement of the inner ball-and-socket. Such an instrument would
7 be based on the mechanical remote-control grasper currently used in advanced industrial
8 applications (Melzer, 1992, *Id.*). Presently, it is not believed that such a design has
9 advanced beyond the conceptual phase for use in MIS.

10 In order to allow a gripper's tip to both pivot and rotate, the axis of pivot preferably
11 should lie along the centerline of the instrument. A need has been identified in the art to
12 achieve this criterion.

13 II. SUMMARY OF THE INVENTION

14 A. *Brief Summary of the Invention*

15 The present invention includes apparatus and methods for MIS. One apparatus
16 comprises a tool which includes a multi-functioning end effector for insertion into a
17 patient, a user control adapted for use by the surgeon externally of the patient, and an
18 intermediate section between the end effector and the user control to translate control
19 instructions from the user control through an actuating mechanism to operate the end
20 effector in one of at least two different functioning states. No instrument exchange is
21 necessary to change between states. The actuation mechanism could be a manually
22 operated mechanical mechanism. Alternatively, it could be partially or fully
23 electromechanical or electrical or electronic. According to one aspect, the end effector is a
24 rigid link mechanism. According to another aspect, the end effector could be a compliant
25 mechanism, at least in part. Another aspect of the invention includes the ability of the end
26 effector to have at least some articulation in addition to other functions.

27 In one aspect of an apparatus according to the invention, the end effector includes
28 first and second jaws. The jaws include surfaces that can effectuate grasping or dissecting,
29 or surfaces that can effectuate cutting by scissors action. Compliant or non-compliant
30 structure between the jaws and actuating mechanism facilitates translation of actuation
31 movement to movement of cutting edges or blades on jaws in a scissors action. Another

1 aspect utilizes compliant structure to enable not only movement of jaws relative to one
2 another in a first plane, but conversion between operation of the tool in such a first state,
3 where the jaws move towards and away from each other in response to a first actuation or
4 input force, but also operation in a second mode or state where jaws move towards and
5 away from each other in response to a second actuation or input force. In one aspect, the
6 device automatically switches from state to state dependent on the input force or the
7 selection of actuation. In one aspect, the device automatically switches from state to state
8 dependent on the input force or the selection of actuation.

9 In a further aspect of an apparatus according to the invention, each jaw is along a
10 longitudinal axis between a proximal end and a distal end, and has a grasping surface along
11 at least a portion of it. A cutting surface or blade is formed in or positioned on or in the
12 margin of one side of the grasping surface of each jaw. In one embodiment, when the
13 grasping surfaces of the jaws are brought together, the cutting blades are on opposite sides
14 for each jaw, but near or in the same plane as the grasping surface of its jaw. When in the
15 first state, the jaws are aligned with the grasping surface of each jaw facing each other and
16 the jaws are moveable generally in a first plane relative to one another between a closed
17 position, where grasping surfaces of the jaws come in close proximity, or into abutment at
18 least at some points, and an open position where there is separation between grasping
19 surfaces. Actuation pivots the jaws between open and closed positions in the first
20 functional state for the tool. When in the second functional state, the blades of the jaws are
21 aligned and moveable by actuation generally in a second plane relative to one another
22 between a closed position, where cutting blades come into close proximity or overlap one
23 another, and an open position where there is separation between cutting blades. Actuation
24 pivots the cutting blades, generally in the second plane in a scissors action between open
25 and closed positions. Actuation forces can be translated to the blades by compliant or non-
26 compliant mechanism(s), or combinations thereof.

27 In one aspect of the invention, at least one jaw has a distal section that is
28 mechanically linked to a proximal section. The distal section can move in the second plane
29 when the tool is in the second functional state (the cutting state), but moves in the first
30 plane in the first functional state (the grasping state).

31 In another aspect of the invention, both jaws have distal sections that are
32 mechanically linked to their respective proximal sections. The distal sections can move in

1 the second plane when the tool is in the second functional state, but move in a first plane in
2 the first functional state.

3 In a still further aspect of the invention, if both jaws have mechanically linked
4 distal sections, those sections can be articulated in the second plane. The articulation can
5 either be in the same direction; to create articulated grasping jaws to either side of the first
6 plane. When the jaws are moved in the first plane, the articulated distal sections function
7 as articulated grasping or dissecting jaws. If the articulation of the distal sections is in
8 opposite directions and the jaws are in a closed position, the distal sections can be moved
9 relative to one another to create two moving scissors blades.

10 In a method according to one aspect of the invention, multiple functions from an
11 end effector can be performed without tool exchange by actuating jaws inside the patient to
12 bring grasping surfaces towards and away from one another in a first functional state, and
13 actuating the jaws so that at least portions of the jaws having cutting surfaces can be
14 brought towards and away from one another in a second functional state. In a further
15 aspect of a method according to the invention, the movement of the jaws in first and
16 second states could be by mechanical linkage or by compliant mechanism. In another
17 aspect, articulation of a section of the jaws adds another function to the end effector.

18 ***B. Objects, Features, or Advantages of the Invention***

19 Multi-functionality in minimally invasive surgery tools and methods is expected to
20 benefit both surgeons and patients by decreasing the number of tool exchanges required,
21 shortening operation time, reducing risk of inadvertent tissue trauma during instrument
22 exchanges, and minimizing disruption of the surgeon's train of thought during a procedure.
23 Having a multifunctional instrument may result in improved surgical techniques since the
24 surgeon will be less likely to use a single function tool for purposes other than its intended
25 purpose. The articulating feature will also add to the versatility of the instrument allowing
26 the surgeon to have non-linear access, which is currently unavailable from existing single
27 function tools.

28 It is therefore a principle aspect, object, feature, or advantage of the present
29 invention to provide an apparatus and method for MIS, which improves over and/or solves
30 problems and deficiencies in the state of the art.

31 Further aspects, objects, features, or advantages of the present invention include an
32 apparatus and method for MIS which:

- 1 (a) is flexible and versatile, including the capability of multifunction and
2 substantial degree of freedom of movement.
- 3 (b) Easily, efficiently, and effectively changes between functions;
- 4 (c) Does not substantially increase size or cost of the apparatus, and may be
5 amenable to miniaturization or automation;
- 6 (d) Reduces time needed for operative procedures;
- 7 (e) Reduces disruption of the process flow of the operation;
- 8 (f) Reduces risk of injury during operations;
- 9 (g) May be implemented in resposables and disposables;
- 10 (h) Retains most or all needed functional requirements of MIS;
- 11 (i) Is durable;
- 12 (j) Is economical;
- 13 (k) Increases the effectiveness of the surgeon and the surgery.

14 These and other aspects, objects, features, or advantages of the invention will
15 become more apparent with reference to the accompanying specification and claims.

16 **III. BRIEF DESCRIPTION OF THE DRAWINGS**

17 Figure 1 is an elevational view of a MIS tool with a multi-functional end effector
18 according to one embodiment of the invention.

19 Figure 2 is an enlarged perspective view of an end effector according to an
20 embodiment of the present invention that could be used with the tool of Figure 1 showing,
21 for generally a side view, the end effector in a first or grasping state (jaws open).

22 Figure 3 an enlarged view of the end effector of Figure 2 but in top plan view and
23 in a second or scissors state (jaws open).

24 Figure 4A is an enlarged view of an embodiment of a actuating handle that could be
25 used with the tool of Figure 1, with portions exposed to show the inner working
26 components of the handle.

27 Figure 4B is an enlarged sectional view taken from the perspective of line 4B-4B of
28 Figure 4A.

29 Figures 5 and 6 show diagrammatically how selection between multiple functions
30 for the end-effector is accomplished at the handle of Figure 4A.

31 Figure 7 is an enlarged perspective view of an end effector for an alternative
32 embodiment according to the present invention. Figure 7 shows a compliant mechanism

1 end effector with its jaws in a normal, neutral or unactuated state, where the jaws have
2 grasping surfaces which are separated less than a maximum amount.

3 Figure 8 is an enlarged end view of the end effector of Figure 7.

4 Figure 9 is similar to Figure 7 but shows the grasping jaws actuated to an open
5 position greater than the neutral position of Figure 7.

6 Figure 10 is similar to Figure 9, but showing the end effector in a grasping state
7 with the jaws in a closed position.

8 Figure 11 is similar to Figures 7, but shows the end effector in a second, different
9 function state, a scissors state with the distal end of the end effector in an open scissors
10 position.

11 Figure 12 is a set of diagrams relating to design of the compliant end effector of
12 Figures 7-11 by topology optimization.

13 Figure 13 is a perspective diagram of the initial solid model based on the solution
14 of Figure 12.

15 Figure 14 is a simplified perspective view of a handle design for the compliant end
16 effector of Figure 7, showing in a cut-away or exposed fashion the inner-actuating
17 components.

18 Figure 15 is a diagrammatic illustration of a system for a semi-robotic use of the
19 compliant end effector such as that shown in Figure 7 and an electroactive actuator.

20 Figures 16A and 16B are graphs showing experimental data of a simulated
21 operation of the compliant end effector of Figure 7.

22 Figure 17A is an isolated perspective view of a third embodiment according to the
23 present invention, showing a multi-functional end effector comprising grasping and cutting
24 jaws, shown in a grasping state (closed position). The jaws are also articulatable.

25 Figure 17B is similar to Figure 17A but shows the end effector in a grasping state
26 (open position).

27 Figure 17C shows the end effector Figure 17A converted to a scissors state or mode
28 with the scissoring sections of the jaws in an open position.

29 Figure 17D shows the end effector of Figure 17A in a third functional position,
30 where distal sections of the jaws are articulated to the side of the centerline of the end
31 effector and the jaws are open in a grasping mode such that the articulated distal sections of
32 the jaws can function as articulated grasping jaws.

1 Figure 17E is similar to Figure 17D but shows the jaws in a closed articulated
2 grasping position.

3 Figures 18A-B are simplified diagrams illustrating how the end effector of Figure
4 17A-E can function as straight grasping jaws, as scissors, or as articulated grasping jaws.

5 Figure 18C is a further illustration of articulation.

6 Figure 19A is a more detailed, enlarged, isolated view of an end effector of the
7 style of the embodiment of Figure 17A-E, further showing structure for allowing
8 mechanical linkage mechanism grasping actuation of the end effector jaws, illustrating the
9 jaws in a grasping state, closed position.

10 Figure 19B is similar to Figure 19A, but shows actuation of the jaws to an open
11 grasping position.

12 Figure 19C is similar to Figure 19B showing actuation of the jaws to an open
13 grasping position with the distal sections of the jaws articulated to the left of the centerline
14 of the end effector.

15 Figures 20A-C are simplified diagrams illustrating how side to side articulation of
16 distal sections of jaws through a cabling arrangement can be produced.

17 Figure 20D is a top plan view of the end effector of Figures 17A-D illustrating how
18 cabling or wires to the articulatable distal sections of each jaw would be connected.

19 Figure 20E is similar to Figure 20D, but shows an alternative cabling connection.

20 Figure 21A is an isolated simplified perspective view of handle for the embodiment
21 of Figure 17A-E, with an exposed view of the interior working components of the handle.

22 Figure 21B is an exploded perspective view of some of the interior working
23 components of the handle of Figure 21A.

24 Figure 21C is an enlarged simplified diagrammatic illustration of some assembled
25 interior working components of the handle of Figure 21A, and the relationship of such
26 components to other interior working components of Figures 21A and B.

27 Figures 22A-E are diagrammatic illustrations of the parts of the inside of the handle
28 of Figure 21A, illustrating the different configurable modes selectable by the surgeon for
29 different functional modes or states of the end effector of Figures 17A-E.

30

1 **IV. DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS OF THE** 2 **INVENTION**

3 *A. Overview*

4 To provide additional understanding of the invention, exemplary embodiments
5 according to the invention will now be described in detail. Some of the exemplary
6 embodiments and the principles related to these embodiments are illustrated in the
7 appended drawings. Frequent reference will be made to the drawings in this detailed
8 description. The same reference numbers will be used to indicate the same or similar parts
9 or locations throughout the drawings unless otherwise indicated.

10 It is to be understood that these exemplary embodiments are provided for
11 illustration of some of the forms the invention can take, and not by way of limitation.

12 *B. General Apparatus Features and Methods*

13 The general context of the exemplary embodiments will be made with reference to
14 MIS surgery, such as laparoscopy. Most of the embodiments will have at least a multi-
15 function end effector that can grasp or cut by scissors action. These are exemplary of
16 functions of the tool. These functions, as well as additional functions or variations of the
17 functions obvious to those skilled in the art, will be included within the scope of the
18 invention.

19 Additionally, certain basic design choices are preferred for the exemplary
20 embodiments, but are not limiting to the general invention. For example, for these
21 exemplary embodiments, an outer diameter of five millimeters is chosen such that the tool
22 can fit through a five-millimeter trocar sleeve. Other outer diameters, many bigger than
23 this, are currently in use in the state of the art. This choice was made in response to the
24 trend towards smaller minimally invasive tools. The articulating tip has been chosen to
25 reach a maximum angle of at least sixty degrees. At the fully rotated positions, the tip
26 preferably can be at least five millimeters from the centerline of the tool. The tool
27 preferably meets the general requirement of a total length of between one and half and
28 three centimeters in total length. It preferably grasps a 0.5 mm suture needle or tissue,
29 opens at least 8 - 15 mm and closes completely. It is preferably between 1 and 3 cm in
30 length, opens or closes in under two hundred ms, and imposes a force sufficient to grasp
31 tissue or a needle. As can be appreciated, these design choices for the exemplary

embodiments are not limiting to the invention, and can vary according to design needs and choices.

C. Exemplary Embodiment One (Non-compliant multi-function cutting and grasping)

1. Structure

By referring to **Figures 1-3**, a first exemplary embodiment designed for use as a minimally invasive surgical instrument is shown and will be referred to as mechanism or tool **10**. As generally illustrated in **Figure 1**, mechanism **10** consists of a handle **12** with mechanical controls, connected to a 32.5 cm long shaft **14** with proximal end **16** and distal end **18**, and 5 mm diameter end-effector **20** (shown in open state) at the end of a distal shaft **18**. In this embodiment, a surgeon inserts one or more fingers in fixed grip **22**, and thumb of the same hand in pivoting grip **24**. Relative movement between grips **22** and **24** (here by rotation of moveable handle **24** in either direction indicated by arrow **25**) by manual hand movement of the surgeon causes movement of the jaws of end effector **20**. These general features are similar to existing MIS tools.

As is also conventional, tool **10** includes a control wheel (rotation knob) **28**, also manually manipulatable (rotatable in either direction indicated by arrow **29**) by the surgeon with the same hand (e.g. index finger), which in turn causes like rotation of shaft **14** and/or other connecting structure. This allows 360 degrees rotation of the orientation of the jaws of end effector **20**.

However, tool **10** is multi-functional in the sense that, depending on the surgeon's positioning of manually selectable switch **26**, the jaws of end effector **20** either grasp (or dissect) or cut (by scissors action). The selection, or change in selection, between those two functions or states, can be done quickly and easily by the surgeon, on the fly, and with the same hand as is used to move the jaws of end effector **20**.

2. End-Effector

Figures 2 and 3 illustrate an end effector **20** in accordance with an aspect of the present invention, and illustrate how grasping and scissors functions can be effectuated from the same end effector **20**. First jaw **30** is elongated between a proximal end **32** and a distal end **34**, and has a grasping surface **36** (which could have portions serrated), an opposite side **38** from the grasping surface, and opposite side walls **40** and **42** between grasping surface **36** and side **38**. Jaw **30** is pivotable about pivot axis **52** defined by pivot

1 pin 46, which is insertable and held in place as shown in distal end 18 of shaft 14. Pivot
2 axis 52 crosses at or close to, and is orthogonal with, central or longitudinal axis 50.

3 Proximal end 32 of jaw 30, on the opposite side of pivot axis 52 from grasping
4 surface 36 of jaw 30, is a pin-in-slot joint connected by a pin 48 to the distal end 58 of a
5 tube or sub-shaft 56 extending from a proximal end 57 in handle 12 through the interior of
6 shaft 14. Movement of sub-shaft 56 along longitudinal axis 50 of shaft 14 causes proximal
7 end 32 of jaw 30 to displace from axis 50, but also change relative fore or aft position
8 along axis 50, which in turn causes jaw 30 to pivot about axis 52 aligned with axis 50, and
9 thus move between a closed position, such as shown in **Figure 3** (near and in alignment
10 with axis 50), and an open position shown in **Figure 2**, extending at an angle from axis 50
11 (see arrow 100 of **Figure 2**). Movement of jaw 30 from closed towards open position is
12 effectuated by moving sub-shaft 56 in a proximal to distal direction. Movement of sub-
13 shaft 56 in an opposite direction moves jaw 30 from open towards closed.

14 Second jaw 60 has two pieces or sections. A fixed section 62 has a proximal end
15 64 fixed to the end of shaft 14 (e.g. welded, pinned, set screw, etc.) and a distal end 66 that
16 extends parallel to axis 50. A moveable section 68 is pivotally connected by pivot pin 70
17 to fixed section 62 and can pivot about axis 54. Pivot axis 54 crosses at or near, and is
18 generally orthogonal to, axis 50, but is also generally orthogonal to axis 52.

19 Moveable section 68 has a proximal end 72 that is pivotally connected by pin 74 to
20 link arm 76, which is itself pivotally connected by pin 78 to the distal end 84 of a second
21 tube or sub-shaft 80 extending from its proximal end 82 in handle 12 through the interior
22 of shaft 14. Pin 74 is on an opposite side of pivot axis 54 from distal end 73 of section 68,
23 and is also to one side of the longitudinal axis of section 68. As can be appreciated,
24 longitudinal movement of sub-shaft 80 causes moveable section 68 of jaw 60 to move
25 between a position generally aligned with axis 50 (see **Figure 2**) to a position pivoted
26 angularly to axis 50 (see **Figure 3**). If section 68 is in the position of **Figure 2**, movement
27 of sub-shaft 80 in a proximal-to-distal direction in shaft 14 causes link arm 76 to push
28 proximal end 72 of section 68 out to the side of axis 50 (see **Figure 3**), which causes distal
29 end 73 of section 68 to swing away from axis 50 in an opposite direction (see **Figure 3**).
30 Section 68 can be moved back to alignment over jaw 30 by reverse movement of sub-shaft
31 80.

As can be seen, sections 62 and 68 of jaw 60, when aligned, approximate the length and shape of jaw 30, and have grasping surfaces that align with similar surfaces on jaw 30. But further, jaw 30 has a sharp edge or blade 90 along a portion of a side margin of its grasping surface 36. Blade 90 is in alignment with a sharp edge or blade 92 (when jaws 30 and 60 are brought together) on an opposite side margin of the grasping surface of jaw 60; in particular, along a side margin of moveable section 68 of jaw 60. Thus, by appropriate design, blades 90 and 92 can pass one another in very close proximity, or even in frictional abutment, to provide cutting by scissors or shearing action, by closing jaws 30 and 60 (by pulling sub-shaft 56 proximally) and reciprocating sub-shaft 80.

Components for end effector 20 are preferably surgical quality metal (e.g. stainless steel, titanium, etc.). Wire electrical discharge machine (EDM) or metal injection molding processes are attractive fabrication methods, because of the small feature sizes involved. Some exemplary dimensions and specifications for one example of tool 10 are as follows:

Component	Length
Jaws (Total length, non-articulated)	15 mm
Jaws opening distance at distal ends for grasping	15 mm
Scissors blade length	7 mm
Scissors opening distance at distal ends	10 mm

3. Handle

End effector 20 could be actuated through traditional mechanical means such as tendon wires or push rods, which could be used with linkages similar to those in existing MIS tools. Many current tools have the surgeon manually open or close a handle that applies tension to a tendon wire. The wire then actuates a slider/crank mechanism that opens or closes the jaws. A tension spring could render the jaws normally closed or normally open. Other actuation mechanisms are possible.

Therefore, there are many available choices as to ways to create and translate or transfer movement or force generated at a position away from the end effector, out to the end effector. In the case of tool 10 of Figures 1-3, linear push-pull force is used to actuate

1 the end effector **20**; in particular, linear push pull force to move jaw **30** in a first plane, and
2 linear push-pull force to move tip **68** of jaw **60** in a second plane.

3 Alternatively to mechanical actuation, electrical actuation could be used by
4 replacing the tendon wire with, e.g., a piezoceramic actuator, shape memory alloy actuator,
5 or electroactive polymer embedded in or connected to the tool's end effector. A handle
6 similar to those on contemporary MIS tools would then control the amount of voltage
7 applied to the actuation device, which would in turn control the position of the tool's jaws.
8 The latter type of actuation system would also allow for amplified force feedback with the
9 incorporation of a force sensor.

10 Other types of actuators possible include, but are not limited to, pneumatic,
11 hydraulic, electroactive or combinations of the same, or combined with mechanical and/or
12 electrical components. Therefore, the precise type of actuation can be selected according
13 to design choice or need. One specific example of a mechanical actuator mechanism is
14 shown in **Figures 1-4**, and is now described in more detail.

15 Referring to **Figures 1-4**, and assuming, in a first case, that jaw **60** is in the
16 longitudinally aligned position of **Figure 2** and that switch **26** is set for clamping action,
17 rotating handle **24** toward fixed handle **22** closes jaws **30** and **60** of end effector **20**
18 (generally in the direction shown by arrow **100** in **Figure 2**, in a plane defined by axes **50**
19 and **54**). Rotating handle **24** away from handle **22** opens jaws **30** and **60** (in that same
20 plane of arrow **100**). The shaft rotation wheel **28** (Fig. **1**) is used to change the rotational
21 position of the end-effector about its axis **50**. Thus, in this case (the "clamping" state or
22 mode of tool **10**), the surgeon sets tool **10** for clamping with thumb switch **26**, and can
23 open and close jaws **30/60** for clamping action by changing the relationship of handles **22**
24 and **24** to each other. Jaw **60** is essentially fixed and jaw **30** moves towards and away from
25 it to clamp or dissect. Of course, handle **12** can be moved in three space, to the extent
26 possible given the constraints of MIS, to position end effector **20** inside the patient.

27 In a second case, assuming jaw **30** is in a closed position (Fig. **3**) and switch **26** is
28 set for scissors action, rotating handle **24** away from handle **22** would cause moveable
29 section **68** of jaw **60** to rotate out from axis **50** towards the position in Fig. **3** (generally in
30 the direction shown by arrow **102** in **Figure 3**, in a plane defined by axes **50** and **52**).
31 Rotating handle **24** toward handle **22** brings moveable section back to jaw **30** (in that same
32 plane of arrow **100**). Thus, in this case (the scissors state or mode of tool **10**), the surgeon

1 sets tool **10** for clamping with finger switch **26**, and can open and close jaws **30/60** for
2 clamping action by changing the relationship of handles **22** and **24** to each other. Here jaw
3 **30** is essentially fixed in place, and jaw **60** moved towards and away from it (although in a
4 different plane than when in clamping mode), to give scissors or shearing action.

5 As previously explained, multi-function is controlled by which sub-shaft **56** or **80** is
6 moved relative end effector **20**. If sub-shaft **56** is moved, jaw **30** pivots and end effector **20**
7 can be used in grasping mode. If sub-shaft **80** is moved, moveable section **68** of jaw **60**
8 pivots, enabling a cutting mode by scissors action. There are a wide variety of ways
9 selective linear actuation of one of two sub-shafts can be accomplished. In this
10 embodiment, rotational movement of moveable handle **24** is translated to linear movement
11 to actuate one or the other of sub-shafts **56** or **80**. One example is described with respect to
12 **Figures 4A-C**, which are highly diagrammatical illustrations of the structure and its
13 operation, as opposed to precise, scaled mechanical views.

14 Each sub-shafts **56** and **80** is a half circular push rod (half-moon shaped in cross-
15 section and oriented through shaft **14** as shown in **Figure 4B**). Their proximal ends **57** and
16 **82** are fixed to collars which connect with U shaped brackets **94** and **96** respectively. A set
17 screw, eccentric clamp, or other releasable connector fixes proximal ends **57** and **82** to its
18 respective collar and bracket **94** or **96**, which are slideable within handle **12**, for example
19 along a track or other retaining structure (shown diagrammatically at ref. no. **98**). Thus, if
20 bracket **94** is slid along track **98**, only sub-shaft **80** will move linearly. Conversely, if
21 bracket **96** is slid on track **98**, only sub-shaft **56** will move.

22 The toggle switch **26** on top of handle **12** controls whether the tool is in cutting or
23 grasping, i.e. selects between translating rotational movement of handle **24** to bracket **96** or
24 **94**. Mechanical links **104** and **105** extend from brackets **94** and **96** rearwardly in handle **12**
25 through channels **114A** and **B** respectively in toggle switch **26**, and terminate in free ends
26 that include a transverse pin extending through and outwardly on opposite sides of each
27 free end of links **104** and **105** (see pin ends **106** and **107** for the free end of link **14**, and pin
28 ends **108** and **109** for the free end of link **105**). A through-hole **110** in the end of handle **24**
29 on the opposite side of handle pivot **112** aligns along an axis **119** when handle **14** is
30 brought to a reference position (e.g. end of travel away from handle **22**). Holes **113A** and
31 **B**, in the interior sides of opposite side walls **13A** and **B** of handle **12**, also are along axis
32 **119**.

Switch **26** is slideable laterally relative to the top of handle **12** between two opposite extremes (here called "right" and "left" relative to the top views of **Figures 5** and **6**). Sliding switch **26** to the right (as shown at arrow **115** in **Figure 5**), shifts both links **104** and **105** to the right. In turn, pin **107** of link **104** enters bore **110** of handle **24** and pin **108** of link **105** enters hole **113A** of wall **13**. Mechanical connection is accomplished between handle **24** and bracket **94**, while handle **24** is disengaged from connection to bracket **96** (and, in fact, bracket **96** is locked against movement by link **105** being held fixed to wall **113** by pin **108**). Rotational movement of handle **24** would be translated into linear movement (see arrow **116** of Fig. **5**) by handle **24**'s pivotal connection to link **104** by pin **107**, which would slide bracket **94** (see arrow **117** in Fig. **5**) and thus linearly move half shaft **80** (see arrow **118** in Fig. **5**) to operate cutting action for tool **10**.

On the other hand, clamping mode is shown in **Figure 6**. Sliding switch **26** to the left (arrow **115** in Fig. **6**) causes links **104** and **105** to follow to the left and move pin **109** of link **105** into hole **110** in handle **24**, and pin **106** of link **104** into hole **113B** in opposite handle wall **13B**. This locks link **105** to move with movement of handle **14**, and locks out link **104** from movement. Movement of handle **24** would be translated to linear movement of link **105** (arrow **116**, Fig. **6**), which causes linear sliding of bracket **96** (arrow **117**, Fig. **6**), which causes linear movement of half-shaft **56** (arrow **118** of Fig. **6**), which effectuates clamping action of end effector **20**. Essentially, one of the U-brackets is locked into place while the other is free to move and is actuated by rotating the moving handle **24**. When the toggle **26** is switched, the other set of linkages is locked and the second set is connected to the moving handle. Thus, tool **10** is given multi-function by simple toggle switching between modes or states at handle **12**.

The components of handle **12** can be fabricated using standard and CNC milling machines, such as are well known, or by other methods.

4. Lumen or Shaft **14**

In this embodiment, both shaft **14** and end effector **20** (when jaws **30** and **60** are closed and aligned along axis **50**) are designed to fit in a 5 mm port. But, of course, it can be designed for other sizes of trocars (e.g. 3-12 mm) likewise. Still further sizes are possible.

Sub-shafts **56** and **80** could be adjacent or in abutment through shaft **14**.
Alternatively, they could be concentric (one or both being tubular). Other configurations are possible.

5. Method of Use

Figures 2 and **3** display end-effector **20** of instrument **10** in its various opened positions. The jaw length, opening dimensions, handle control style and location were determined through collaboration with a practicing surgeon. **Figures 2** and **3** also display the mating surface finishes of the jaws. A textured surface is desirable for grasping; but a smooth, sharp edged surface is needed for cutting. For this reason the front 7 mm section of the jaws are smooth while the rear portion is textured. A small amount of texture was also added at the very distal ends of the jaws to allow for improved grasping ability at the tip.

In one embodiment of the tool of **Figures 1-3**, the following performance features were realized:

Function	Force
Grasping force	1.34 lb.
Maximum Handle force	9.0 lb.
Pull-Off Force	2.5 lb. (using red rubber tubing)
Cutting Force	2.0 lb.

D. Exemplary Embodiment Two (Compliant multi-function cutting and grasping)

1. Structure

A "mechanism" has been defined as a mechanical device used to transfer or transform motion, force, or energy. A "compliant" mechanism also transfers or transforms motion, force, or energy, but, unlike rigid-link mechanisms, compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than from movable joints only. Compliant mechanisms are single piece flexible structures that utilize elastic deformation to achieve motion transmission. The rigid-linked mechanism of tool **10** of **Figures 1-3** could alternatively be implemented in a compliant mechanism.

1 There are a vast number of ways the end effector **20** could be implemented in a compliant
2 mechanism. A variety of methods of design and manufacture of compliant mechanisms
3 are known. Commercially available software exists to assist in design of passive
4 structures. Software has been developed at for the design of compliant mechanisms. A
5 discussion of the same can be found at Dzedzic, R., Frecker, M., Haluck, R. 2002. Design
6 of Multifunctional Compliant Mechanisms for Minimally Invasive Surgery. Minimally
7 Invasive Therapy and Allied Technologies, incorporated by reference herein.

8 **Figures 7-16** illustrate an alternative exemplary embodiment of the invention
9 utilizing a compliant mechanism end effector for multi-function clamping or scissors
10 cutting. This second embodiment, referred to herein as tool **10B**, includes generally a
11 handle **12** (e.g. Fig. 14) with actuating mechanism, an end effector **20** with jaws **30** and **60**,
12 and a shaft **14** connecting handle **12** with end effector **20**.

13 The general principles of tool **10B** are similar to tool **10** of **Figures 1-3**. A user can
14 select between states or modes (clamp or scissors) by finger-operated switch **26** extending
15 out of the housing for handle **12**. If clamp mode is selected, rotation of handle **24** towards
16 or away from handle **22** moves facing clamping surfaces of jaws **30** and **60** towards or
17 away from each other. If scissors mode is selected, rotation of handle **24** towards or away
18 from handle **22** moves blades **90** and **92** in the sides of jaws **30** and **60** towards or away
19 from each other. A rotation control or wheel **28**, fixed to shaft **14**, allows the surgeon to
20 rotate the end effector about axis **50** of tool **10B**. Differences from tool **10** of Figs. 1-4
21 include the following.

22 **2. End-Effector**

23 End effector **20** of tool **10B** is a compliant mechanism. It includes what will be
24 called a compliant web **120** of flexible members between an attachment end **122** adapted
25 for attachment to shaft **14**, and a distal end **124** which forms an integral junction with jaws
26 **30** and **60**.

27 One difference from tool **10** is that the compliant end effector **20** of tool **10B** has
28 what is called a "neutral" position (Fig. 7) for clamping mode, which exists when no forces
29 are applied to proximal end **122**. As shown in Fig. 7, the neutral position comprises jaws
30 **30** and **60** spread apart less than (e.g. approximately 1/2) their maximum distance. The
31 spread is in the plane of axes **50** and **54**.

1 Web **120** here is comprised of multiple flexible members **130A-D** between
2 proximal end **122** and distal end **124**. The material could be titanium or other surgical
3 grade metal.

4 In this version, clamping and scissors modes of tool **10B** could be produced as
5 follows:

6 (a) for clamping action:

- 7 1) A sub-shaft through shaft **14** which is connected to the proximal end
8 of end effector **20B**, can be actuated to apply a predetermined
9 amount of linear pushing force against a point on portion **132** (see
10 **Fig. 8**) of proximal end **122** of end effector **20B**. The portion of **20B**
11 including point **132**, which is substantially concentric to the portion
12 **134** (**Fig. 8**), can move relative to portion **134**. As a result of such
13 force and movement, the flexible members **130**, in combination with
14 a c-shaped member **138**, move in such a manner to spread jaws **30**
15 and **60** at distal end **124** of end effector **20B** farther apart (see **Fig. 9**)
16 than in the neutral position (**Fig. 7**), but in the plane of axes **50/54**.
17 2) A predetermined amount of linear pulling force at point **132** of
18 proximal end **122** would cause flexible members **130** to close jaws
19 **30** and **60** in plane **50/54** (see **Fig. 10**).
20 3) Subsequent opening and closing of jaws **30** and **60** could be effected
21 by repeated those steps.

22 (b) for scissors action:

- 23 1) First, portion **132** is pulled to bring the jaws together as in **Fig. 10**.
24 While holding that position, a sub-shaft through shaft **14** applies
25 predetermined linear pushing force against a point on portion **134** of
26 proximal end **122** of end effector **20B**. As a result of such force and
27 movement, flexible members **130** and C-member **138** move in a
28 manner which reconfigure jaws **30/60** into a scissors mode. The
29 scissors neutral position is closed. Instead of further widening jaws
30 **30/60** in the **50/54** plane, such force at that different position would
31 move jaws **30/60** from the closed position of **Fig. 10**, to a spread
32 position but in the plane of axes **50/52** (see **Fig. 11**), where blades **90**

and **92** formed in opposite side margins of the grasping surfaces of jaws **30** and **60** would be substantially in the same plane.

- 2) Application of a predetermined linear pulling force against a point on portion 134 of proximal end **122**, would then cause convergence of blades **90** and **92** in or near plane **50/52**, such that blades **90** and **92** could converge and slightly overlap for cutting action.
- 3) Release of pulling force would allow jaws **30** and **60** to return to the position of **Figure 11**, ready for another cutting stroke or strokes, if desired.

Conversion back to clamping mode could be accomplished by:

- 1) Applying a predetermined force to point 132 of proximal end **122**, which would move jaws **30** and **60** the plane **50/54**.

In this example of tool **10B** of **Figures 7-11**, the following dimensions exist:

Component	Length
Jaws (Total length)	36 mm
Jaws opening distance at distal ends for grasping	12 mm
Scissors blade length	12.5 mm
Scissors opening distance at distal ends in maximum open position	7 mm

Thus, web **120** and end effector **20** could essentially be manufactured from one integral piece of material, and utilize the design and compliant features to perform the multiple functions performed by the fixed link mechanism of tool **10**.

3. Handle

As indicated by the functional description of compliant end effector **20B**, above, certain linear forces can be translated to the end effector to actuate the end effector in at least two different functional modes or states. A variety of methods could be used to translate linear forces, including linear forces of varying magnitude and direction, to the end effector. One example is shown and described with respect to **Figures 1-4**. Two sub-shafts **56** and **80** provide push and pull linear force to two different points or locations at

the end effector. The actuating force from handle **12** of **Figure 4** could be used to change direction between push and pull for either sub-shaft, but further, manual actuation through handle **24** can provide variable force to either sub-shaft by the amount of rotational force imparted to handle **24** by the amount of squeezing pressure or separation force exerted by the hand of the surgeon relative to handles **22** and **24**.

Another example of an actuation mechanism to supply linear force to the end effector is shown in simplified form at **Figure 14**. **Figure 14** illustrates handle **12** with the interior exposed. Handle **12** for tool **10B** could be similar to handle **12** described with respect to tool **10**. It could deliver linear movement via sub-shafts in shaft **14** which could be used to operate compliant end effector **20** of tool **10B**.

A toggle switch **26**, like described with respect to tool **10**, could determine alignment of the rotational output of handle **24** (could be from a gear arrangement **151, 152** between points **150** and link **142**) with respect to one of two linear movement transmission paths through double slider **148**. A first transmission path would translate rotational movement of handle **24** via gears **151, 152**, to link **144**, which would push the top end of slider **148** fore and aft, depending on direction of movement of handle **14**. The bottom of slider **148** would be connected to a push rod that sends one source of linear movement to the compliant mechanism. A similar transmission path comprises of a second link **144** and second slider **148** could be connected to a second push rod to a second source of linear movement to the compliant mechanism. The precise arrangement and components to accomplish can vary according to design choice.

According to another aspect of the invention, what is called a static balance mechanism could optionally be included with the actuation system. In the case of a compliant end effector made out of titanium, for example, the compliant design will translate external forces into bending movement determined by the configuration of the flexible members in the compliant mechanism to generate the clamping or scissors actions. Application of a force to overcome the inherent stiffness in the compliant mechanism itself is required, before additional force to generate force at the grasping or scissors jaws. A static balance mechanism equalizing the potential energy due to the inherent stiffness of the end effector, so that the surgeon does not feel or have to overcome the inherent stiffness of material when operating the tool. Springs **158** (and another spring on the other side) shown in **Figure 14** are part of one type of static balance mechanism. By

1 selection of their spring constant, position, and the link lengths and orientations of the
2 transmission path of forces between handle **24** (the input) and the linear output of handle
3 **12**, static balance can be achieved.

4 In the above-described manner, manually actuatable linear forces could be
5 transmitted through shaft **14** to end effector **20** to power the clamping/dissecting or scissors
6 actions of jaws **30** and **60**. The conversion between clamp and scissors is accomplished by
7 actuating the toggle switch **26**. Thus, **Figures 7-14** illustrate another exemplary
8 embodiment of a multi-function MIS tool. Static balance could also be added, as
9 described.

10 a) Piezoelectric Inchworm Actuator for the Compliant 11 Embodiment –

12 The compliant embodiment of the present invention can be actuated by means other
13 than a manual actuator as discussed above. A piezoelectric inchworm may be used as an
14 alternative means of actuation for the compliant grasper-scissors. One possible example is
15 a commercially available inchworm actuator from Burleigh, for example. (See, e.g.,
16 http://www.exfo.com/en/products/gf_Family104.asp, Inchworm 800 series).

17 The compliant tool **10B** requires a high actuation force. For instance, the gripper
18 manufactured from titanium requires an actuation force of 10N over a stroke of
19 approximately 0.31 mm to completely close the jaws. In addition, the means of actuation
20 must be small enough to be inserted in tubes currently used in minimally invasive surgery
21 (current tubes often have a diameter of 8 mm). These restrictions make piezoelectric
22 inchworms a candidate for use in actuation of the compliant tool.

23 The piezoelectric inchworm actuator can be controlled by a computerized control
24 system **220**. **Figure 15** shows a schematic of the entire control system for the compliant
25 gripper. The position of the instrumented forceps (jaws **30/60**), X_h , and the force measured
26 at the end-effector (**20**), F_g , are sensed and used to control both the inchworm actuator **200**,
27 V_{ic} , and the force generation mechanism (not shown) in the user input handle **12**, F_r . The
28 end-effector **20** and user input device **12** are instrumented with LVDT displacement
29 sensors to measure their position. Through active computer control, the motion of the
30 gripper **20** is precisely scaled-down from the input motion provided by the pair of
31 instrumented forceps **30/60**. Local force measurements are obtained through the use of a
32 single piezoelectric element present in the actuator, which is wired separately from the rest

1 of the piezoelectric stacks. In this way, the element may be used continuously as a force
2 transducer. The resulting signal must be filtered to remove unwanted high frequency
3 content and scaled so that the reflected force falls within the range of forces sensible to a
4 human operator.

5 **4. Shaft/Lumen 114**

6 Like with the embodiment of **Figures 1-3**, shaft **14** could utilize sub-shaft(s)
7 slideable in a bore through shaft **14**. If more than one sub-shaft, they could be side-by-
8 side, or concentric (tubular). Tendons with or without sliders could also be used.

9 **5. Method of Design**

10 There are a variety of ways the structure of a compliant end effector could be
11 designed and implemented. The basic functions of a grasping/cutting end effector have
12 been shown and described herein. And, as described above, one way to implement a
13 compliant mechanism is to build structure that effects grasping (jaws converge in a first
14 plane) if pushed with a linear force at one location and effects scissors cutting (blades on
15 sides of jaws and jaws converge in a second plane) if pushed at a different location (or
16 pulled from the same location). Such a structure could be designed through trial and error
17 or empirical methods.

18 Optimization of such structure could be accomplished through a variety of methods
19 or through using any of a variety of design tools, including software programming that
20 allows the functions to be entered, along with other basic design constraints or parameters,
21 and the program would design an optimized configuration. One such method is discussed
22 below.

23 **a) Optimization Routine Used to Design Compliant Tools**

24 The optimization routine is based on a topology design method for compliant
25 mechanisms with multiple input and output requirements. Topology design refers to the
26 design of the connectivity of the elements in the mechanism. To design a compliant
27 mechanism that will produce a specific output displacement with a certain input force, a
28 mechanism having minimal stiffness (i.e. maximum compliance) in the direction of the
29 desired output is optimal. Simply using optimization to design for a structure with minimal
30 stiffness will result in a solution that has members of zero or minimal area, i.e., the least
31 stiff structure is one with minimum volume. This degenerate solution results from
32 neglecting the requirement that the mechanism must have sufficient stiffness to supply the

1 force at the output point, as well as not fracture or buckle as the motion is executed. Thus,
 2 the desired solution may be thought of as a mechanism that is both compliant enough to
 3 execute the opening and closing of the jaws of a grasper and stiff enough to grip with
 4 sufficient force, or, similarly, a device with sufficient compliance to perform the shearing
 5 motion of scissors while also supplying sufficient cutting force. The design requirement
 6 then becomes one of maximum compliance in the path of motion plus sufficient stiffness in
 7 the direction of the output force.

8 The analysis may be divided into two separate loading cases: case C for cutting
 9 and case G for grasping. The analyses of the two load cases essentially are identical, thus
 10 the following equations will initially only consider only case C. To generate a structure
 11 having both the necessary compliance and stiffness, both loading cases C and G will be
 12 further divided into a flexibility condition and a stiffness condition. For the flexibility
 13 condition, force f_C is applied producing displacement field u_{C1} , and a dummy load f_{dC} is
 14 applied at the output point producing virtual displacement field v_C . The mutual potential
 15 energy (MPE) is used as a measure of flexibility, where maximizing MPE results in a
 16 compliant solution with the deflection at the point of interest maximized in the desired
 17 direction. Note that simply designing for minimum strain energy will result in a solution
 18 with maximum stiffness where all element areas are at the upper bound, thus it is desirable
 19 to design for a compromise solution of minimum strain energy and maximum mutual
 20 potential energy. MPE is a function of the stiffness matrix K_1 , the actual displacement u_{C1}
 21 and the virtual displacement v_C , and it is defined as in (1):

$$\begin{aligned}
 MPE_C &= (f_{dC})^T \cdot u_{C1} \\
 &= (K_1 v_C)^T \cdot u_{C1} \\
 &= v_C^T K_1 u_{C1}
 \end{aligned} \tag{1}$$

27 To analyze the stiffness condition, the same force f_C is applied at the input
 28 point, but, in order to model the tool's resistance at the point where the output force is
 29 applied, the output point is now held fixed. Strain energy (SE) can be used as a measure of
 30 stiffness of the design, as is often done in structural optimization, where minimizing strain
 31 energy results in a solution with maximum resistance. Strain energy is defined as in (2),

where u_{C2} is the actual displacement due to f_C when the output point is fixed, and K_{C2} is the new stiffness matrix, which differs from K_1 because of the additional fixed degrees of freedom.

$$SE_C = (u_{C2})^T K_{C2} u_{C2} \quad (2)$$

The strain energy and mutual potential energy now represent two competing design objectives and must be combined into a single objective function using a method such as a weighted sum of SE and MPE. The weighted sum approach has its difficulties because SE and MPE may differ by orders of magnitude and thus present a scaling problem. This difficulty may be eliminated by defining the objective function, F , as a ratio of MPE to SE, which results in the objective function given by (3) (note that minimizing SE is analogous to maximizing its reciprocal $1/SE$).

$$F = \text{Max} \left(\frac{MPE_C}{SE_C} \right) = \text{Max} \left(\frac{v_C^T K_1 u_{C1}}{(u_{C2})^T K_{C2} u_{C2}} \right) \quad (3)$$

Equation (3) is the objective function for optimizing load case C, and an analogous equation is used for optimizing load case G. For a single tool to perform both C and G, we combine the functions into a single objective function using a weighted sum technique as in (4):

$$\begin{aligned} F &= \text{Max} \left[\alpha \left(\frac{MPE_C}{SE_C} \right) + (1 - \alpha) \left(\frac{MPE_G}{SE_G} \right) \right] \\ &= \text{Max} \left[\alpha \left(\frac{v_C^T K_1 u_{C1}}{(u_{C2})^T K_{C2} u_{C2}} \right) + (1 - \alpha) \left(\frac{v_G^T K_1 u_{G1}}{(u_{G2})^T K_{G2} u_{G2}} \right) \right] \quad (4) \end{aligned}$$

The scalar weighting variable Δ may then be adjusted to tweak the solution or to give more weight to a particular load case. The constraint equations for the optimization problem come from the equilibrium equations for each displacement variable (5), the limits on the design variables (6), and the maximum volume constraint (7).

The solution procedure follows that of ground structure based topology optimization; hence, the procedure begins with a ground structure or dense web of elements. The elements' cross-sectional areas, A_i , are the optimization design variables and are assumed circular. This type of topology optimization is a special case of sizing optimization, such that the process adjusts the cross-sectional area of each element in the ground structure to obtain a solution with optimal performance. Ultimately, many of the elements' cross-sectional areas will diminish or decrease to the lower bound and the remaining elements will define the structure's topology. The formal optimization problem is now given by the objective function F in (4) and the following set of constraint equations, where l_i is element length, V^* is the maximum volume of material, and N is the number of design variables.

$$\begin{aligned} K_1 u_{C1} &= f_C & K_1 u_{G1} &= f_G \\ K_1 v_C &= f_{dC} & K_1 v_G &= f_{dG} \\ K_{C2} u_{C2} &= f_C & K_{G2} u_{G2} &= f_G \end{aligned} \quad (5)$$

$$A_{lower} \leq A \leq A_{upper} \quad (6)$$

$$Vol = \sum_{i=1}^N A_i l_i \leq V^* \quad (7)$$

A three-dimensional ground structure of frame elements is desirable as the basis for the optimization problem to allow for motions in different planes, such as multiple input and output forces and displacements that lie in orthogonal planes. The 3-D model can be set up with a ground structure of "unit cubes." In contrast to the full ground structure that connects each node to every other node, the unit cube structure consists of a mesh of $1 \times 1 \times 1$ cubes connected at the cube faces where each node in the cube is connected to every other node in the cube. The unit cube arrangement significantly decreases the total number of elements, which decreases computation time, while still providing acceptable solutions. The sequential linear programming technique for constrained minimization, as provided by MATLAB and similar finite element analysis programs, is desirable for solving the optimization problem. Using MATLAB's linear programming function, `linprog`, the linear

1 program can be solved and used to update the values of the element areas. The step size, or
2 maximum amount by which the areas may change for each iteration, must be limited to
3 provide a move limit on the approximation of the linearized objective function.

4 Convergence occurs when either the change in the objective function or the change in each
5 design variable decreases to a critical value.

6 The following example illustrates the optimization analysis used for designing the
7 compliant multifunctional scissors-grasper tool. The setup for this problem is a 7x3x2
8 node design domain shown in **Figure 12** where the problem is symmetric about both the
9 $y=2$ and $z=0$ planes, thus the figure shows only a fourth of the problem. In **Fig. 12**, f_C and
10 f_G = input forces, ΔC and ΔG = output deflections, both relative to two unique functions
11 (e.g. cutting and grasping). The starting point (set of initial areas) was randomly
12 generated, the areas were bounded between 0.001 and 1 cm², the maximum step size for
13 each element in an iteration was 10% of its previous value, and unit forces were used. The
14 weighting factor was set to 0.5 (i.e. both cases weighted equally), and essentially the same
15 solution was obtained for all values of the volume constraint with at least a 25% volume
16 fraction. **Figure 12** displays the result from the MATLAB program, along with the full
17 7x5x3 node solution (where all four symmetric sections are displayed).

18 Solid modeling software, such as PTC's Pro/Engineer, can be used to generate a
19 model that exhibits the same characteristics as the unit cube model analyzed through the
20 MATLAB software. **Figure 13** shows a model generated by Pro/Engineer that behaves in
21 the same manner as the unit cube model (the "full solution") of **Figure 12**. As can be seen,
22 the input forces f_C and f_G can be applied to the back side of the solid model shown in
23 **Figure 13**, and the opposite ends deflect by output displacements ΔC and ΔG (i.e. the two
24 different output functions). It should be noted, however, that the solid model shown in
25 **Figure 13** is made of solid titanium. As such, this solid model does not exhibit the
26 characteristics that would be desirable for a MIS tool. In order to achieve the output
27 displacements ΔC and ΔG desired, the input forces f_C and f_G would have to be
28 tremendously high. This is simply not practicable for a MIS tool. Therefore, it is desirable
29 to have a solid model that behaves like the unit cube model of **Figure 12**, but does not
30 require the high input forces, like the solid model of **Figure 13**, in order to achieve the
31 output displacements necessary for MIS.

Figure 7 shows a second solid model generated through Pro/Engineer that behaves exactly like the models shown in **Figures 12** and **13**, but requires less input force to achieve a required output displacement. Essentially, the solid model of **Figure 13** has been elongated to create the model of **Figure 7**. Elongating the model creates lever arms. These lever arms allow a smaller input force f_C or f_G to produce a greater output displacement ΔC and ΔG . The key to understanding this is realizing that the moments necessary to create the output displacements in the solid model of **Figure 13** are generally equal to the moments created in the solid model of **Figure 7**. Because the moments are the same, the input forces necessary to achieve the desired output displacements in the solid model of **Figure 7** are far less than the input forces in the solid model of **Figure 13**. By laws of mechanics, the greater the lever arm (moment arm or radius), the less the input force to create the same moment and resulting output displacement.

6. Method of Use

Function	Force
Grasping force	0.4 lb. Closing 0.21 lb spreading (opening)
Handle force	1.95 lb. Opening-cutting 0.5 lb closing-cutting 1.75 opening-grasping 1.5 lb. Closing-grasping
Pull-Off Force	0.34 lb. (using red rubber tubing)
Cutting Force	0.08 lb.

The method of using tool **10B** has been described above. The compliant nature of tool **10B** provides the ability to obtain some mobility from deflection of the flexible member. Energy is stored in the flexible members of the compliant web. This can be advantageously utilized to effectuate the functions of the end effector, while the mechanism is designed so that of the user can select between multiple functions, if desired. **Figures 16A** and **B** illustrate the forces in the pushrods that can be used with the compliant end effector of tool **10B** to effect tip displacement in a simulation based on the design of tool **10B**. This type of use of compliant structures appear to be promising for

miniaturization of MIS end effectors, because of lack of need for rigid link assembly and the potential for binding or malfunction over time when made very small. Compliant surgical instruments also tend to be easier to clean and sterilize for reusable use than traditional mechanically linked or hinged mechanisms.

E. Exemplary Embodiment Three (Non-compliant multi-function cutting and grasping and articulating)

1. Structure

Figures 17-22 illustrate a third exemplary embodiment according to the present invention. This tool, referred to as tool **10C** to differentiate it from tools **10** and **10B**, operates similarly to the fixed link mechanism tool **10** of **Figures 1-3** with the following differences.

2. End-Effector

Tool **10C** adds what will be considered a third function, namely articulation of the distal ends of both end-effector jaws. This allows the additional function of being able to articulate (in either direction from axis **50**) the clamping action of the end effector for greater dexterity in clamping and dissecting. Articulation of distal tips can be done independently of the clamping action or can be selectively enabled.

Below are parameters for an example of tool **20C**:

Component	Length
Jaws (Total length, non-articulated)	15 mm
Jaws opening distance at distal ends for grasping	15 mm
Scissors blade length	7 mm
Scissors opening distance at distal ends	10 mm
Articulated end maximum offset from longitudinal axis of instrument	90 degrees

The design of the end effector of tool **10C** is illustrated conceptually in **Figures 17A-E**. The jaws are essentially mirror images of each other. Therefore, for embodiment

1 **10C**, the top jaw in **Figure 17A** will be generally indicated by reference number **60**, and
2 the bottom jaw by reference number **60'**.

3 **Figures 17A and B** show how jaws **60** and **60'** operate in a first mode; a clamping
4 mode where the distal tips **68** and **68'** of each jaw are straight. Each jaw **60** and **60'** has a
5 base section **62** or **62'** pivotally mounted along axis **52** to distal end **18** of shaft **14**. Base
6 sections **62** and **62'** are adapted to pivot in a plane defined by axes **50** and **52** in response to
7 actuation, e.g. linear movement from a sub-shaft, such as will be described later. As
8 shown in **Figures 17A and B**, this allows jaws to function as clamping members when base
9 and moveable sections of each jaw are aligned along axis **50**. By linear action of a sub-
10 shaft or other member extending from a handle **12** to proximal ends of jaws **60** and **60'**,
11 jaws **60** and **60'** can be moved between closed clamping position (**Figure 17A**) and opened
12 clamping (or dissecting) position (**Figure 17B**).

13 **Figures 19A-C** illustrate generally one way of generating clamping movement of
14 jaws **60** and **60'** with a linearly moving sub-shaft or tube (alternatively called slider **230**).
15 Each jaw **60** and **60'** has a proximal end **232** that extends proximally of pivot axis **52** and
16 includes an elongated slot **234** or **234'**. The elongated slots **234** and **234'** are angularly
17 disposed relative to axis **50** and further, are in opposite directions to one another (as seen in
18 **Figures 19A-C**).

19 A common pin **236** has opposite ends which extend laterally out of the distal end of
20 slider **230** into slots **234** and **234'**. When pin **236** is in the position of Fig. **19A** (with pin
21 **236** in the proximal ends of slots **234** and **234'**), the distal ends of base sections **62** and **62'**
22 of jaws **60** and **60'** would be pulled into alignment with axis **50**. This would close jaws **60**
23 and **60'** (see Fig. **19A**). When slider **230** moves to push pin **236** to the distal ends of slots
24 **234** and **234'**, jaws **60** and **60'** would open (Fig. **19B**).

25 But further, like the moveable section **68** described with respect to tool **10** in
26 **Figures 1-3**, both jaws **60** and **60'** have a moveable section, **68** and **68'** respectively, that
27 can pivot around a pivot pin **70** or **70'** (defining pivot axes **54** and **54'**). The structure of
28 these jaws **60** and **60'** is such, however, that moveable sections **68** and **68'** can pivot in both
29 directions relative to axis **50** (on either side of the same). The basic principle of
30 articulation of the tips **68** of the jaw is shown by the diagrams of **Figures 18A and B**. The
31 two parts of the jaw (base section **62** and moveable section **68**) are connected by a simple
32 pin joint located on the instrument's centerline. **Figure 18C** illustrates exemplary

1 dimensions for the combination **62** and **68**. Therefore, independent of the opening of jaws
2 **60** and **60'** as shown in **Figures 17D** and **E** and **Figure 19C**, sections **68** and **68'** could be
3 articulated away from alignment with axis **50**. As illustrated in **Figs. 17D** and **E** and **Fig.**
4 **19C**, they could form an articulated clamp on either side of axis **50**, over a range of off-
5 axis angles.

6 This articulation of tips of the jaws **60** and **60'** is another functional mode for a MIS
7 tool. Slider **230** could be operated to close or open jaws **60** and **60'** with the moveable
8 sections articulated together in either direction to increase the flexibility and versatility of
9 clamping action of tool **10C**. **Figure 18C** provides an example of additional dimensional
10 and functional parameters for one design of articulatable sections **68** and **68'**.

11 The articulation or rotation of the tips of the jaws may be accomplished in various
12 ways. Two examples are mechanical actuation, or by an electro-mechanical interface.
13 Others are possible. **Figures 20A-C** illustrate the general principle of one example of a
14 mechanical actuation of the articulation function.

15 Attached to the tip are two tendon lines, **250A** and **250B**, that extend down the long
16 axis of the instrument. In a normal or reference position (**Figure 20A**), tip **68** is extended
17 straight from base section **62** (distally along axis **50**). Appropriate tension on both lines
18 **250A** and **B** would essentially hold or lock tip **68** in that position. In the orientation shown
19 in **Figures 20A-C**, pulling on line **250A** (and releasing tension on line **250B**) will pivot the
20 tip **68** to the left around pivot pin **70** (or axis **54**) (see **Figure 20C**). By pulling on line
21 **250B** (and releasing tension on line **250A**), the tip will pivot to the right (see **Figure 20B**).
22 Thus, by this relatively simple method, control over articulation of the tip **60** or **60'** of each
23 jaw **60** and **60'**, in either direction, can be actuated by linear forces (e.g. from handle **12** or
24 otherwise).

25 It is to be understood that several discrete intermediate angles could be achieved for
26 the tip articulation. To achieve locking in intermediate pivot positions, a ratchet-type
27 mechanism can be used. In a prototype embodiment, a standard socket wrench was used.
28 The two tendons were attached on either side of the socket wrench such that the two
29 connection points and the pivot point of the wrench are in line. When the wrench was
30 turned to one side it simultaneously released tension of one line while applying tension to
31 the other. This resulted in required force to pivot the tip being supplied, while still

1 maintaining tension in both tendons. In practice, such an optional locking mechanism
2 would be integrated into the device.

3 **Figure 20D** illustrates in more detail how the distal ends of the tendon lines could
4 be attached to a tip **68**. Steel cables **250A** and **250B** could be soldered or otherwise
5 attached (see points **251** and **253** respectively) to opposite sides of the distal end of a
6 moveable section **68** of a jaw **60**. Cables **250A** and **250B** could extend proximally back
7 from end effector **20**, through shaft **14**, to handle **12**. As illustrated in **Figures 20A-D**,
8 cables **250A** and **250B** act as tendon lines. By pulling on line **250B**, tip **68** will move to
9 the right from the viewpoint of **Fig. 20B**. Pulling on line **250A** will move tip **68** to the left
10 (**Fig. 20C**). If both lines **250A** and **250B** are maintained at relatively equal lengths, and in
11 tension, tip **68** will align with axis **50**.

12 The same structure could be used with the other jaw, **60'**, such that each jaw **60** and
13 **60'** would have two cables, **250A** and **B**, and **250A'** and **250B'** respectively, that extend
14 back through shaft **14** to an actuator mechanism. **Figure 20E** shows that instead of having
15 two cable ends and two solder points per tip **68**, a single cable could simply be formed in a
16 U-shape at its middle and soldered at a single point **251B**, and with opposite free ends
17 extended to handle **12**, and connected to appropriate concentric tubes. Thus, by suitable
18 user controls (preferably in or around handle **12**), the articulation of the distal tip **68** of both
19 jaws **30** and **60** can be controlled.

20 By appropriate control and actuating mechanisms, the user could close jaws **60** and
21 **60'** together (as in **Fig. 17A**), and by concurrently pulling cable **250A** of one jaw **60** or **60'**,
22 and cable **250B** of the other jaw **60'** or **60**, tips **68** and **68'** would articulate in opposite
23 angular directions (as in **Figure 17C**). Reversing the process, i.e. pulling cable **250B** of
24 jaw **60** and cable **250A** of jaw **60'**, would move tips **68** and **68'** back to the position of **Fig.**
25 **17A**. Thus, scissors action can be accomplished.

26 Alternatively, to simplify a scissors function, one tip **68** or **68'** could be maintained
27 in a straight position aligned with axis **50**, and the other tip **68'** or **68** articulated angularly
28 outward, by pulling on the appropriate cable **250A** or **250A'**, and then bringing the tip back
29 by pulling the other cable **250B** or **250B'**.

30 3. Handle

31 Manually actuated operation of the grasp (straight ends) mode, grasp (articulated
32 ends) mode, or cutting mode could be accomplished by various ways. The linear push rod

1 actuation of grasping movement for jaws **60** and **60'** could be as shown and described with
2 respect to **Figures 19A-C**, the common pin in slots arrangement. Rotational motion from
3 handle **14** could be translated to linear motion in a number of ways, including ways
4 previously discussed.

5 Articulation of tips left or right, and the cutting action could be actuated by
6 appropriate linkage to convert rotational motion of handle **24** to pulling forces on any of
7 the four cables or tendon lines **250A**, **250B**, **250A'** or **250B'**, either alone or in combination.
8 Additionally, a variety of ways exist for holding a tendon line in tension when a
9 companion tendon line is being pulled.

10 One specific example of a system for actuating the three functions discussed above
11 is illustrated with reference to **Figures 21A-C** and **22A-E**, which illustrate a control and
12 manual actuation mechanism to provide both clamping action according to linear
13 movement of a push rod or slider **230** such as shown in **Figures 19A-B**, articulation of tips
14 **68** and **68'** for articulated clamping as shown in Fig. **19C** by manipulation of cables
15 attached to tips **68**, and scissors action by manipulation of cables attached to one tip **68** or
16 **68'**.

17 As described, a notable feature of mechanism **10C** is the combination of cutting,
18 grasping and articulating into a single multi-functional instrument. The end-effector **20**
19 shown in **Figures 17-22** is comprised of an upper jaw **60** and lower jaw **60'**, each having a
20 front or tip section **68** or **68'** and rear section **62** or **62'**. The front and rear sections are
21 connected with a pin joint (along axis **52**) to allow for rotation in the orthogonal plane to
22 the grasping motion. The front and rear sections together form 15 mm grasping jaws,
23 while the front 7 mm section **68** or **68'** alone can be articulated to introduce articulated
24 grasping or cutting features to the device. The grasping motion is operated by a push rod
25 and pin in slot mechanism connected in the rear of the end-effector jaws as shown in
26 **Figures 19A-C**. The cutting and articulation motions are operated using four steel cables
27 (**250A** and **B**, **252A** and **B**) soldered to the front portions of the end-effector jaws (two for
28 each jaw **60/60'**).

29 The handle **12** also contains some notable mechanisms. As further described
30 below, the four cables from the end-effector connect to the front end of four concentric
31 tubes **350A** and **B**, and **352A** and **B**, placed around the grasping push rod or slider **230**.
32 The top notch of vertical fork(s) of sliding links mates with the disk at the rear of each tube

1 and pull or free the cable(s) or push rod required for each function to operate. The
2 concentric tubes were designed to allow the end-effector shaft to rotate freely without
3 twisting the cables around the shaft itself. This type of connection provides a mechanical
4 coupling between the rotational motion of the shaft and the linear motion of the sliding
5 links to actuate the cables and push rod at any angular position of the end-effector.

6 More specifically, handle 12 of **Figure 21** includes the following primary parts.

7 A sub-shaft (or push rod or slider) 230 that is rotatably supported in hollow shaft 14
8 between a proximal end near the rear of handle housing 12 and a distal end that is
9 connected to jaws 60 and 60' in the manner of **Figures 19A-C**. Sub-shaft 230 extends out
10 of handle 12 and through shaft 14 to end effector 20. Like the configuration of **Figures**
11 **19A-C**, a transverse pin 236 in the distal end of sub-shaft 230 cooperates with slots 234
12 and 234' in the proximal ends of jaws 60 and 60' so that linear movement of sub-shaft 230
13 causes opening and closing of jaws 60 and 60' in clamping mode. A wheel control 28,
14 fixedly mounted on sub-shaft 230, allows the surgeon to rotate end effector 20 three
15 hundred sixty degrees relative to axis 50.

16 Four tubes 350A, 350B, 352A and 352B are concentrically mounted around sub-
17 shaft 230 and are slideable along sub-shaft 230. At the proximal end of each tube 350A,
18 350B, 352A and 352B is fixed a disc 341, 343, 345, and 347, respectively, each of which is
19 rigid to and moves with its respective tube. At the distal end of each tube 350A, 350B,
20 352A and 352B is a flange 342, 344, 346, and 348 respectively, which is rigid to and
21 moves with its respective tube. Cables 250A, 250B, 252A and 252B, are fixed (e.g. by
22 soldering or clamped by a screw) to flanges 342, 344, 346, and 348 respectively. Flanges
23 342, 344, 346, and 348 are preferably rotationally offset or radially offset relative to
24 centerline 50 so that there is open space between each cables exit from the proximal end of
25 shaft 14 to its respective flange.

26 As can be appreciated, this arrangement provides each cable a terminating structure
27 in handle 12 that is moveable only linearly and generally parallel to axis 50. Therefore,
28 any of the four cables can be pulled by sliding the appropriate concentric tube along sub-
29 shaft 230. Thus, articulation control, in both directions, for either tip 68 or 68' is available
30 at handle, and articulate can be effected through linear motion.

31 Moreover, each tube is independently slideable. Therefore, any combination of
32 articulation of tips 68 and/or 68' is possible through the movement of any one or more of

1 the tubes, alone or in combination. Still further, wheel control 26 allows rotation of the
2 orientation of jaws 60 and 60', and thus their tips 68 and 68' at the end effector over a
3 complete 360 degrees range, Without any tangling of the cables because the tubes can
4 freely move along with subshaft when rotated.

5 Actuation of a grasping action for jaws 60 and 60' can be effectuated by linear
6 movement of sub-shaft 230 along axis 50. One way is by moving control wheel 26 along
7 axis 50, or otherwise applying forces that cause sub-shaft 230 to move along axis 50. This
8 action could be accomplished by a wide variety of methods, including those previously
9 discussed herein, both manual and motor or actuator driven.

10 Control of actuation of tips 68 and/or 68' can similarly be achieved through a wide
11 variety of methods, manual or automated. The specifics and complexity can be left to the
12 designer based on considerations deemed relevant.

13 One example of a system for providing actuation of grasping (straight ends),
14 grasping (articulated end(s)), and cutting, is illustrated at **Figures 21A-22E**, with particular
15 reference to **Figures 21A-C**.

16 Handle 22 is fixed to the handle housing 12. Handle 24 is rotatably mounted to
17 housing 12, and rotates towards handle 22 around pivot axis 25. Handle 24 includes a key
18 slot 410 which receives and retains the key head 412 at one end of handle link 402. The
19 other end 414 of link 402 is T-shaped.

20 A set of three what will be called sliding links 370, 380 and 390 fit side by side in
21 cage 406.

22 A combination articulation and cut/grasp switch 400 has opposite heads 420 and
23 422 joined by a reduced size intermediate section 424. Two tongues 426, 428 extend from
24 the top side of intermediate section 424. Tongue 426 is the width of a single sliding links
25 and tongue 428 is the width of 2 sliding links. There is a gap between these 2 tongues the
26 width of on sliding link.

27 The geometry of each sliding link 360, 370, and 380 is illustrated in **Figures 21B**
28 and **C**.

29 Shortest link 360 includes a vertical fork 361 with a slot 362 sized to slideable
30 receive the thickness of control wheel 26, a proximal arm 363 with a T-slot 364 sized to
31 sliceable receive T-head 414 of handle link 402; and a distal arm 365 including a cut-out
32 366 sized to sliceable receive tongue 426 of switch 400. The length of link 360 between

1 ends **363** and **365** is much shorter than the length of cage **406**, so that link **360** can slide
2 independently of links **370** and **380**, and within cage **406**.

3 Middle sliding link **370** is similar to link **360** relative to its vertical fork and slot
4 **371/372**, its proximal arm and t-slot **373/374**, and a middle section with bottom cut-out
5 **375/376**. The main differences are that fork **371** is farther distally than fork **361**, and a
6 distal leg **377** extends farther distally and includes a second fork **378** having a slot **379**.
7 Fork **378** is also pivotally connected at pivot **393** to arm **377**, and pivots around point **392**
8 in a parallel plane to the plane defined by fork **371** arm **373** and arm **377**. Furthermore,
9 fork **378** is pivotally pinned to handle housing **12** at its middle (see pivot pin hole **393**).
10 Thus, fork **378** can not move as a whole with sliding link **370**, but pivots when sliding link
11 **370** slides.

12 Sliding link **380** is similar to link **370** relative to its vertical fork and slot **381/382**,
13 its proximal arm and t-slot **383/384**, and a middle section with bottom cut-out **385/386**, and
14 a distal leg **387** extending distally and including a second fork **388** having a slot **378** with
15 fork **388** being pivotally connected at pivot **394**; and fork **388** is pivotally pinned at **395** to
16 housing **12**, like fork **378**. The main differences are that fork **381** is farther distally than
17 fork **371**. Fork **388** is spaced the same distance from fork **381** as fork **378** is from fork **271**.

18 When assembled, intermediate portion **424** of switch **400** is positioned laterally in
19 cage **406** in alignment with the longitudinal slots along the sides of cage **406**, with opposite
20 heads **420** and **422** of switch **400** positioned outside on opposite sides of cage **406**.
21 Therefore, any movement of switch **406** lateral to axis **50** will cause following movement
22 of cage **406**. Sliding links **360**, **370**, and **380** are placed side-by side through the open top
23 of cage **406** in the order shown in **Figure 21B**, and with cut-outs **366**, **376**, and **386** aligned
24 with intermediate section **424** of switch **400**. In such position, each proximal end **363**,
25 **373**, **383** of links **360**, **370**, and **380** are laterally aligned at the rear end of cage **406**.

26 End guide **405** is installed in the rear end of cage **406** as shown in **Figure 21**. It has
27 an opening through which can pass T-head **414** of link **412**, but serves to support and guide
28 the middle of link **402**, which would extend generally straight back to its connection to slot
29 **410** in handle **24**. End guide does not allow lateral movement of T-head **414** relative to
30 cage **406**. Cover **404** would be installed over cage **406**, which has a longitudinal slot
31 through which forks **361**, **371**, **379**, **381**, and **388** extend. Also, cover would be fixed
32 against movement by connection to the body of handle **12**.

1 This sub-assembly of cage, sliding links, and switch is supported inside handle
2 housing **12** in a manner that allow it to move laterally somewhat, but not along its
3 longitudinal axis, which would be parallel to sub-shaft **230** and axis **50** of tool **10C**. But
4 further, sliding links **360**, **370**, and **380** can slide longitudinally within cage **406**; link **360**
5 substantially, link **370** less, and link **380** less, as their opposite ends limit such travel.

6 Still further, switch **400** can slide transversely of the longitudinal axis of cage **406**,
7 but when a tongue **426**, **428**, or **230** is aligned with a cut-out **366**, **376**, or **386**, the
8 respective sliding link(s) can not slide longitudinally if switch **400** is held against
9 longitudinal movement, or the respective sliding link(s) move is correspondence with
10 longitudinal movement of switch **400**. Conversely, if a tongue is not aligned with such a
11 cut-out, that sliding link can slide longitudinally relative to switch **400**. The respective
12 link(s) simply slide over the middle section of switch **400** as no tongue impedes such
13 movement.

14 **Figures 21A and C** show the relationship of the sliding links **360**, **370**, and **380**
15 with concentric tubes **350A**, **350B**, **352A**, and **352B** when tool **10C** is assembled. When
16 assembled, notches **362**, **372**, **382**, **379** and **389** are positioned to receive the edge of
17 control wheel **26**, disc **345**, disc **343**, disc **347**, and disc **341**, respectively, allowing rotation
18 but not longitudinal movement of the same, unless the sliding link of the respective notch
19 is moved along its allowed path of travel. This arrangement puts control over grasping
20 action of the tool jaws by control of movement of sliding link **360**, because such movement
21 controls longitudinal movement of sub-shaft **320**. It puts control over articulation of tips
22 **68** and **68'** by control of movement of sliding links **370** and/or **380** because such movement
23 controls pulling of cables **350A** and **B** and **352A** and **B**, which control left and right
24 concurrently articulation of tips **68** and **68'**. It puts control over cutting action by control of
25 movement of sliding link **370**, because such movement controls pulling of cables **350A** and
26 **B** which controls articulation movement of one tip **68** away from and back to fixed tip **68'**
27 to effectuate scissors action.

28 The logical organization of this multi-functional tool **10C** can be shown with
29 reference to the state diagrams of **Figures 22A-E**.

30 Straight end grasping mode: Handle **24** is moved to its end limit closed to fixed
31 handle **22**. Switch **400** is moved laterally so that sliding link **370** is positioned in the gap
32 between tongues **426** and **428** and cut-outs **376** and **386** are aligned with tongue **428**. This

1 lateral motion of switch 440 also pulls end 414 of link 402 into t-slot 364 of link 370
2 therefore providing a linkage from link 370 through link 402 to 410 the moving handle. ,
3 Thus, tips 68 and 68' would be straight (aligned along axis 50). Switch 400 is pulled all
4 the way out. The geometries are configured so that this action will pull cage 406, and thus
5 all of links 360, 370, and 380, to a position that aligns T-head 414 with T-slot 364 in link
6 360. This also has control wheel 26 to its rearmost position, and thus, likewise, sub-shaft
7 230. As indicated in **Figure 22A**, tips 68/68' would therefore be straight, aligned and
8 closed (gripping action--jaws closed).

9 Thus, switch 400 can slide back and forth along slot 410 which lengthens and
10 shortens the cables, but the tongues in the cut-outs make both sliding links 370 and 380
11 slide together, the same direction and the same distance. This therefore causes any
12 articulation of tips 68 and 68' to be concurrent and in the same direction. Articulation can
13 be either to the left or right, and over a range from straight to maximum angle. But further,
14 since link 360 is linked to handle 24, jaws 60 and 60' can be opened and closed, even when
15 tips 68/68' are articulated, by movement of handle 24. See **Figure 22B**.

16 Compare then the scissors mode: Switch 400 is moved front or back to an
17 intermediate position between fully forward and fully backward. Cage 406 is moved
18 laterally by pushing switch 400 laterally such that T-head 414 is now in T-slot 374 of
19 sliding link 370. During cutting mode, tongue 426 is located in slot 366 of link 370, link
20 380 is located in the gap between tongues 426 and 428, and tongue 428 is located in slots
21 376 and 386 of links 380 and 390. and head 420 of switch 400 is captured against
22 longitudinal movement in slot 440; effectively locking links 360 and 380 from sliding or
23 moving (and thus locking out grasping or articulation of tip 68'). Therefore, rotational
24 movement of handle 24 would translate into linear movement of link 402, which would
25 slide sliding link 370, which slides concentric tubes 352A and 352B, which are connected
26 to cables 252A and 252B (both sides of tip 68'). Forward movement of handle 24 towards
27 handle 22, causes rearward movement of link 402 and sliding link 370, causes rearward
28 sliding of tubes 352A and due to the reversing pivoting motion of 378, forward motion of
29 352B is produced Sliding links 360 and 380 are locked in place, so tip 68 stays in a
30 straight position. Opposite movement of handle 24 produces an opposite action. This
31 process can be repeated to repeat scissors action. See **Figure 22C**.

The preferred feature of disallowing articulation when cutting is accomplished by the fact that a section of 400 is rigidly captured in opening 442 preventing any forward or rearward sliding motion of the articulation switch 400. On the other hand, the functionality of switch 400, in combination with the sliding links, allows articulation (if desired), during clamping action, by allowing sliding links 370 and 380 to move (in unison) while sliding link 360 is connected to handle link 402. The surgeon merely adjusts switch 400 forward/rearwardly along slot 440, and slides switch 400 one way along slot 440 for articulation of tips 68/68' in one direction relative to axis 50, and the other way for articulation the other way.

Thus, actuation of multi-function tool 10C is accomplished by manual manipulation of multi-action switch 400 and moveable handle 24. Switching of articulation/ function toggle switch 400 between 2 lateral positions sets whether tool 10C is in grasping or cutting mode. While in cutting mode, articulation is not allowed by the physically blocking of the forward/rearward motion of the articulation switch by 400's position in slot 442. Articulation is possible during grasping mode when 400 is not engaged in slot 442 and forward motion of 400 in slot 440 is allowed. Sliding 400 forward and rearward operates articulation. Pivoting handle 24 operates cutting or grasping.

4. Shaft 14

Shaft 14 can be similar or the same to those previously discussed, or some other way of translating appropriate motion to the end effector can be used.

5. Method of Use

While in grasping mode, end effector 20 can also be articulated to the left or right by sliding the articulation switch forward or backward. During cutting, the articulation feature is disabled. To avoid accidental switching between functions, the toggle switch can only be switched between cutting and grasping when the jaws of the instrument are in the closed, unarticulated position.

A prototype of tool 10C accomplished the following:

Function	Force
Grasping force	1.1 lb
Force Input at Handle	9.0 lb
Pull-Off Force	2.3 lb. (using red rubber tubing)
Cutting Force	1.4 lb

1

2 ***F. Options and Alternatives***

3 It will be appreciated that the present invention can take many forms and
4 embodiment. The included exemplary embodiments are given by way of example only,
5 and not by way of limitation to the invention, which is solely described by the claims
6 herein. Variations obvious to one skilled in the art will be included within the invention
7 defined by the claims.

8 For example, the concepts of the invention are applicable to laparoscopy, but can
9 also be applied to other MIS techniques and/or procedures requiring similar advantages.
10 Examples include, but are not limited to, gynecology, urology, thoracic, arthroscopy, ENT,
11 pediatric, neurosurgery.

12 Furthermore, the invention can be applicable to developing procedures. A few
13 examples include robotic, flexible scopes, and catheter-based surgeries.

14 The exemplary embodiments have been described in the context of a grasper and/or
15 cutter. Other functions are possible. Examples are dissection (moving ends outwardly
16 against tissue instead of grasping by closing, or using the blunt end with both jaws closed
17 to scrape or separate tissue).

18 Further, other adjunct functions can be added to the tool. One example is
19 cauterization (by electrification of at least one tip end). Others include such things as
20 irrigation, suction, or other functions, which could be delivered to the internal surgical site
21 with the device (e.g. by attaching the distal end of an irrigation or other tube or delivery
22 conduit to an articulatable jaw member).

23 In-between maximum rotation and the straight position of the articulating tips,
24 structure could be used to allow the tool to lock into a plurality of intermediate positions.
25 Some type of ratcheting system (operating like a ratchet wrench), might be used to
26 accomplish this. Or there could be some infinitely variably adjustable mechanism to allow
27 the surgeon the ability to lock the tip at any angle between end limits.

28 Other means of actuating the articulation and opening/closing of jaws themselves
29 may be employed. For example, the tendon wire/ratchet mechanism discussed could be
30 replaced with a more compact mechanism for mechanical actuation. The articulation and

- 1 jaw opening/closing might also be accomplished by small electro-mechanical actuators
2 controlled by the surgeon using a trigger or other input device on the tool handle.
3 Any of the embodiments, pin-jointed or compliant, could utilize mechanical link
4 joint and/or compliant actuation.
5 ***

1 **V. CLAIMS**

2 What is claimed is:

- 3 1. An end-effector for utilization at a surgical site on or in a patient comprising:
- 4 (a) a working end adapted for surgical functioning and including an interface adapted
- 5 for operative connection to an actuating mechanism;
- 6 (b) said working end being configurable to
- 7 (1) a first state capable of a first surgical function;
- 8 (2) a second state capable of a second surgical function;
- 9 (3) wherein selection of said first or second state is effected through said
- 10 interface.
- 11 2. The end-effector of claim 1 wherein said interface comprises a non-compliant
- 12 mechanism.
- 13 3. The end-effector of claim 1 wherein said interface comprises a compliant mechanism.
- 14 4. The end-effector of claim 1 wherein the working end comprises at least one portion
- 15 which is moveable relative to another portion.
- 16 5. The end-effector of claim 4 wherein at least one of said one portion and said another
- 17 portion is moveable towards and away from the other.
- 18 6. The end-effector of claim 5 wherein said one portion comprises a first grasping surface
- 19 moveable in a first plane.
- 20 7. The end-effector of claim 5 wherein said another portion is a second grasping surface
- 21 having a portion in said first plane and having a portion that is moveable outside of said
- 22 first plane.
- 23 8. The end-effector of claim 5 wherein said one portion is a first jaw pivotable in a first
- 24 plane and said another portion is a second jaw positionable in said first plane.
- 25 9. The end-effector of claim 8 wherein said second jaw comprises at least a portion that is
- 26 moveable outside of said first plane.
- 27 10. The end-effector of claim 9 wherein said portion of said second jaw is pivotable in a
- 28 second plane.
- 29 11. The end-effector of claim 10 wherein said second plane is generally perpendicular to
- 30 said first plane.
- 31 12. The end-effector of claim 1 wherein said first surgical function is grasping.
- 32 13. The end-effector of claim 12 wherein said second surgical function is cutting action.

- 1 14. The end-effector of claim 13 further comprising a third state for a third surgical
2 function.
- 3 15. The end-effector of claim 14 wherein the third surgical function is articulation of the
4 working end.
- 5 16. The end-effector of claim 1 wherein the first surgical function is grasping and the
6 second surgical function is articulation of the grasping.
- 7 17. The end-effector of claim 1 wherein the interface is adapted to translate linear motion.
- 8 18. The end-effector of claim 1 wherein the interface is adapted for connection to a
9 mechanically actuated mechanism.
- 10 19. The end-effector of claim 1 wherein the interface is adapted for connection to a
11 manually actuated mechanism.
- 12 20. The end-effector of claim 1 in combination with an actuating mechanism.
- 13 21. The end-effector and actuating mechanism of claim 20 wherein the actuating
14 mechanism comprises a control and a connection between the control and the interface
15 of the end effector.
- 16 22. The end-effector and actuating mechanism of claim 20 wherein the control comprises
17 handle including a manually actuatable member for creating a force for translation
18 through the connection to the end effector.
- 19 23. The end-effector of claim 20 wherein the control comprises a non-manually powered
20 force generator.
- 21 24. The end-effector of claim 123 wherein the force generator is an electrically powered
22 device.
- 23 25. The end-effector and actuating mechanism of claim 20 further in combination with a
24 surgical tool.
- 25 26. The end-effector of claim 1 further comprising a third state.
- 26 27. The end-effector of claim 26 wherein the third state is capable of a third surgical
27 function.
- 28 28. The end-effector of claim 26 wherein the third state comprises an enhancement of at
29 least one of said first and second states.
- 30 29. The end-effector of claim 28 wherein said first surgical function comprises grasping
31 and said third state comprises articulation of said grasping function relative to a
32 reference position.

- 1 30. The end-effector of claim 1 wherein the interface comprises a compliant mechanism,
2 wherein the compliant mechanism switches between first and second states dependent
3 upon magnitude and location of input force to the compliant mechanism.
- 4 31. The end-effector of claim 1 wherein selection between first and second states is without
5 working end exchange from the site.
- 6 32. The end-effector of claim 1 wherein the two states can be performed with portions of a
7 single working end.
- 8 33. The end-effector of claim 1 wherein the end-effector is adapted for minimally invasive
9 surgery.
- 10 34. A method of providing multiple surgical functioning at a surgical site on or in a patient
11 comprising:
12 (a) configuring a working end of a surgical tool for a first surgical function;
13 (b) reconfiguring the working end for a second surgical function without exchange of
14 said working end.
- 15 35. The method of claim 34 wherein selection of said first or second surgical functions is
16 effected through an interface.
- 17 36. The method of claim 34 wherein said interface comprises a non-compliant mechanism.
- 18 37. The method of claim 34 wherein said interface comprises a compliant mechanism.
- 19 38. The method of claim 37 wherein the compliant mechanism switches between said first
20 and second surgical functions dependent upon magnitude and location of input force to
21 the compliant mechanism.
- 22 39. The method of claim 34 wherein said working end comprises a first jaw pivotable in a
23 first plane and a second jaw positionable in said first plane.
- 24 40. The method of claim 39 wherein said second jaw comprises at least a portion that is
25 moveable outside of said first plane.
- 26 41. The method of claim 34 wherein said first surgical function is grasping.
- 27 42. The method of claim 34 wherein said second surgical function is cutting action.
- 28 43. The method of claim 34 further comprising a third surgical function.
- 29 44. The method of claim 43 wherein the third surgical function is articulation of the
30 working end.
- 31 45. The method of claim 34 wherein the first surgical function is grasping and the second
32 surgical function is articulation of the grasping.

- 1 46. A multifunction tool for use in minimally invasive surgery, comprising:
- 2 (a) an elongated shaft or flexible scope adapted to be inserted through an incision in a
- 3 patient's body, and having opposite first and second ends;
- 4 (b) a control handle on the first end;
- 5 (c) a tool head on the second end, the tool head including a pair of jaws pivotal about a
- 6 first axis so as to provide a grasping function and pivotal about a second axis so as
- 7 to provide a cutting function; and
- 8 (d) an actuator operatively connected to the handle and the tool head to move the jaws
- 9 in response to user input at the handle.
- 10 47. The tool of claim 46 wherein the jaws each have a grasping surface and a cutting edge.
- 11 48. The tool of claim 46 wherein the actuator includes a push rod for pivoting the jaws
- 12 about the first axis.
- 13 49. The tool of claim 46 wherein the actuator includes wires for pivoting the jaws about the
- 14 second axis.
- 15 50. The tool of claim 46 wherein the first and second axes are perpendicular to one another.
- 16 51. The tool of claim 46 wherein the tool head is articulated such that the grasping and
- 17 cutting functions are performable at various angles.
- 18 52. The tool of claim 46 wherein each jaw includes an inner end pivotal about the first axis
- 19 and an outer end pivotal about the second axis.
- 20 53. The tool of claim 52 wherein the second ends of the jaws are pivoted in opposite
- 21 directions for the cutting action.
- 22 54. The tool of claim 52 wherein the second ends of the jaws are pivotal in the same
- 23 direction about the second axis to provide for articulated grasping and cutting.
- 24 55. The tool of claim 46 wherein the actuator is a compliant mechanism.
- 25 56. The tool of claim 55 wherein the compliant mechanism has an input interface that
- 26 changes the orientation and plane of movement of the jaws in response to the location
- 27 and force applied to the interface.
- 28 57. A multifunction end-effector tool for use in minimally invasive surgery, comprising:
- 29 (a) an mechanism adapted to be inserted through an incision in a patient's body, the
- 30 mechanism comprising;

- 1 (b) a tool head, the tool head including a pair of jaws pivotal about a first axis so as to
2 provide a grasping function and pivotal about a second axis so as to provide a
3 cutting function; and
- 4 (c) an interface adapted for operative communication with a control external of the
5 patient's body and to an actuator operatively connected to the tool head to move the
6 jaws in response to user input from a control.
- 7 58. The tool of claim 57 wherein the jaws each have a grasping surface and a cutting edge.
- 8 59. The tool of claim 57 further comprising an actuator, wherein the actuator includes a
9 push rod for pivoting the jaws about the first axis.
- 10 60. The tool of claim 57 further comprising an actuator which includes wires for pivoting
11 the jaws about the second axis.
- 12 61. The tool of claim 57 wherein the first and second axes are perpendicular to one another.
- 13 62. The tool of claim 57 wherein the tool head is articulatable such that the grasping and
14 cutting functions are performable at various angles.
- 15 63. The tool of claim 57 wherein each jaw includes an inner end pivotal about the first axis
16 and an outer end pivotal about the second axis.
- 17 64. The tool of claim 57 wherein the second ends of the jaws are pivoted in opposite
18 directions for the cutting action.
- 19 65. The tool of claim 64 wherein the second ends of the jaws are pivotal in the same
20 direction about the second axis to provide for articulated grasping and cutting.
- 21 66. The tool of claim 57 further comprising an actuator which comprises a compliant
22 mechanism.
- 23 67. The tool of claim 66 wherein the compliant mechanism has an input interface that
24 changes the orientation and plane of movement of the jaws in response to the location
25 and force applied to the interface.
- 26 68. A surgical instrument for performing multiple surgical tasks comprising:
27 (a) a shaft having a proximal portion and a distal portion;
28 (b) a handle positioned on the proximal portion of the shaft;
29 (c) jaws pivotable relative to each other, positioned on the distal portion of the shaft;
30 and
31 (d) an actuation system for imparting articulation motion to the jaws.

- 1 69. The surgical instrument of claim 68 wherein the pivotable jaws comprise
2 multifunctional scissors, a grasper, a dissector, a cauterizer, or an irrigator.
- 3 70. The surgical instrument of claim 68 wherein the actuation system comprises a
4 mechanical actuator, an electrical actuator, a pneumatic actuator, a hydraulic actuator,
5 an electroactive material, or a combination thereof.
- 6 71. The surgical instrument of claim 70, wherein the mechanical actuator is mechanically
7 linked to an actuating rod or tendon wire disposed within the shaft, which tendon wire
8 is in turn linked to the distal portion of the shaft, for effecting movement of the jaws
9 from a closed position to an actuated position; for retaining the jaws in the actuated
10 position; and enabling the jaws to return to the closed position.
- 11 72. The surgical instrument of claim 70, wherein the electrical actuator is electrically
12 linked to an electroactive material embedded within, bonded to, or connected to the
13 jaws for effecting movement of the jaws from a closed position to an actuated position;
14 for retaining the jaws in the actuated position; and enabling the jaws to return to closed
15 position.
- 16 73. The surgical instrument of claim 70, wherein the electrical actuator or electroactive
17 material system comprises a switch or array of switches and electronic components for
18 controlling the flow of electrical current along the shaft to the jaws.
- 19 74. The surgical instrument of claim 70 wherein the actuated position comprises a cutting,
20 grasping, dissecting, cauterizing, or irrigating configuration.
- 21 75. The surgical instrument of claim 68 wherein said instrument is configured for
22 minimally invasive surgical tasks.
- 23 76. The surgical instrument of claim 68, wherein multifunctionality of the pivotable jaws is
24 enabled by a compliant mechanism.
- 25 77. A surgical instrument for performing multiple surgical tasks comprising:
26 (a) a shaft having a proximal portion and a distal portion;
27 (b) a handle mounted on the proximal portion of the shaft;
28 (c) two-part jaws pivotable relative to each other, mounted on the distal portion of the
29 shaft, said jaws having a proximal portion and a distal tip, wherein the tips of said
30 jaws are able to articulate in a plane perpendicular to a plane of jaw opening and
31 closing; and
32 (d) an actuation system for imparting articulation motion to the jaws.

- 1 78. The surgical instrument of claim 77 wherein the two-part jaws comprise scissors, a
2 dissector, or a grasper.
- 3 79. The surgical instrument of claim 77 wherein the device that enables relative rotation
4 between the two-part jaws comprises a hinge, a slot, or a gear system.
- 5 80. The surgical instrument of claim 77, wherein the jaw actuation system is mechanically
6 linked to push rods or tendon wires disposed within the shaft, which rods or wires are
7 in turn linked to the distal portion of the shaft, for effecting movement of the two-part
8 jaws from a closed position to an actuated position; for retaining the jaws in the
9 actuated position; and for enabling the jaws to return to the closed position.
- 10 81. The surgical instrument of claim 77, wherein the jaw actuation system is electrically
11 linked to an electroactive material embedded within, bonded to, or connected to the
12 two-part jaws for effecting movement of the jaws from a closed position to an actuated
13 position; for retaining the jaws in the actuated position; and for enabling the jaws to
14 return to the closed position.
- 15 82. The surgical instrument of claim 80 wherein the actuated position comprises a cutting,
16 dissecting, or grasping configuration.
- 17 83. The surgical instrument of claim 81 wherein the actuated position comprises a cutting,
18 dissecting, or grasping configuration.
- 19 84. The surgical instrument of claim 77 wherein said instrument is configured for
20 minimally invasive surgical tasks.
- 21 85. The surgical instrument of claim 77 wherein the jaws are able to be articulated
22 simultaneously or independently.
- 23 86. The surgical instrument of claim 77 wherein the two-jaws are able to be locked in
24 intermediate positions.
- 25 87. The surgical instrument of claim 80 wherein a ratchet-type device retains the two-part
26 jaws in an actuated position.
- 27 88. The surgical instrument of claim 81 wherein a ratchet-type device retains the two-part
28 jaws in an actuated position.
- 29 89. The surgical instrument of claim 77, wherein multifunctionality of the pivotable jaws is
30 enabled by a compliant mechanism.
- 31 90. The surgical instrument of claim 89 further comprising a static balance mechanism to
32 the actuating mechanism for the compliant mechanism.

- 1 91. The surgical instrument of claim 77 further comprising the jaws are rotatably about a
- 2 center axis of the shaft.

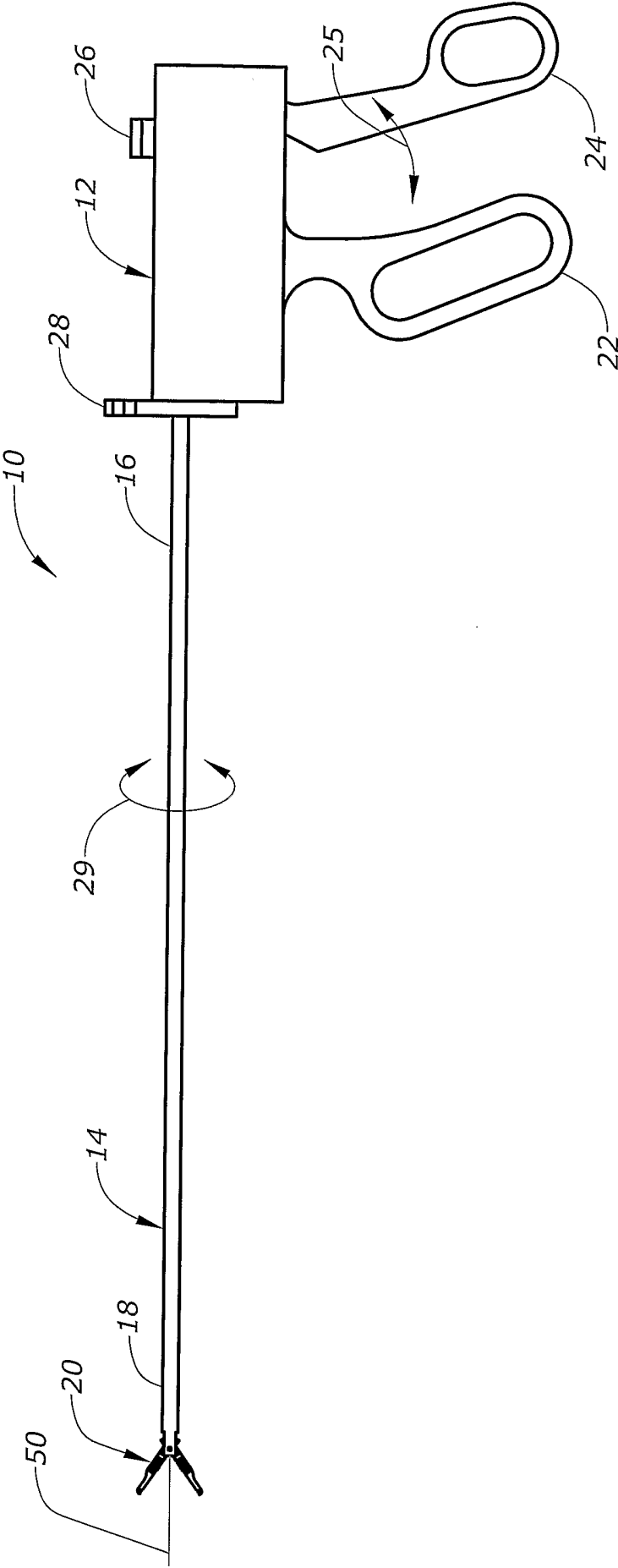


Fig. 1

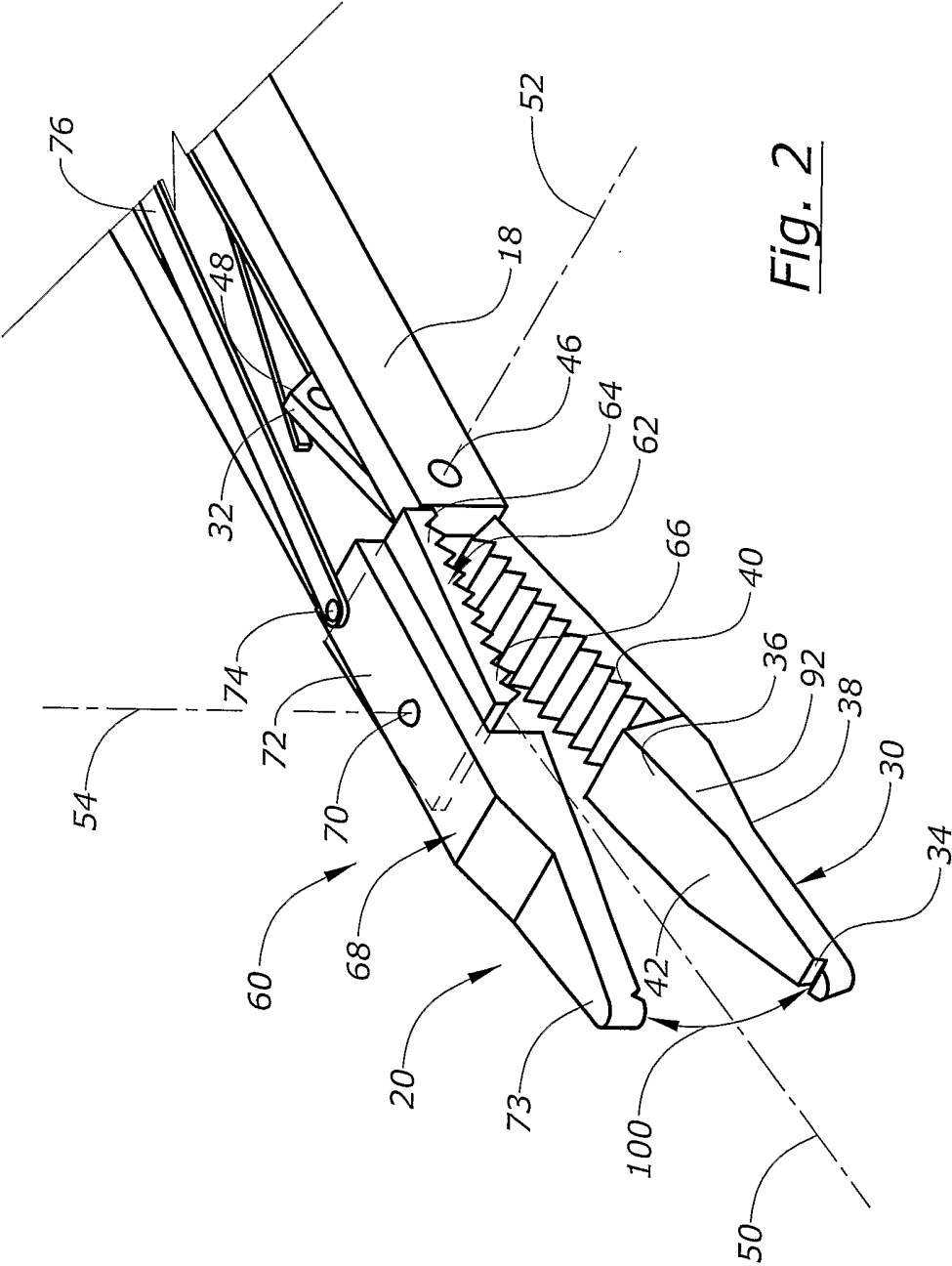


Fig. 2

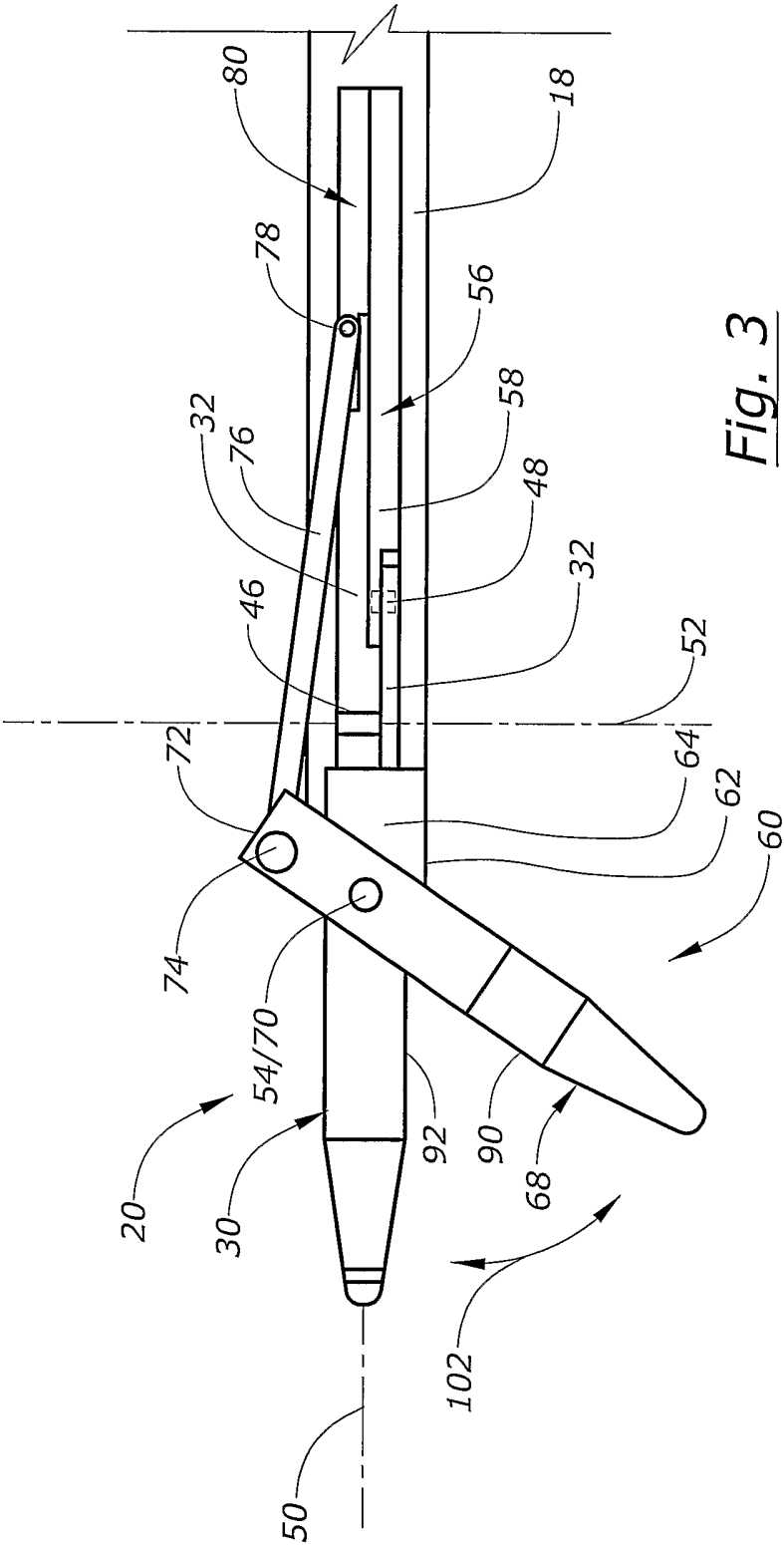


Fig. 3

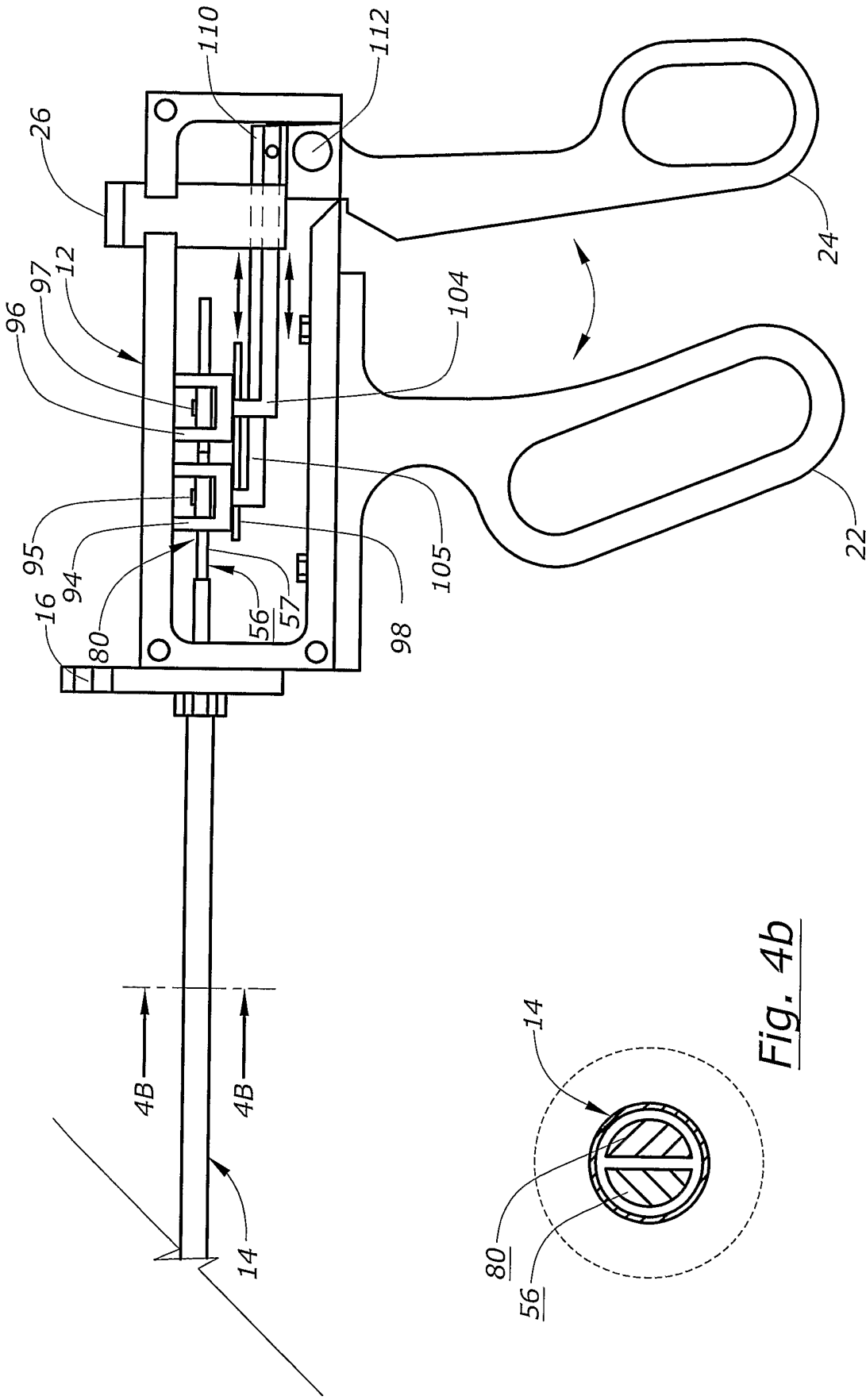


Fig. 4a

Fig. 4b

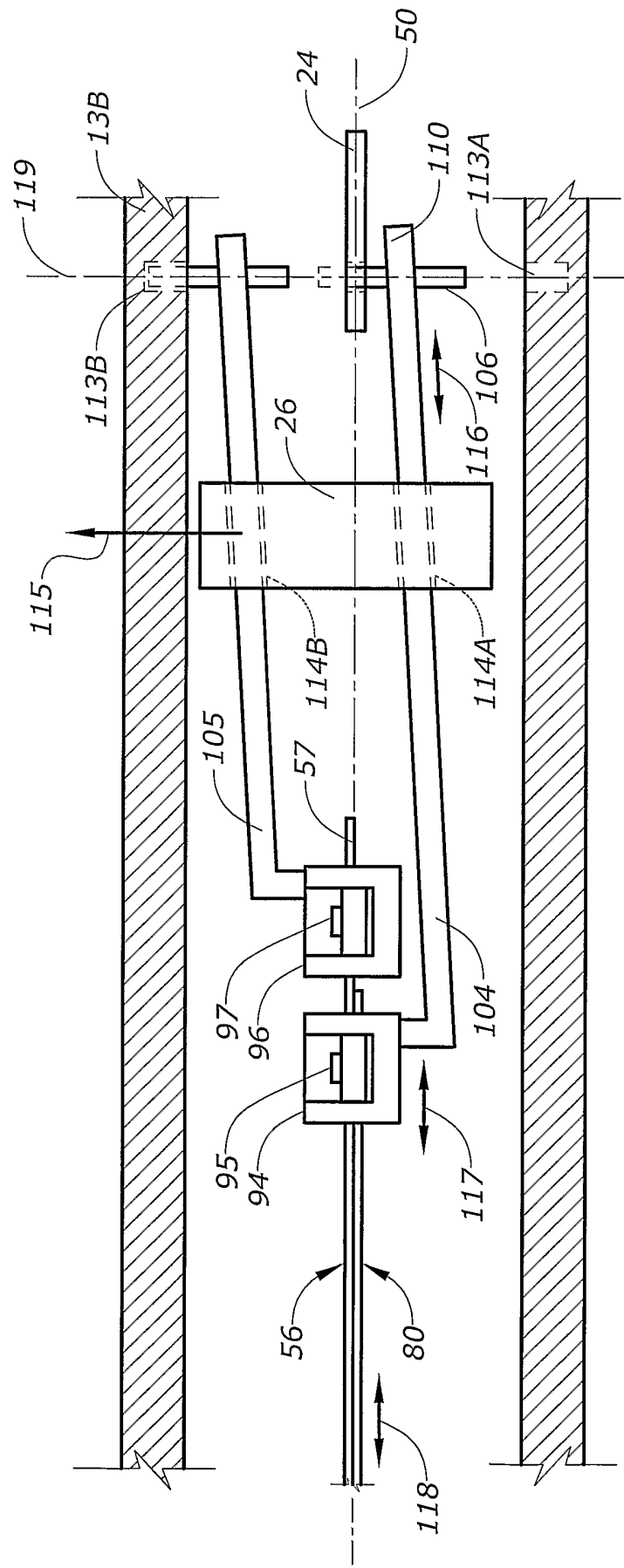


Fig. 5

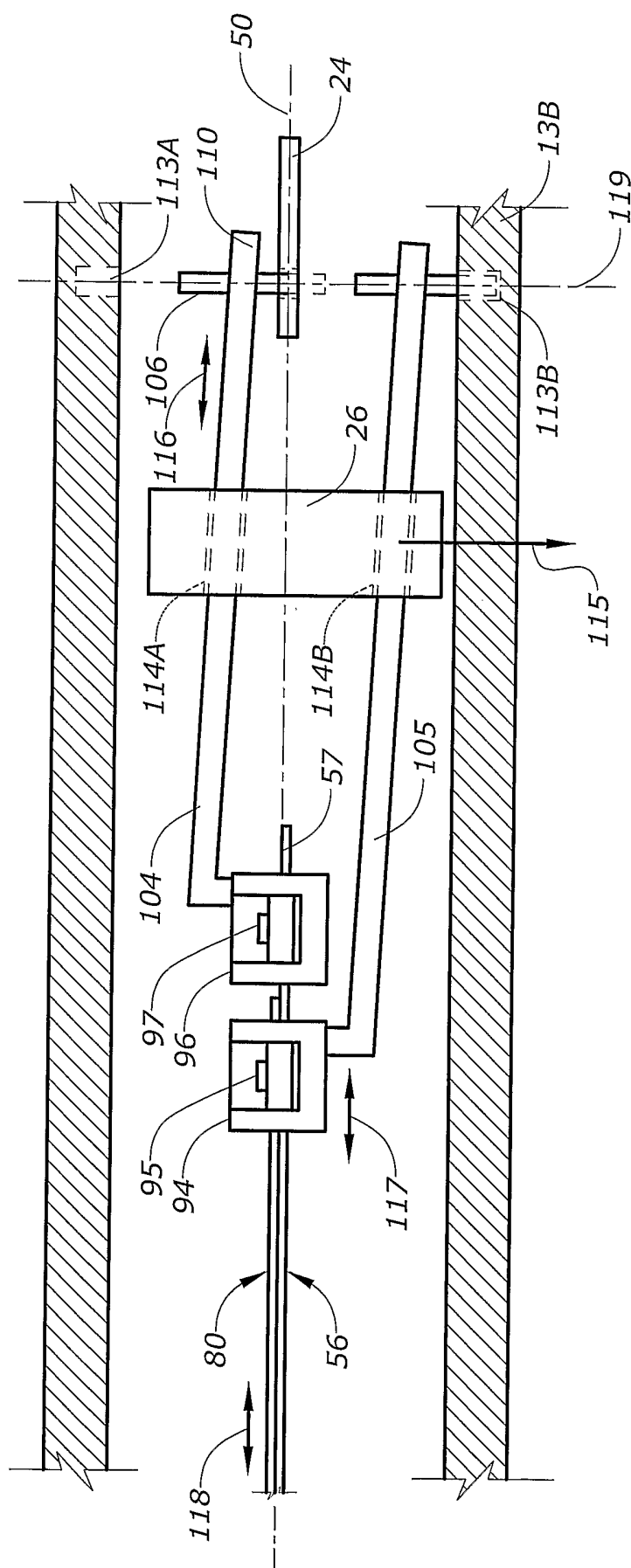


Fig. 6

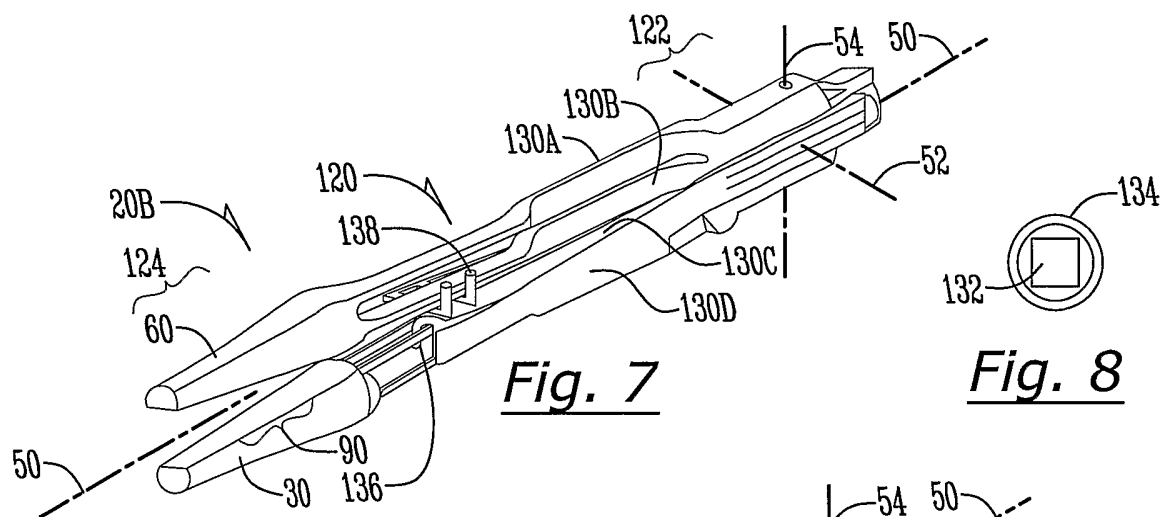


Fig. 7

Fig. 8

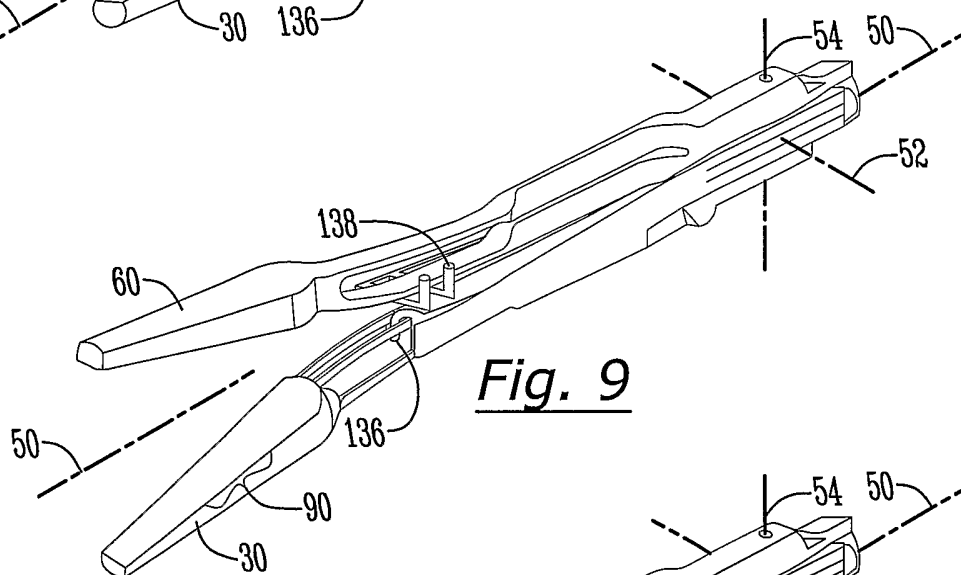


Fig. 9

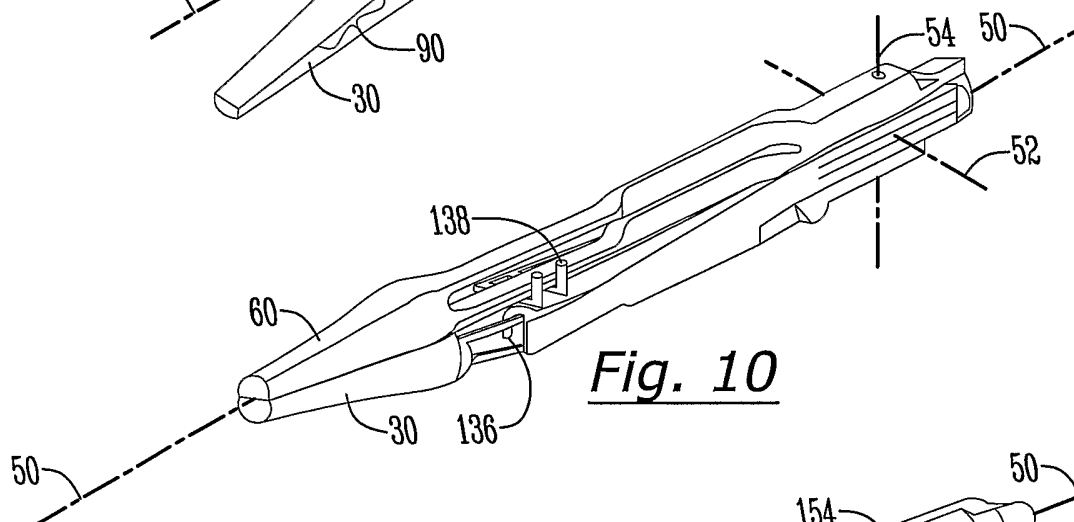


Fig. 10

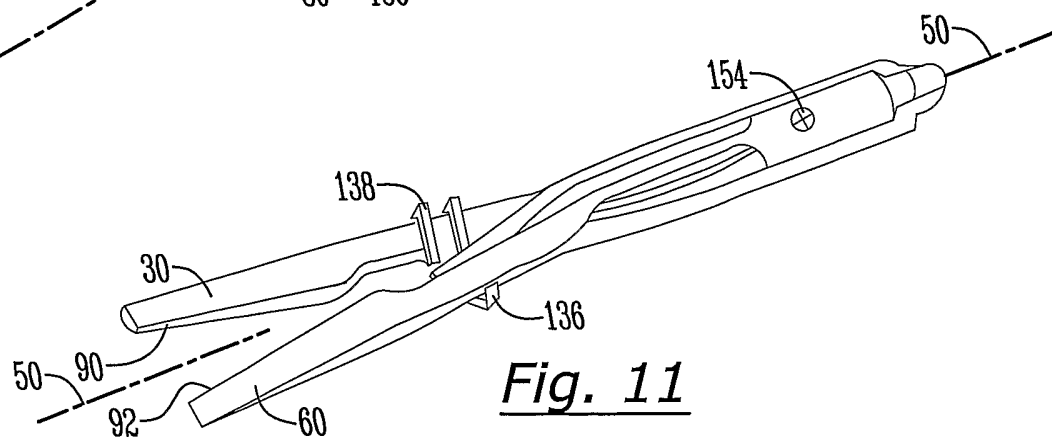


Fig. 11

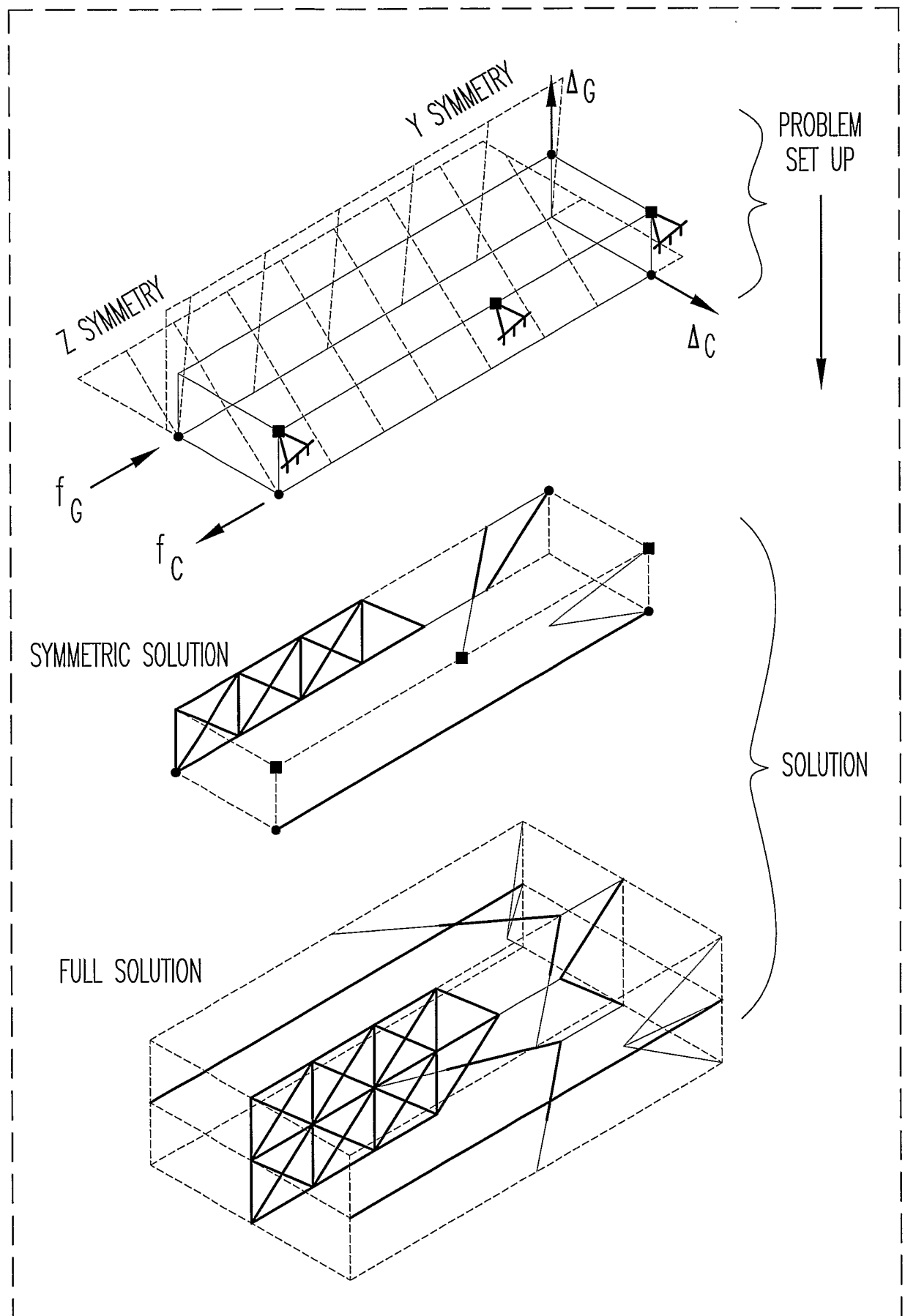
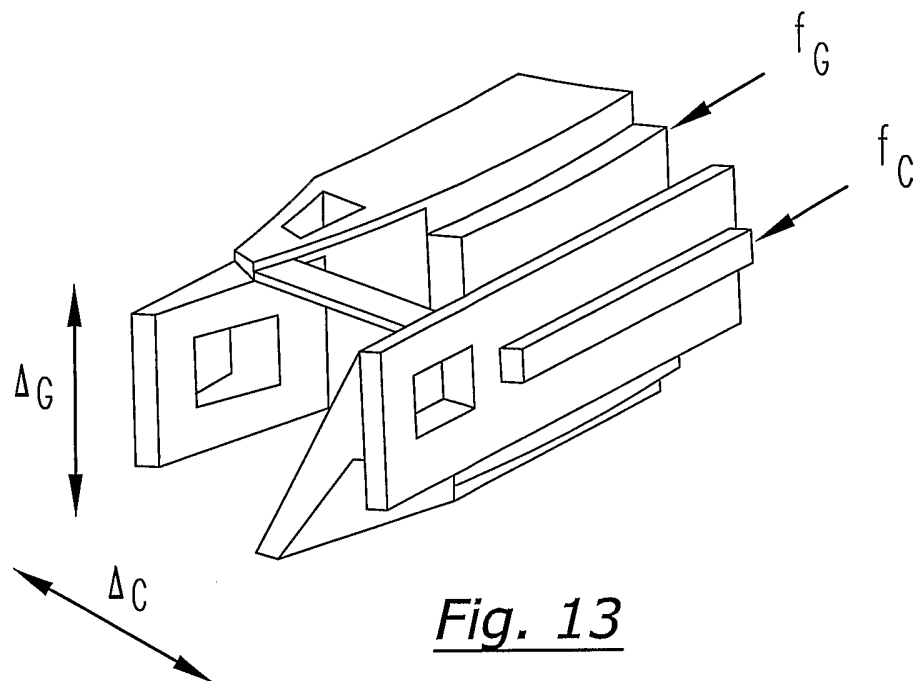
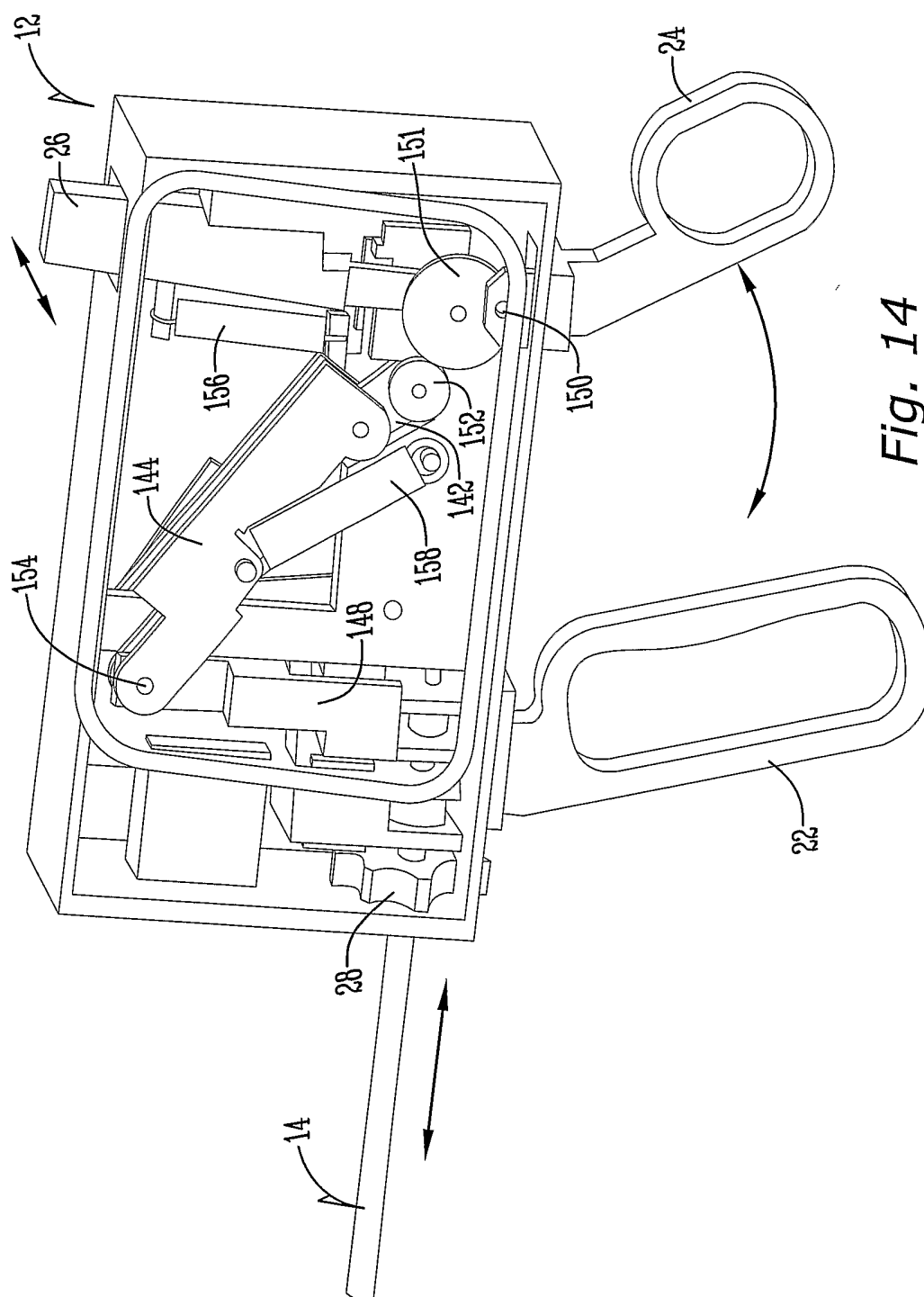


Fig. 12





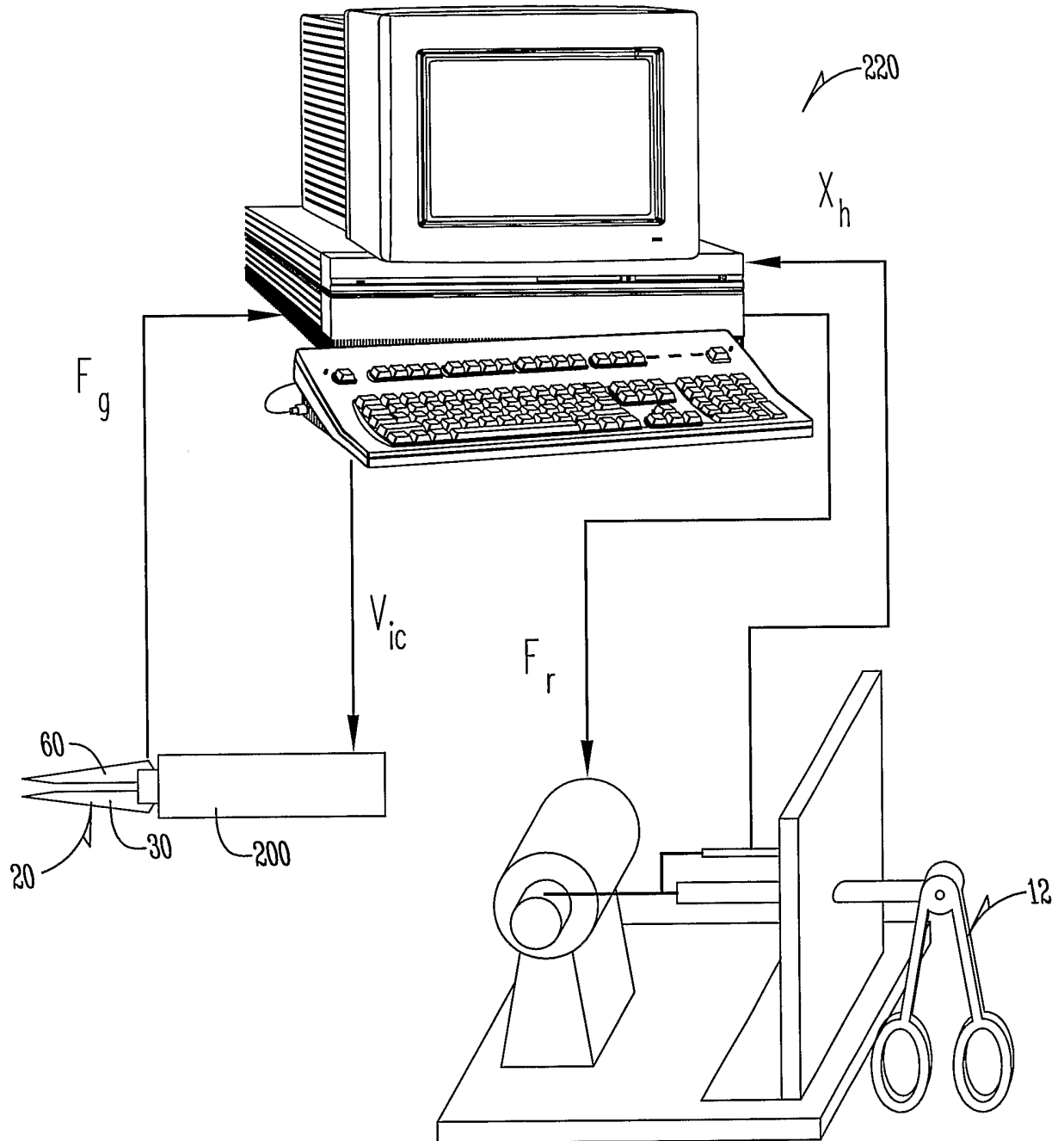


Fig. 15

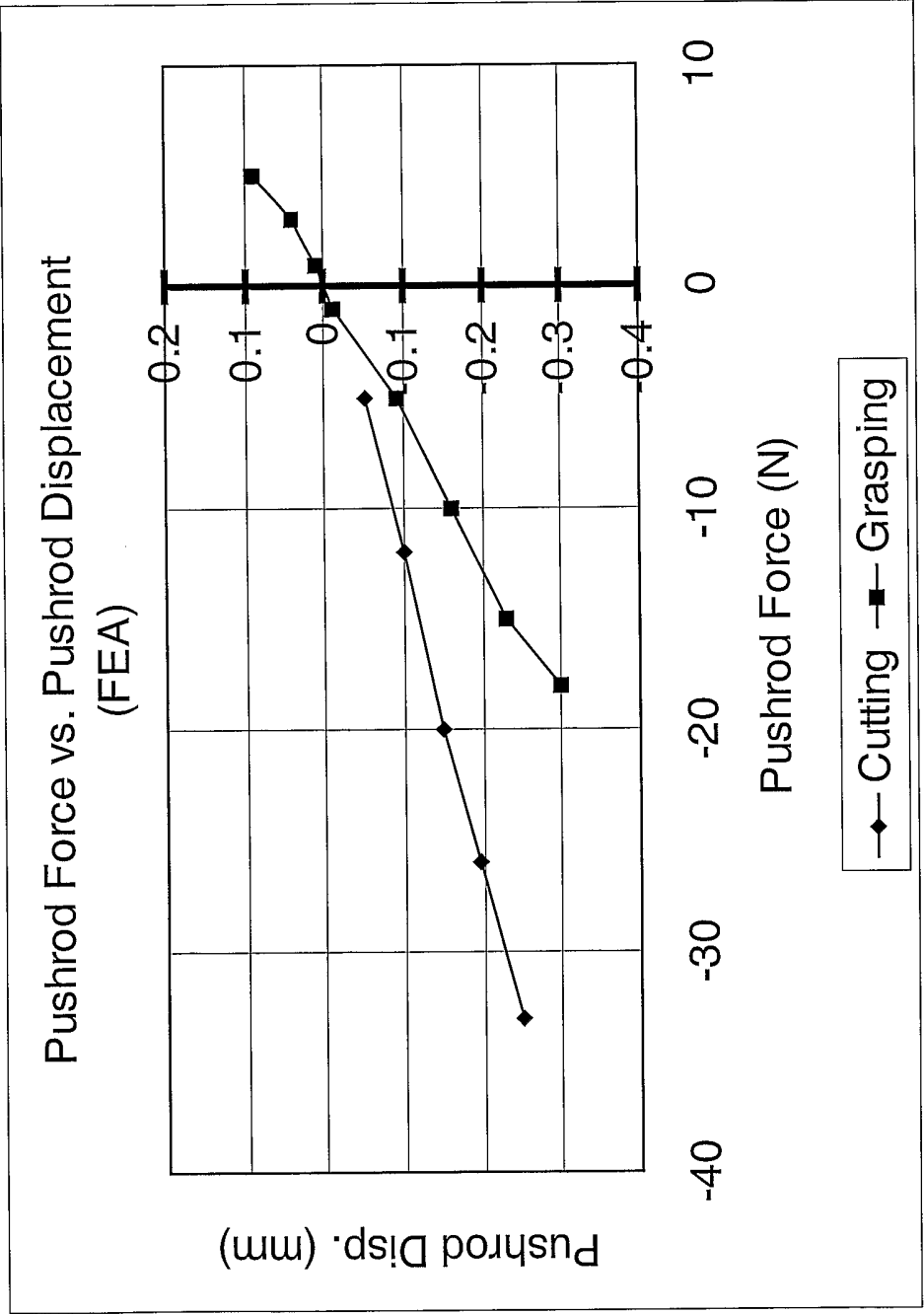


Fig. 16A

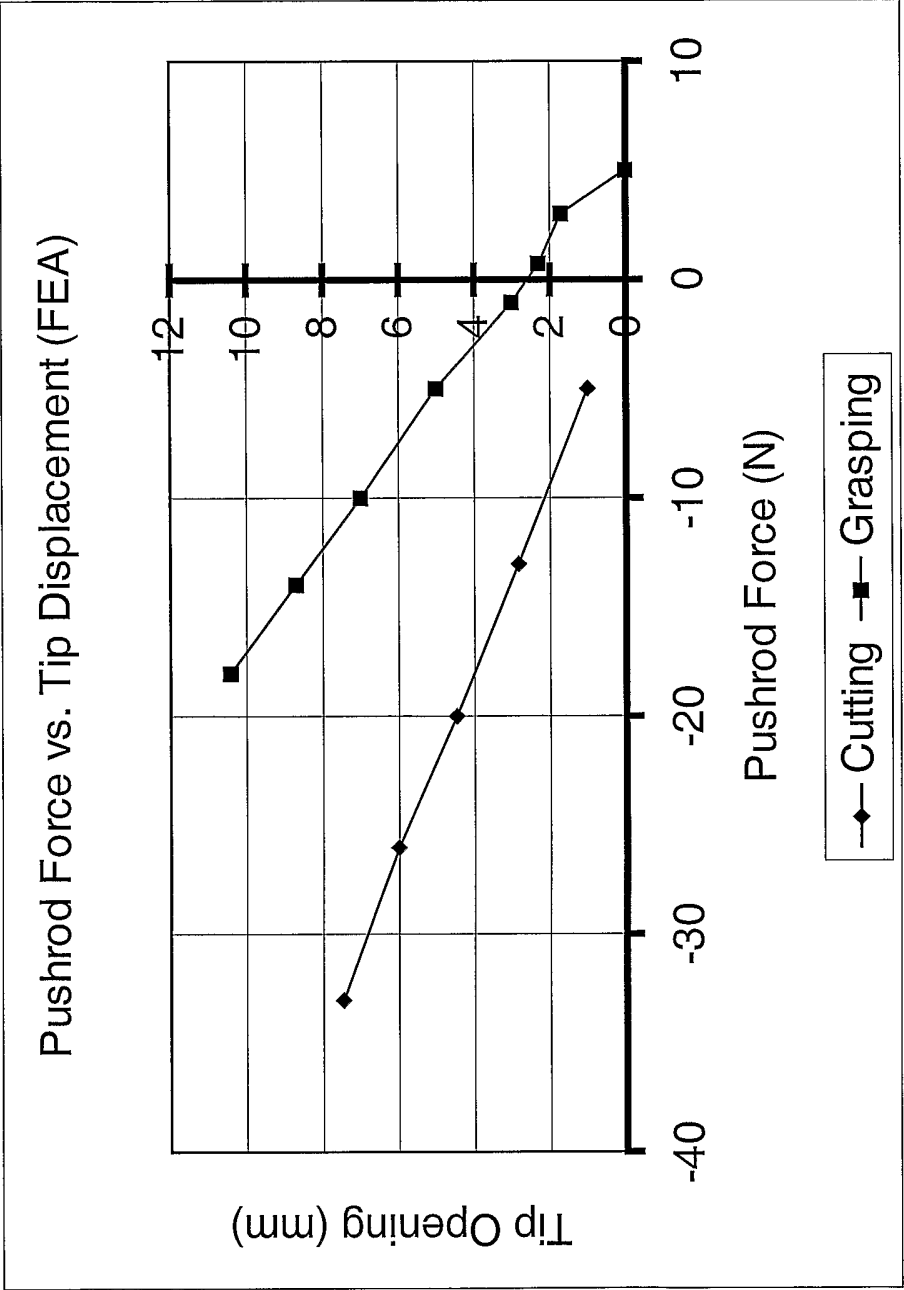


Fig. 16B

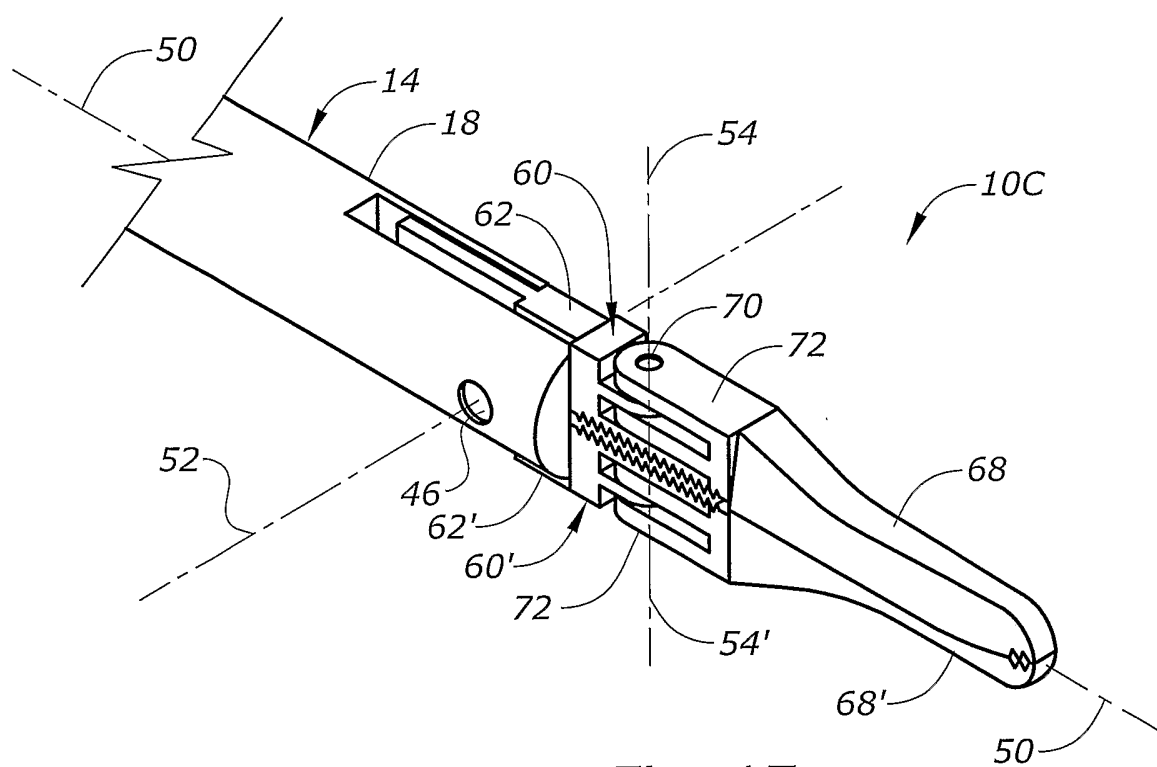


Fig. 17a

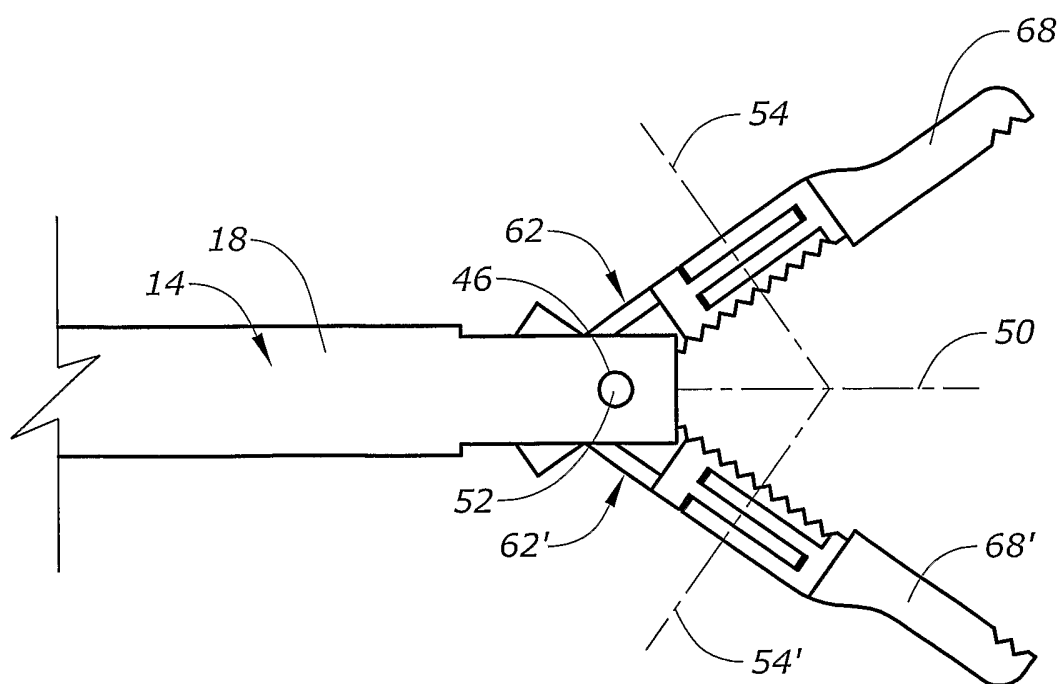


Fig. 17b

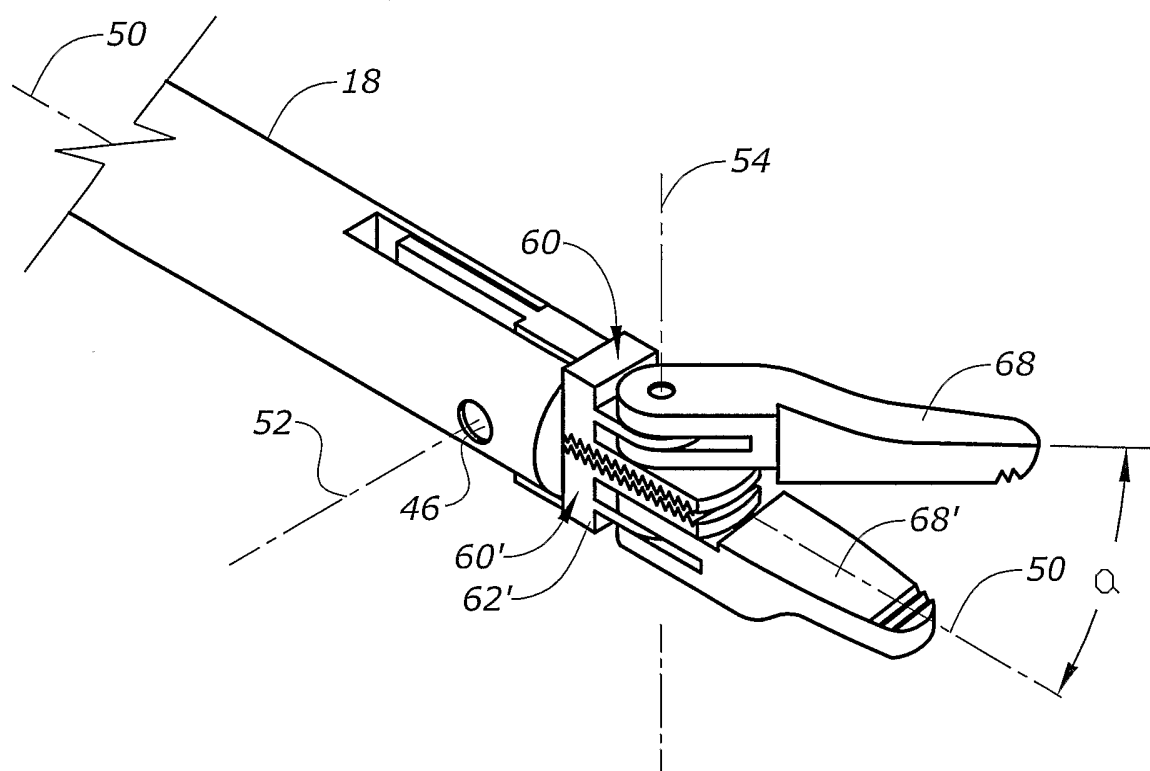


Fig. 17c

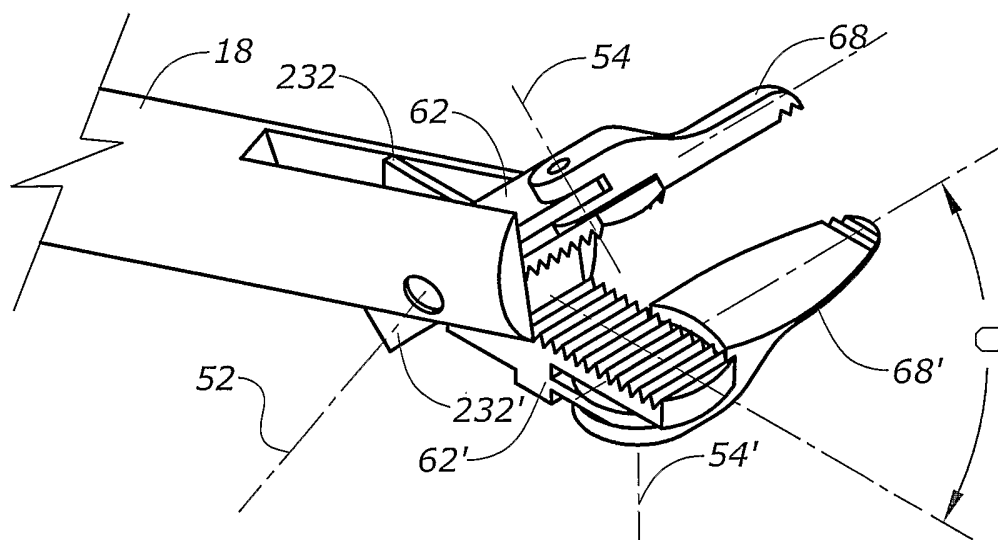


Fig. 17d

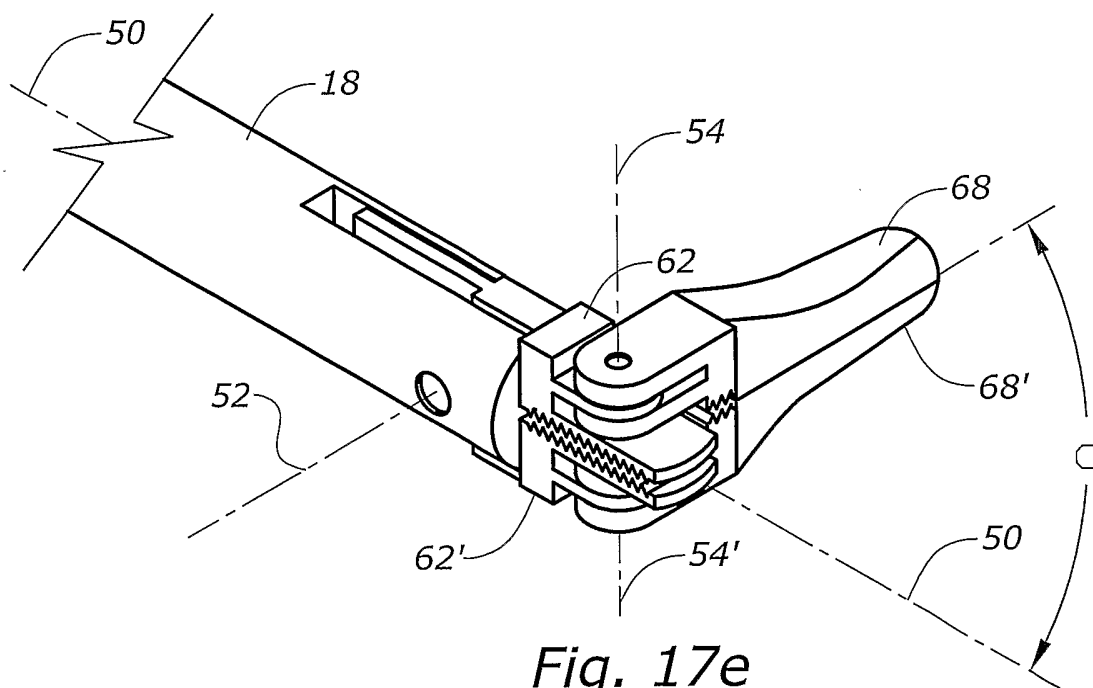


Fig. 17e

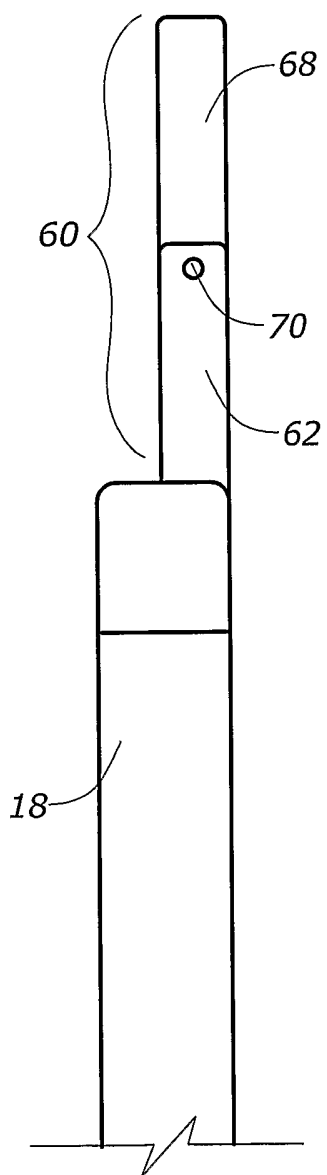


Fig. 18a

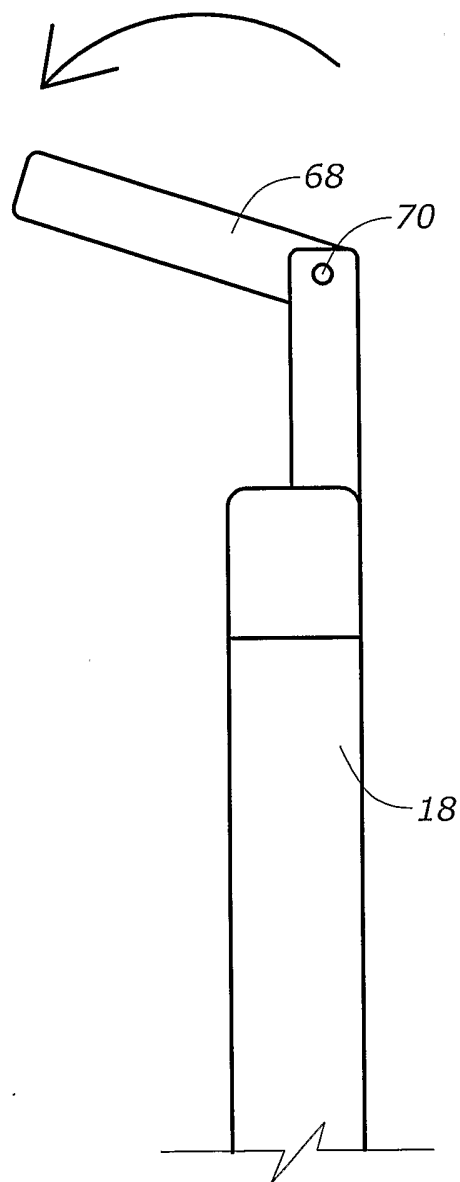


Fig. 18b

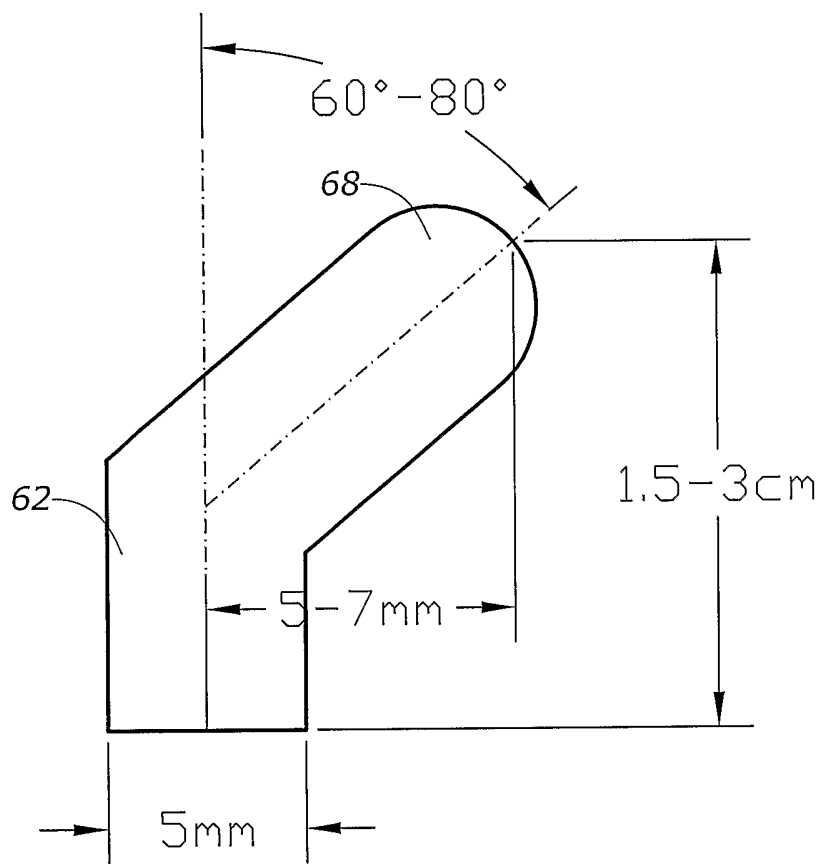


Fig. 18c

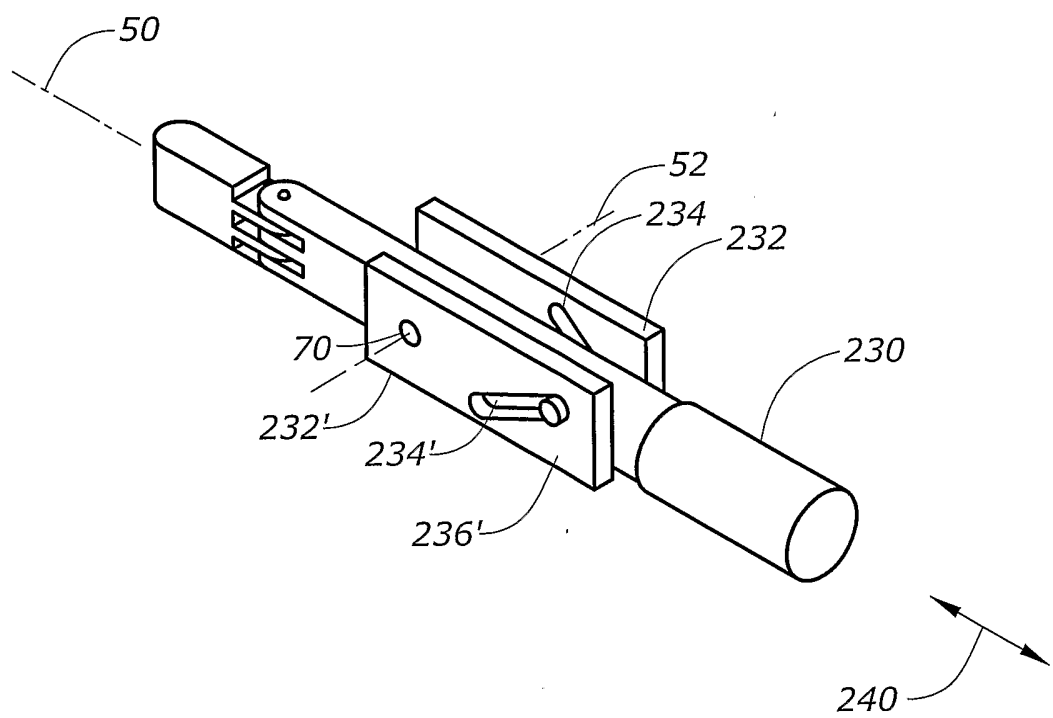


Fig. 19a

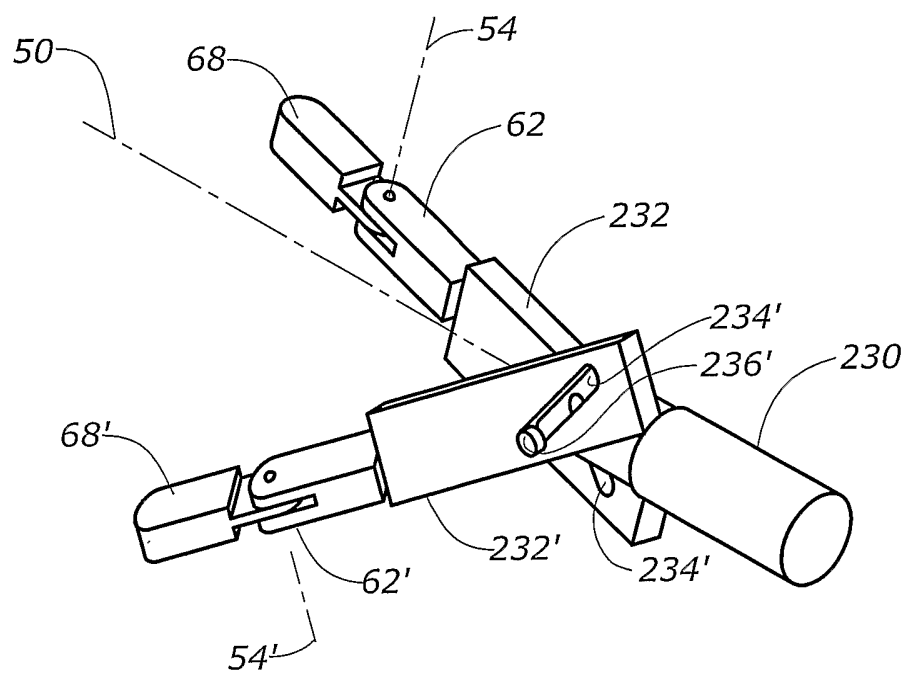


Fig. 19b

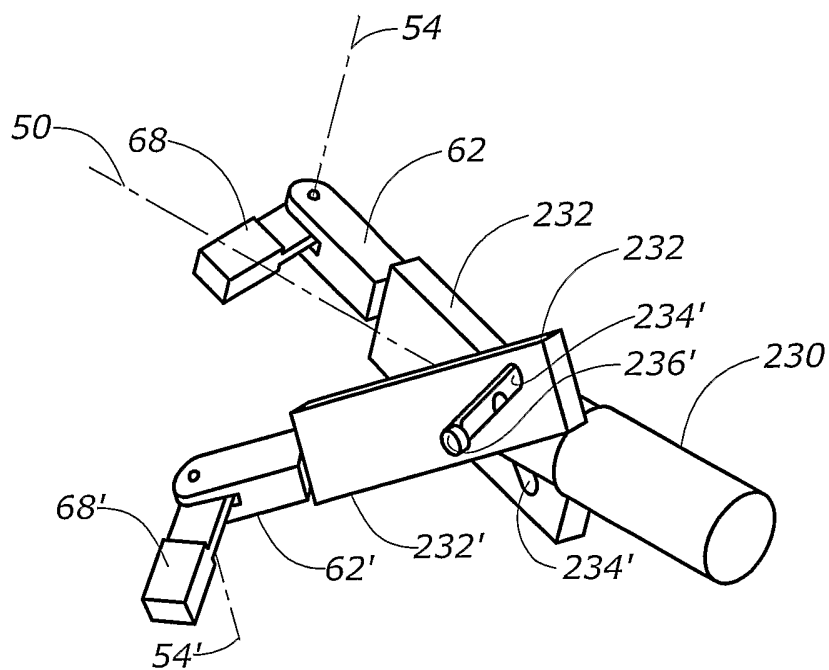


Fig. 19c

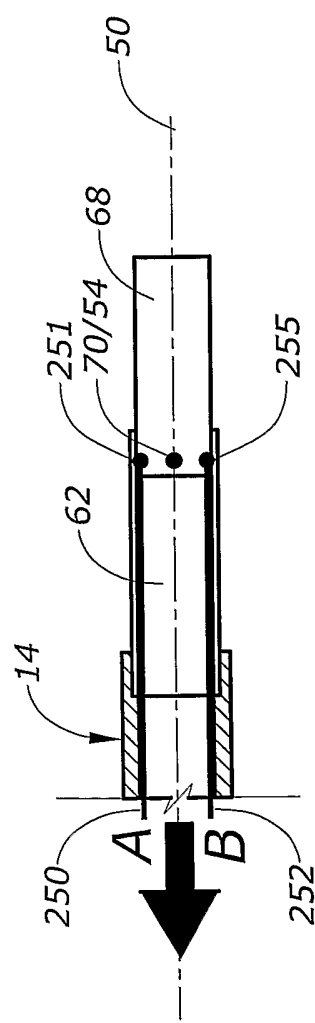


Fig. 20a

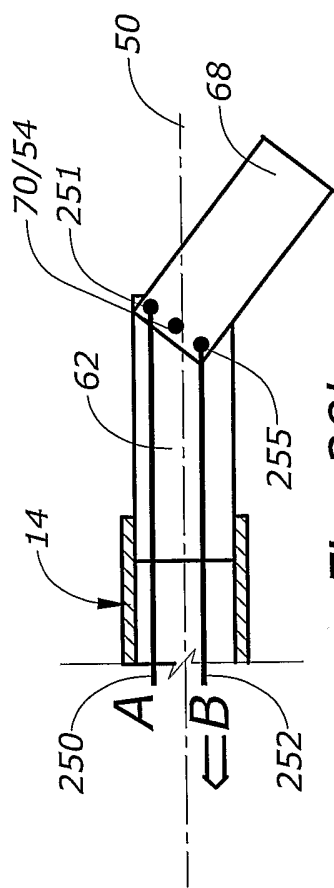


Fig. 20b

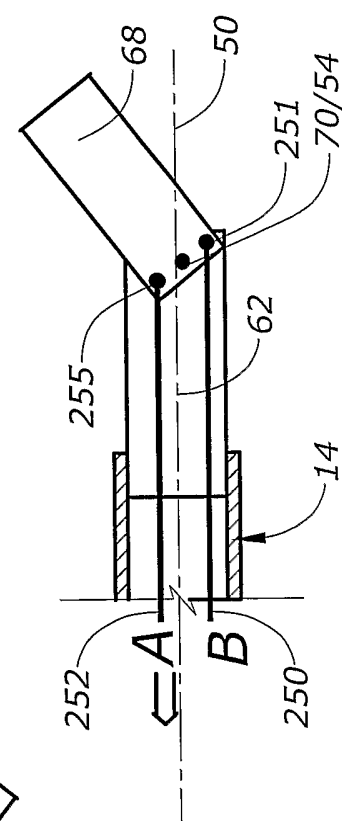


Fig. 20c

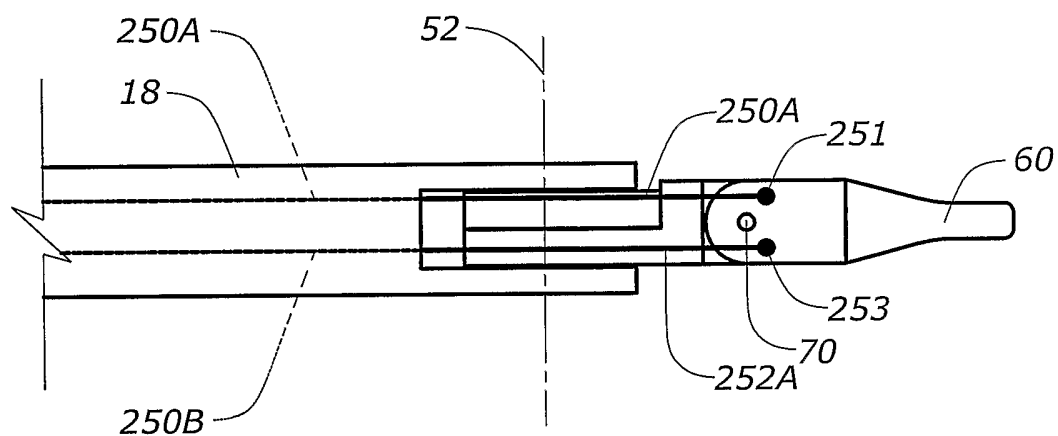


Fig. 20d

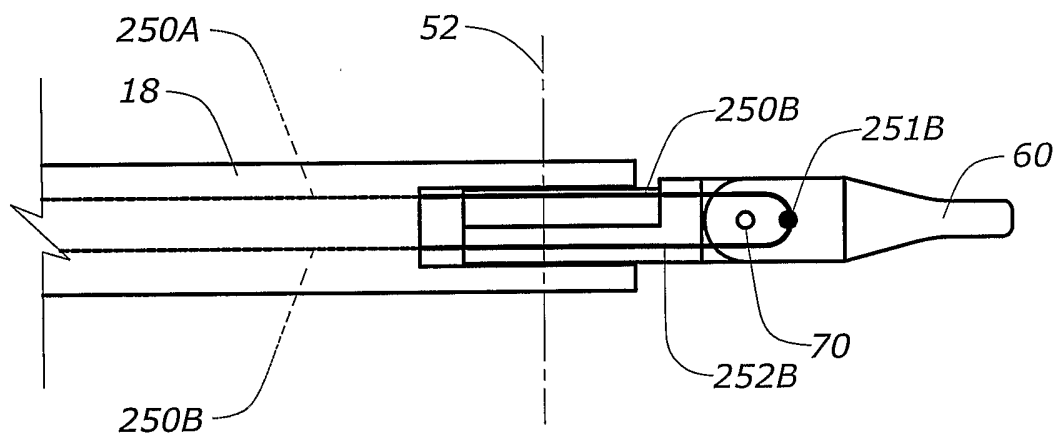


Fig. 20e

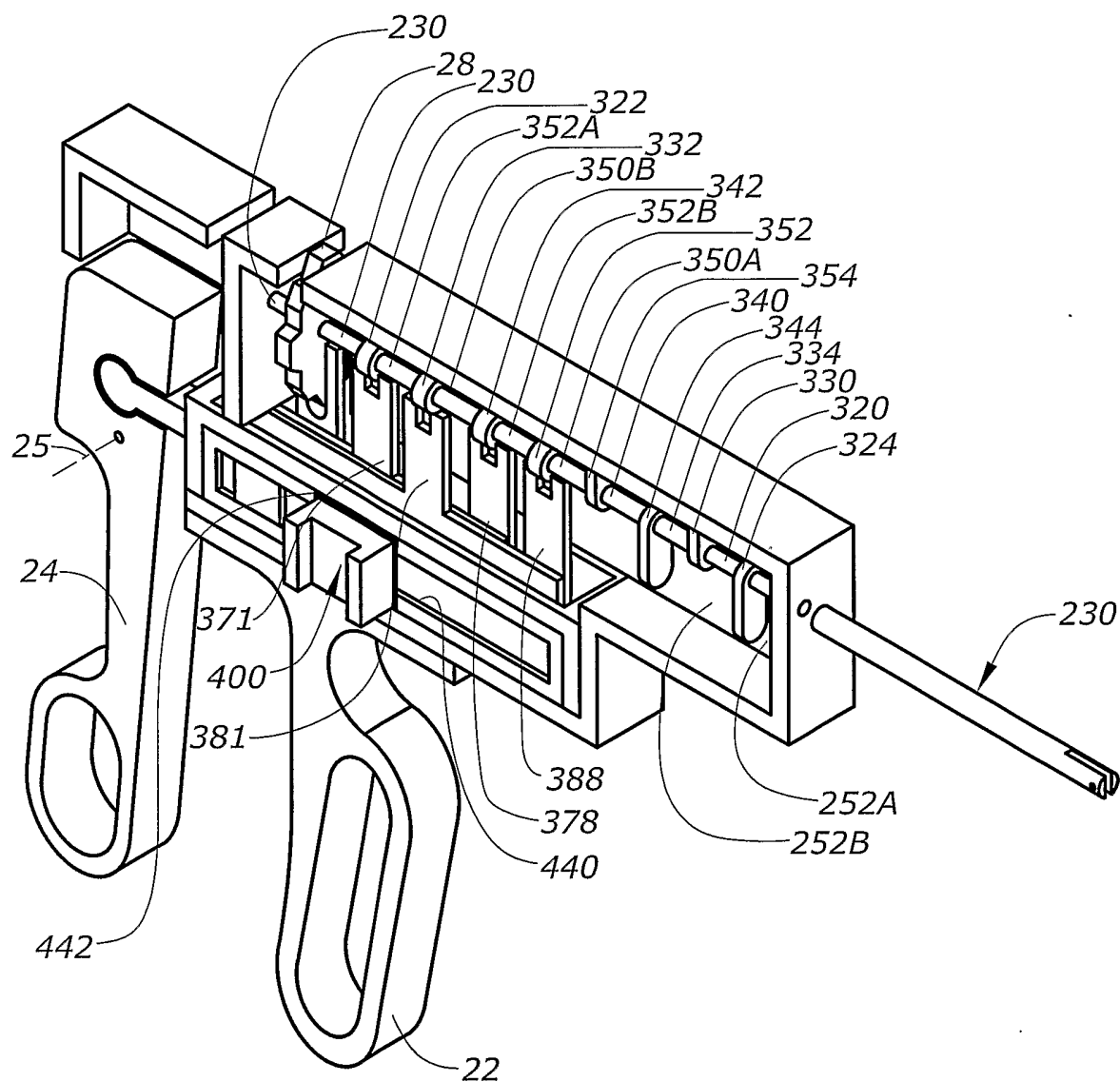


Fig. 21a

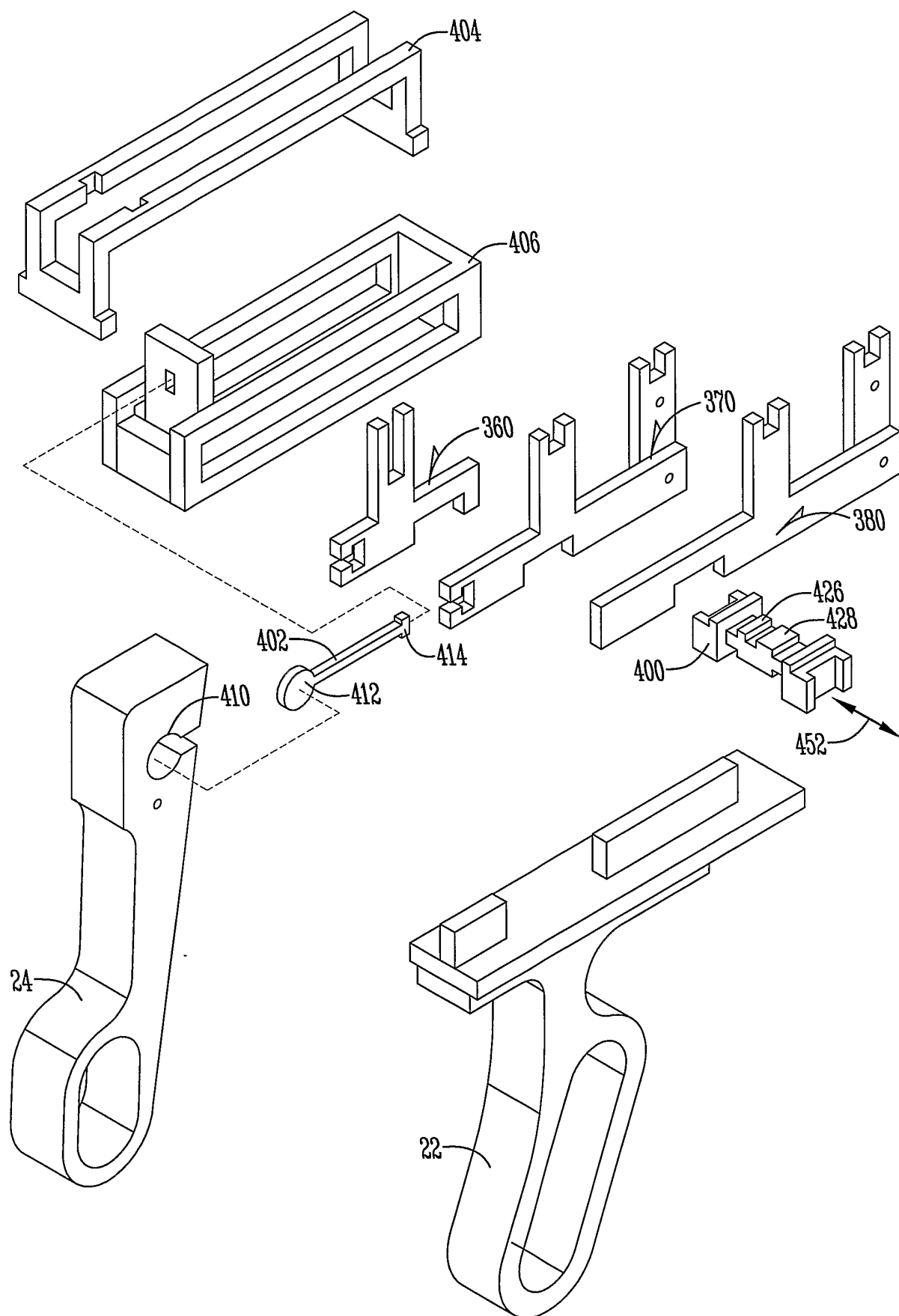


Fig. 21B

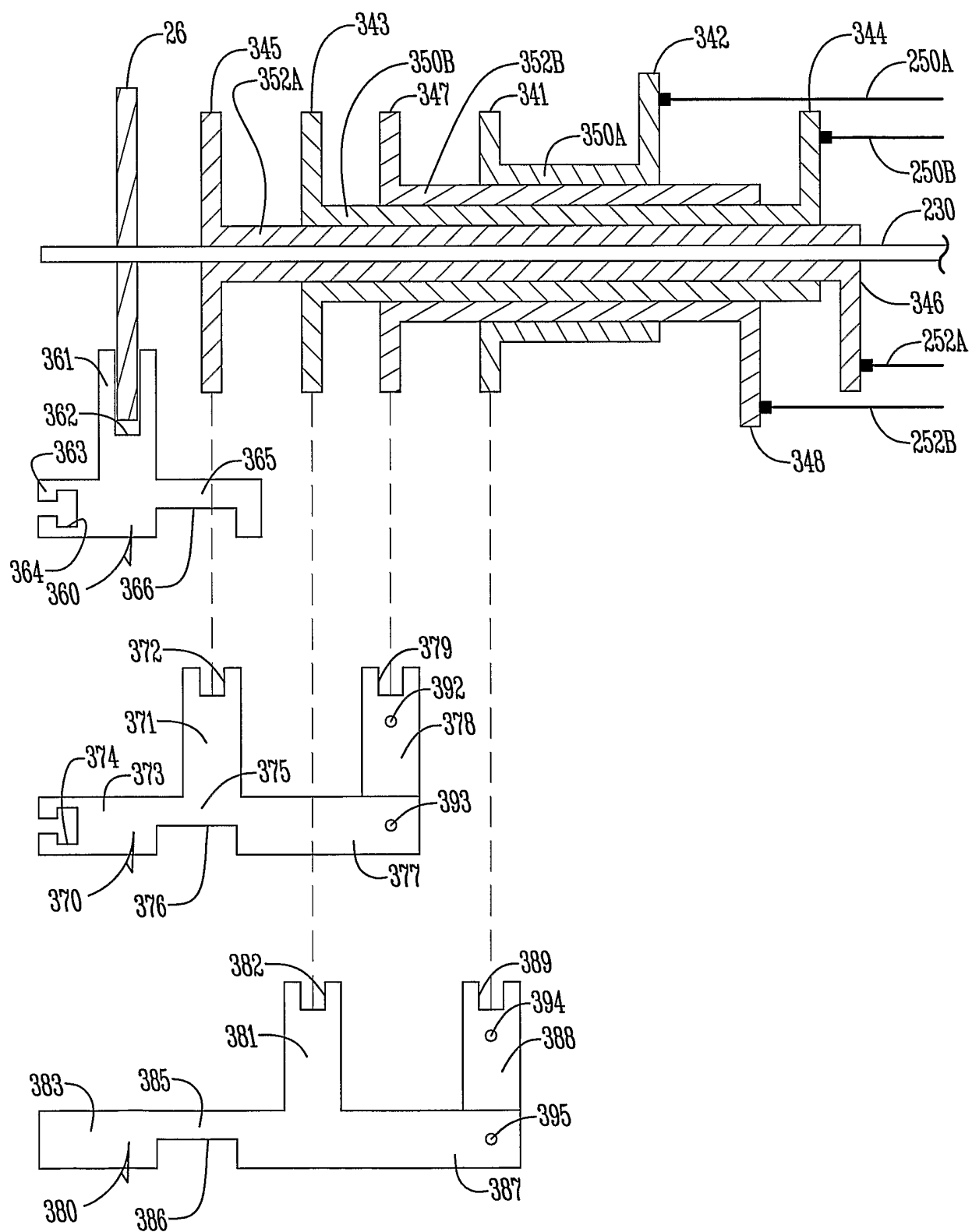


Fig. 21C

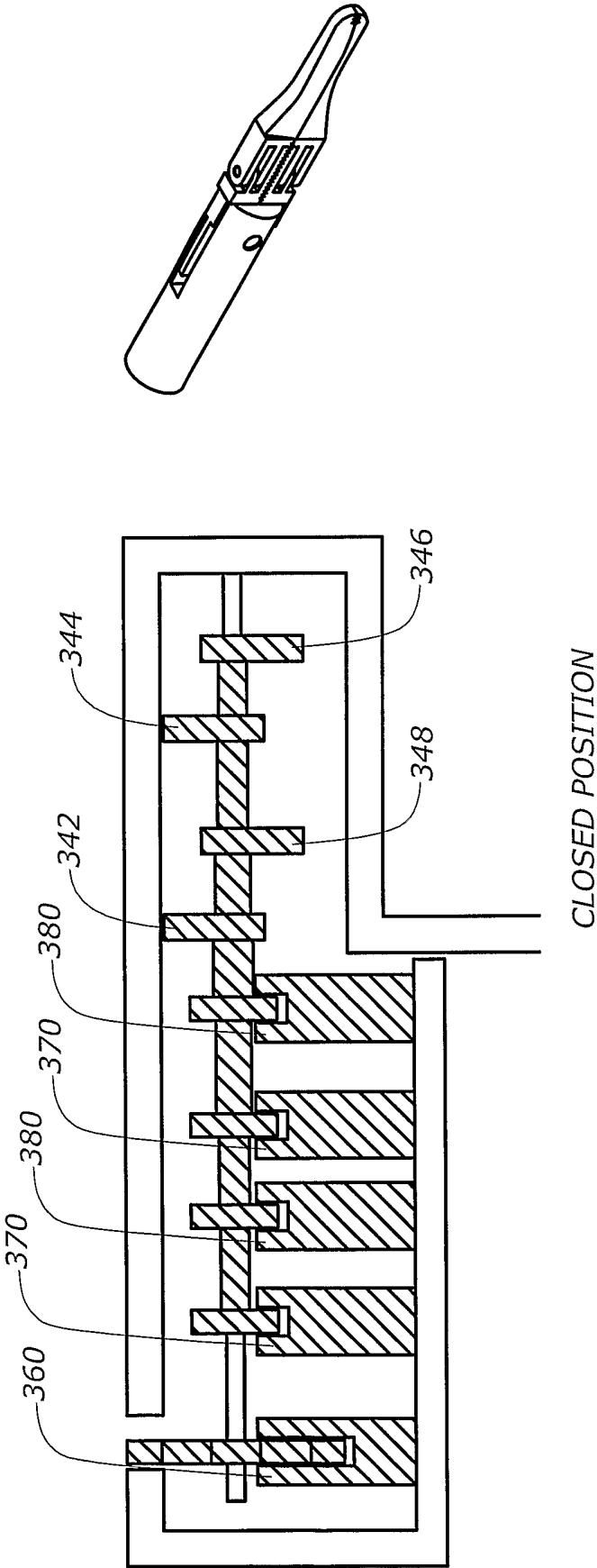
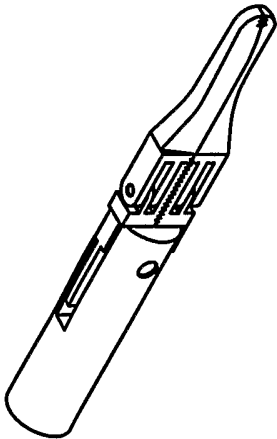
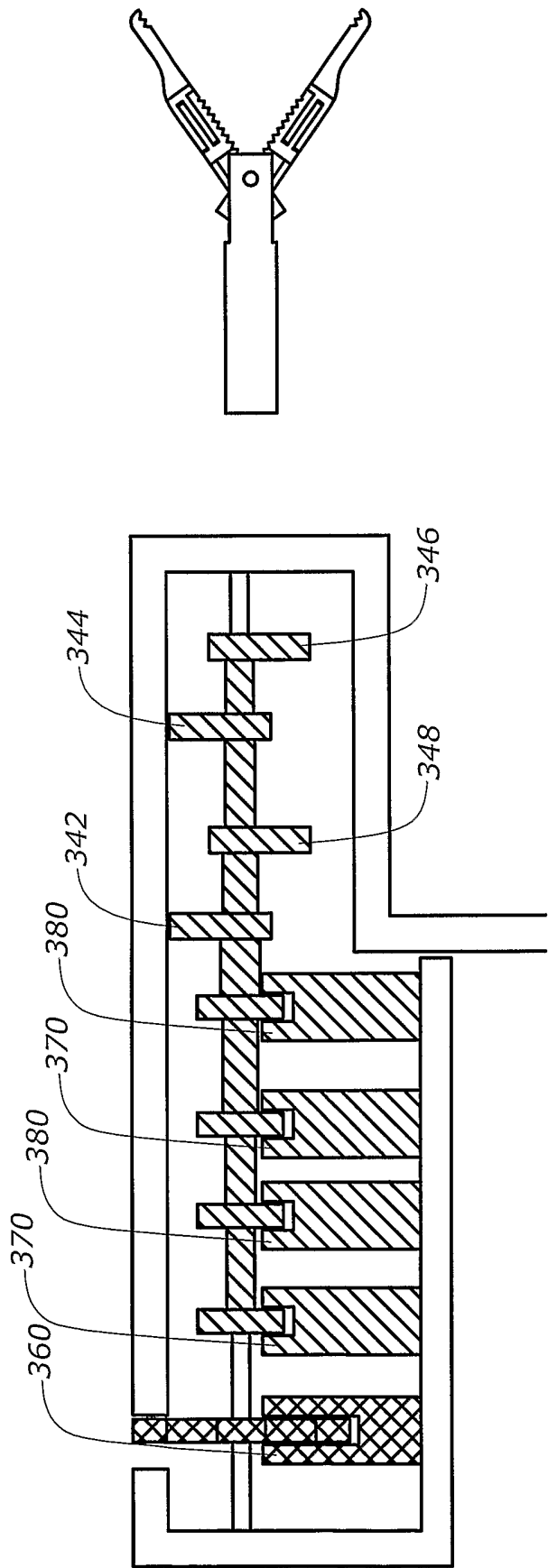


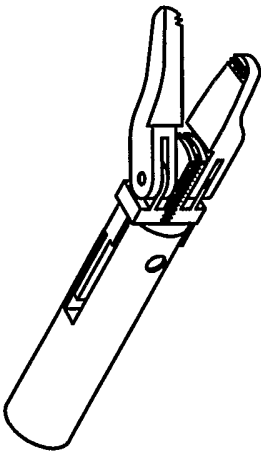
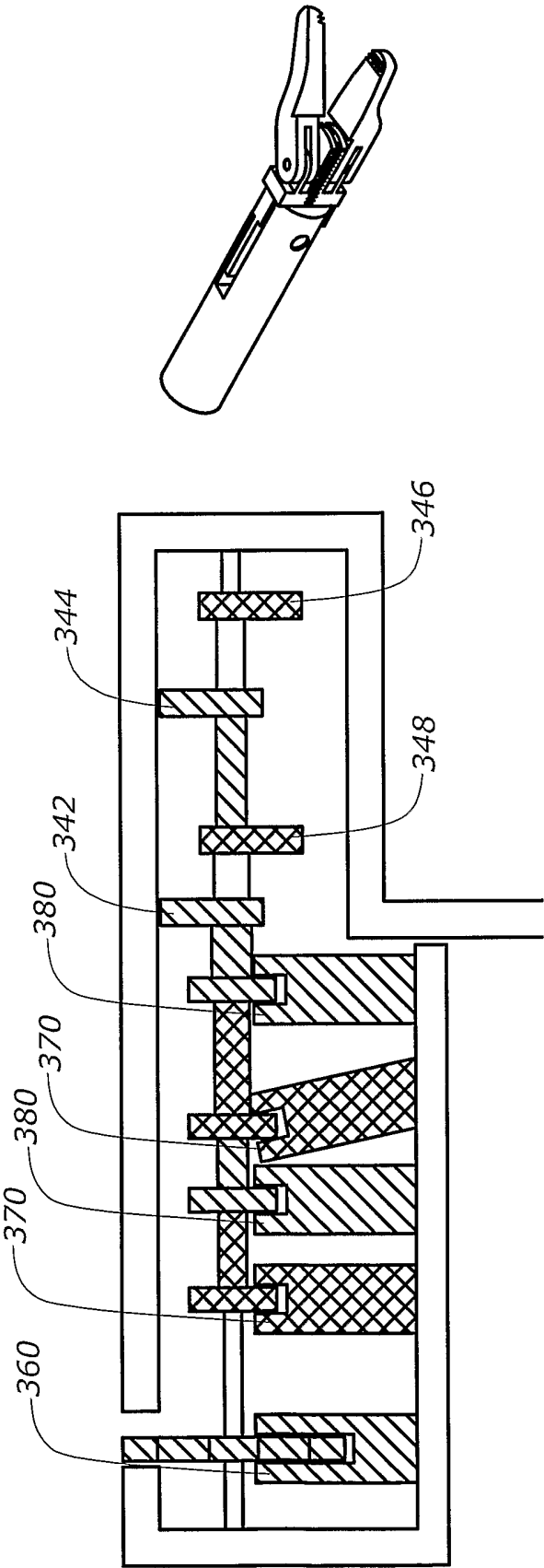
Fig. 22a





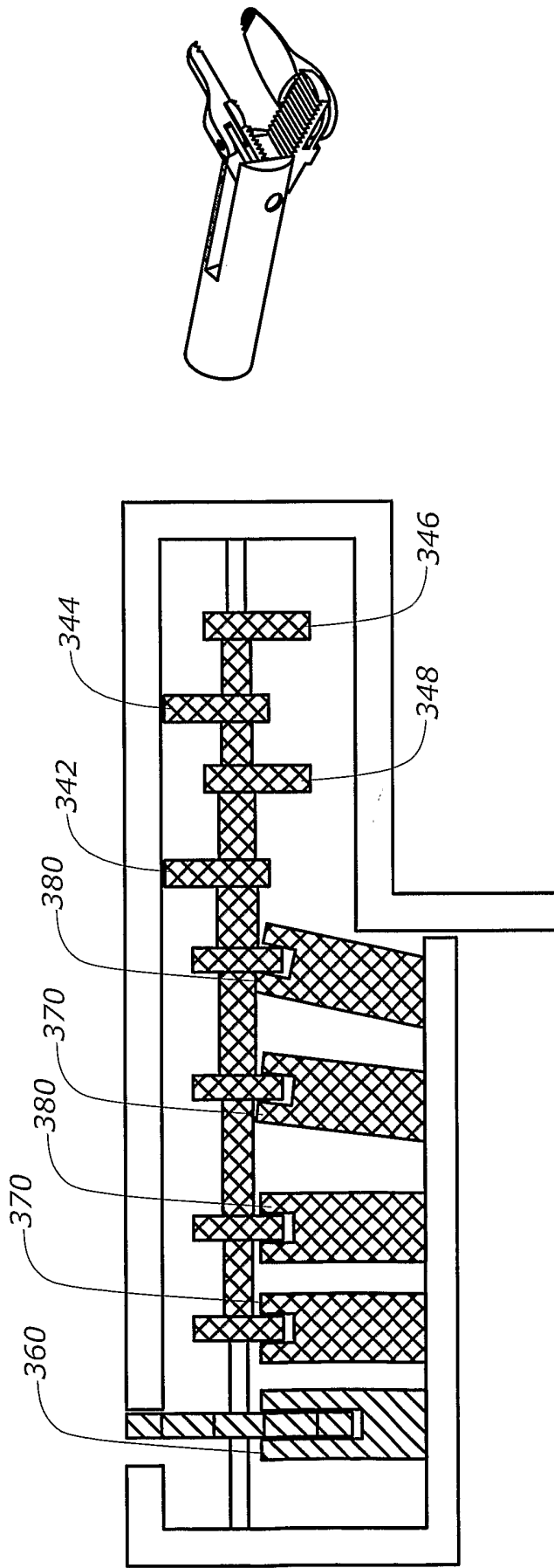
OPEN GRASPING POSITION

Fig. 22b



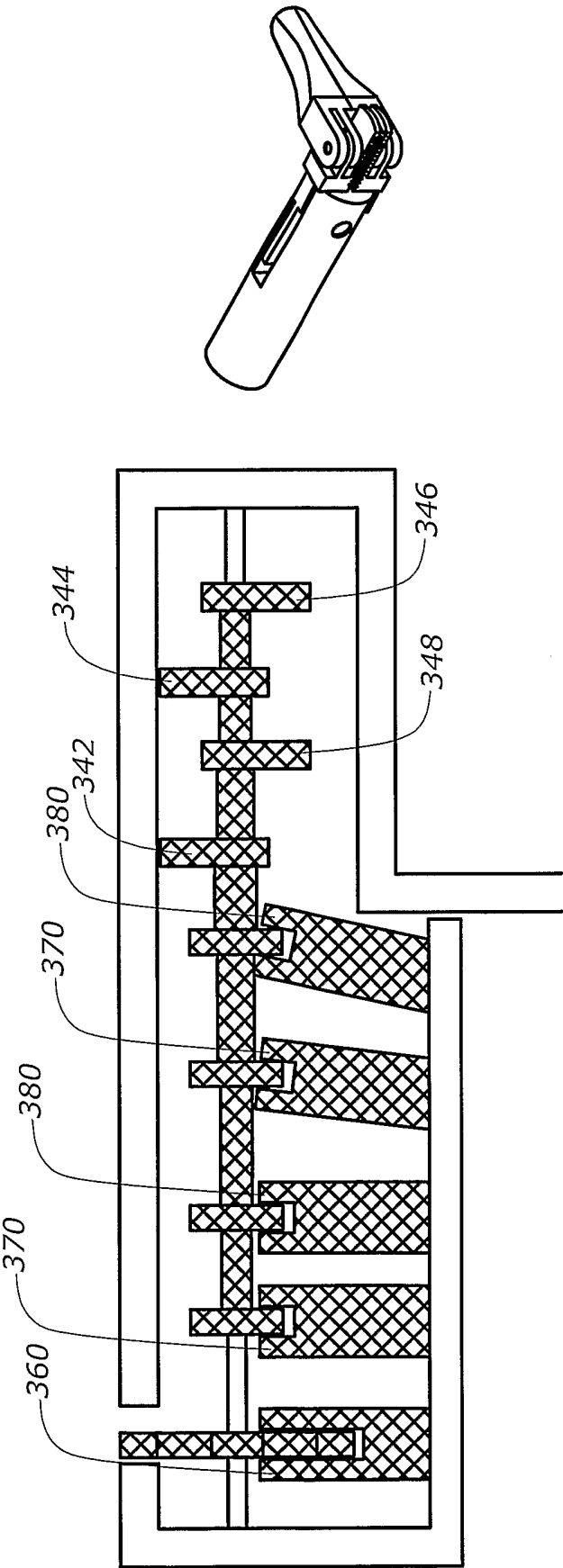
OPEN CUTTING POSITION

Fig. 22c



CLOSED ARTICULATED GRASPING POSITION

Fig. 22d



OPEN ARTICULATION POSITION

Fig. 22e

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 02/24918

A. CLASSIFICATION OF SUBJECT MATTER
 IPC 7 A61B17/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 IPC 7 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99 29238 A (MOLL FRANCISCUS LAURENS ;KALMANN MENNO (NL); SURGICAL INNOVATIONS) 17 June 1999 (1999-06-17) the whole document ----	1,3-13, 46-53, 57,68,77
X	US 6 126 665 A (YOON INBAE) 3 October 2000 (2000-10-03) the whole document ----	1,3-12, 14-22, 68-70, 77-89 46,57
A	US 5 542 949 A (YOON INBAE) 6 August 1996 (1996-08-06) the whole document ----	1,3-6, 68,77 46,57
X	US 5 984 938 A (YOON INBAE) 16 November 1999 (1999-11-16) the whole document ----	1,68,77 46,57
	--- -/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
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- *&* document member of the same patent family

Date of the actual completion of the international search

29 November 2002

Date of mailing of the international search report

06/12/2002

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Authorized officer

Hansen, S

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 02/24918

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 43 38 510 A (REBEL MARCUS) 30 June 1994 (1994-06-30) the whole document ----	1,3-6, 46,57, 68,77
A	WO 00 33723 A (EVANS PHILIP C ;FLAK VOLKMAR (US); GUTHART GARY S (US); MOLL FREDE) 15 June 2000 (2000-06-15) abstract; figures 1,2,23 ----	1,2, 17-33, 46,57, 68,77
A	US 5 808 665 A (GREEN PHILIP S) 15 September 1998 (1998-09-15) abstract; figure 1 -----	1,2, 17-33, 46,57, 68,77

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 02/24918

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☒ Claims Nos.: 34-45
because they relate to subject matter not required to be searched by this Authority, namely:
Rule 39.1(iv) PCT - Method for treatment of the human or animal body by surgery
2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 02/24918

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Information on patent family members

International Application No

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