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(54) **ROBOTICALLY CONTROLLED MEDICAL INSTRUMENT WITH A FLEXIBLE SECTION**

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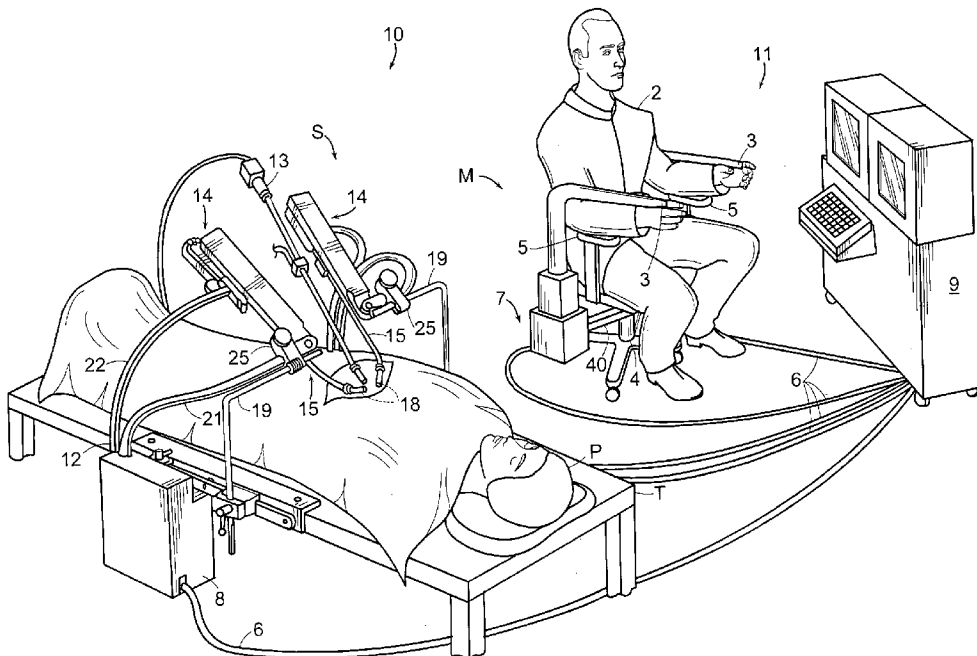
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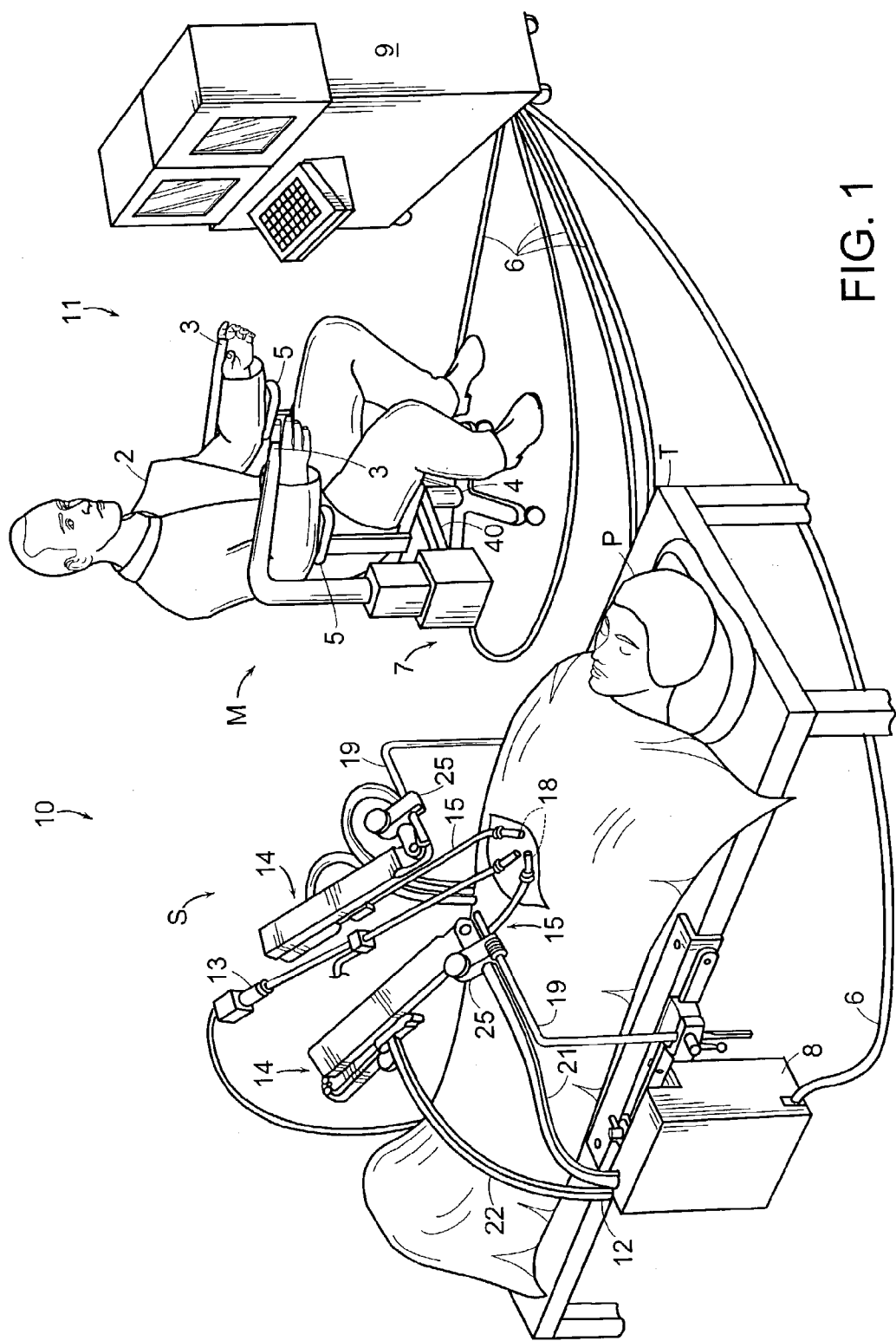
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(57) **ABSTRACT**

A robotically controlled medical instrument includes a bending section with a unibody construction, a tool supported at a distal end of the bending section and used to perform a medical procedure on a subject such as a human patient, and an electronic controller that controls the bending section to provide at least one degree-of-freedom of movement.





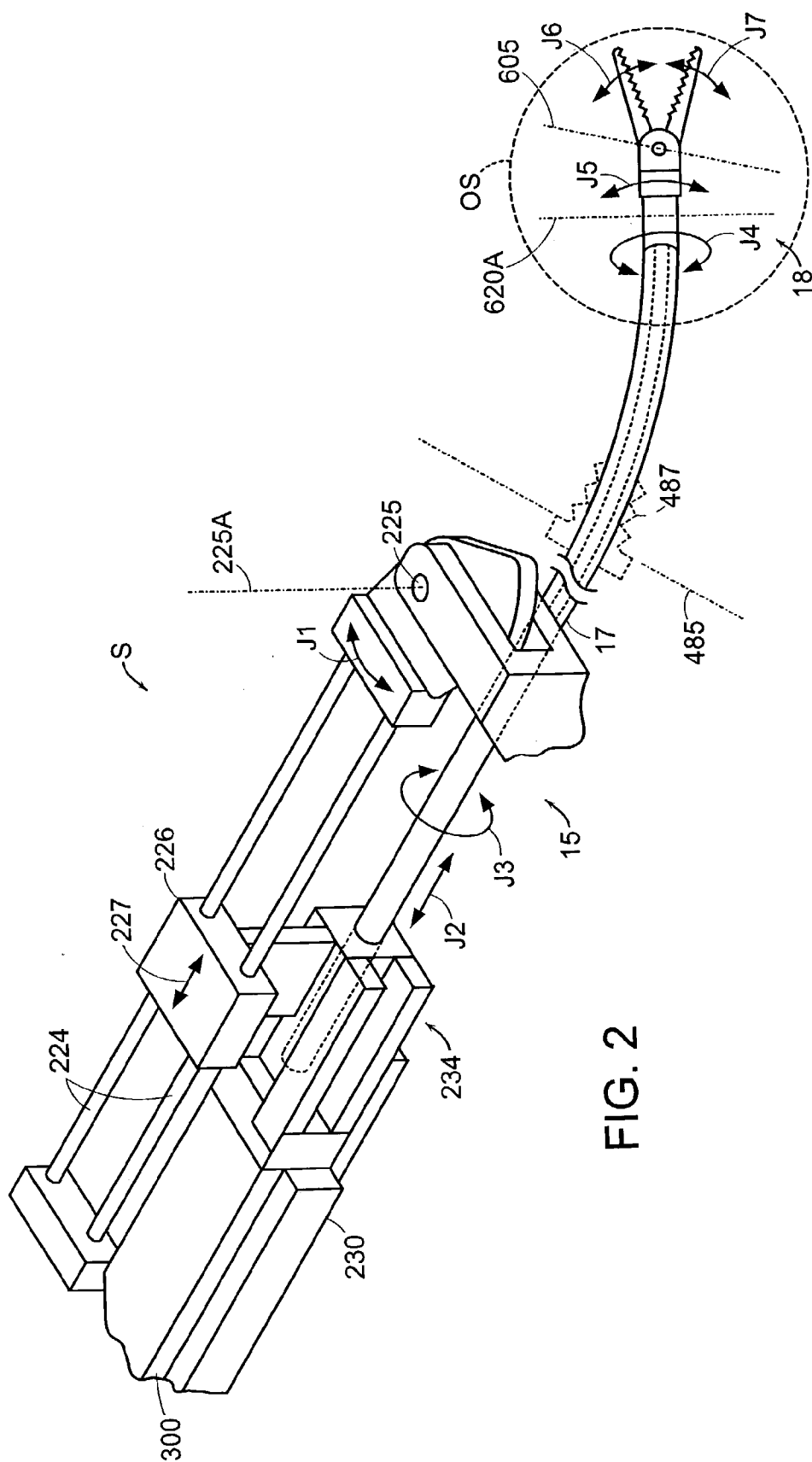


FIG. 2

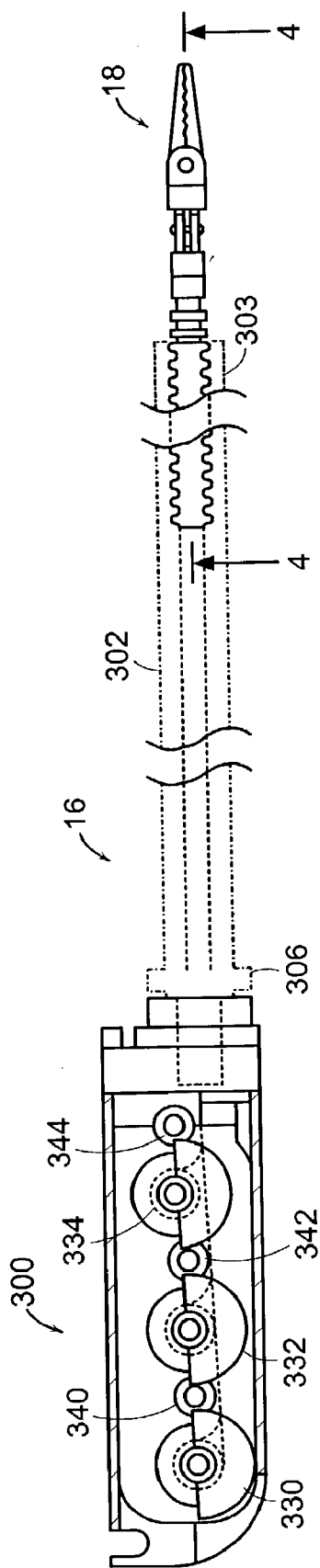


FIG. 3

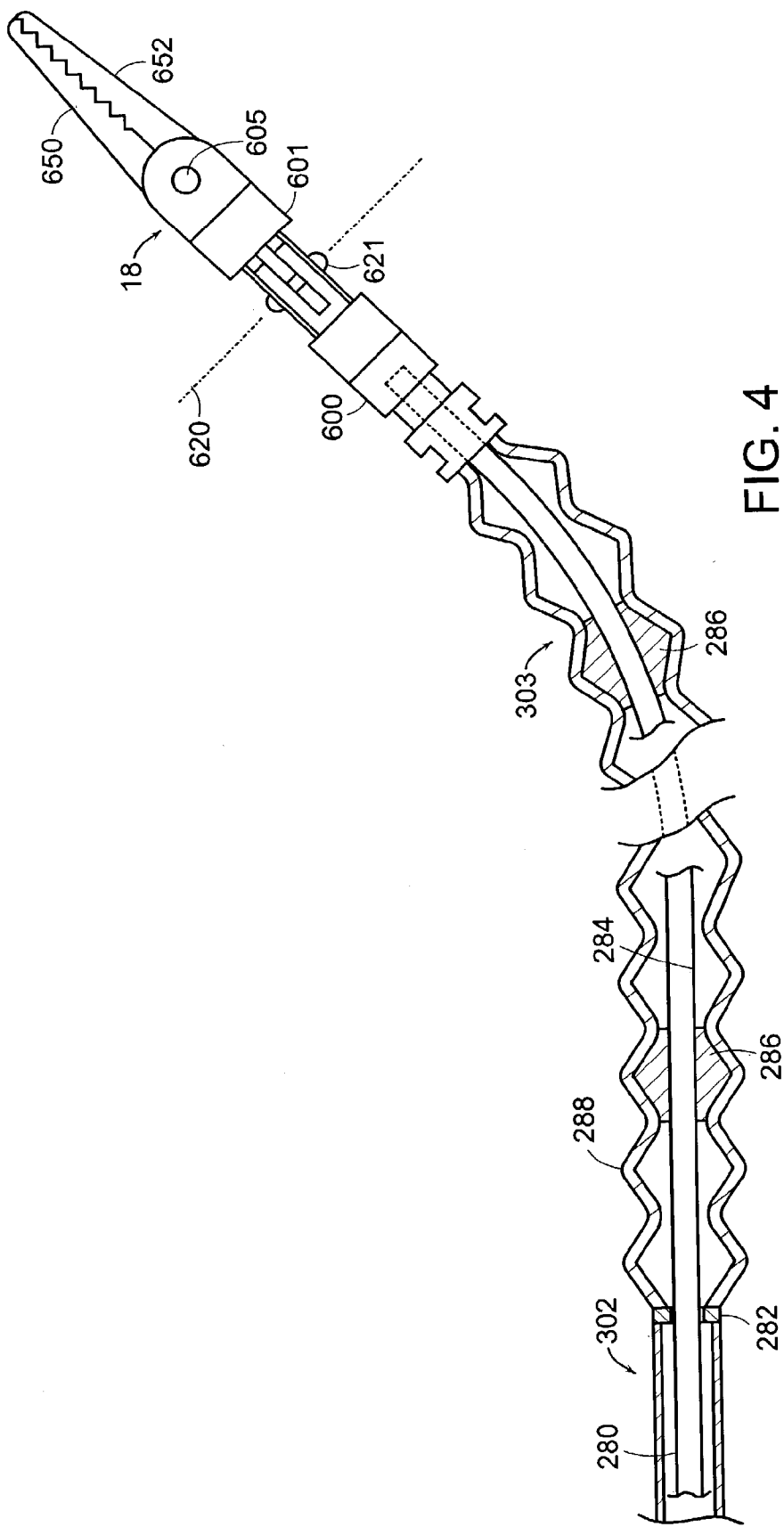


FIG. 4

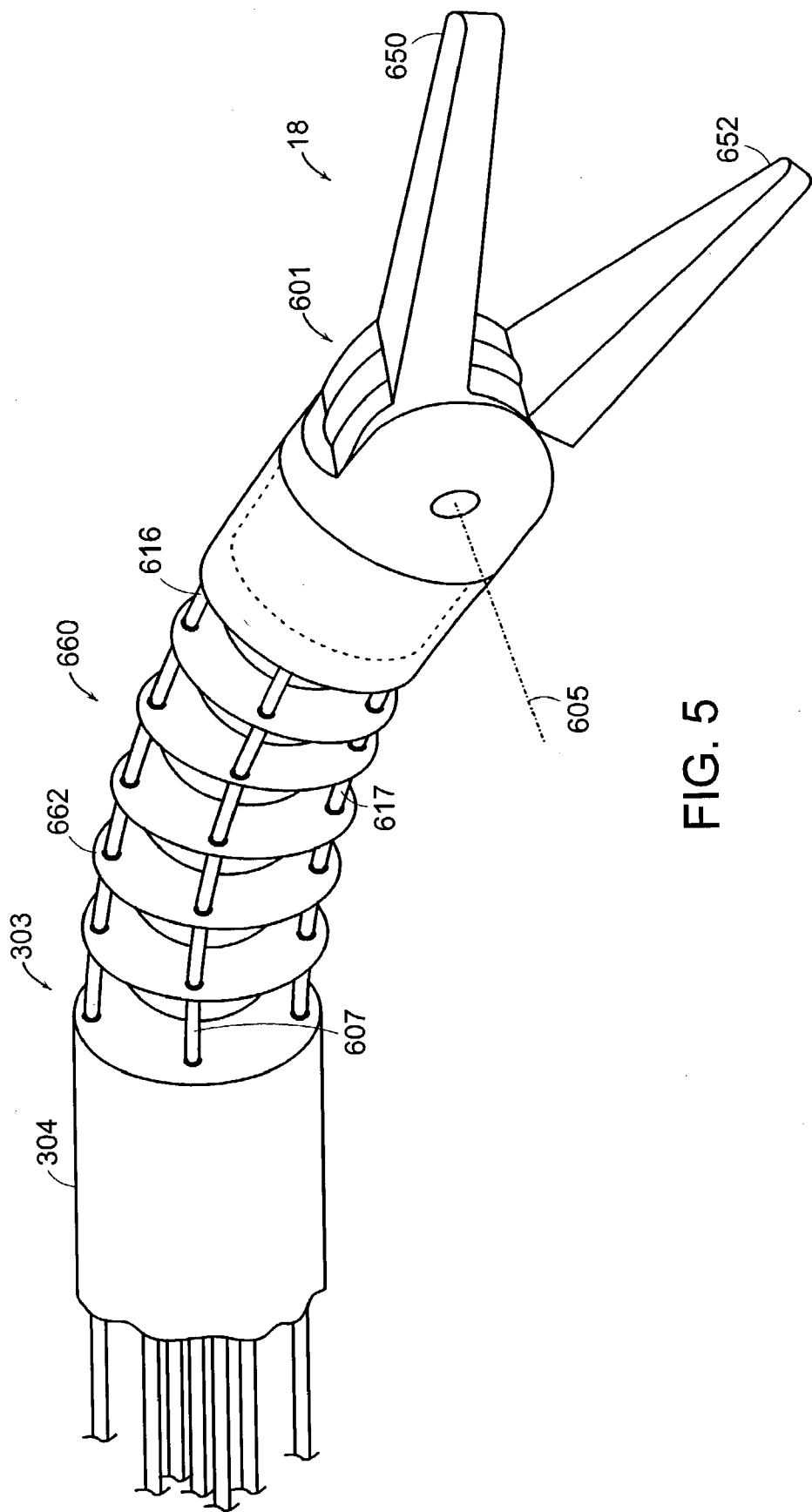


FIG. 5

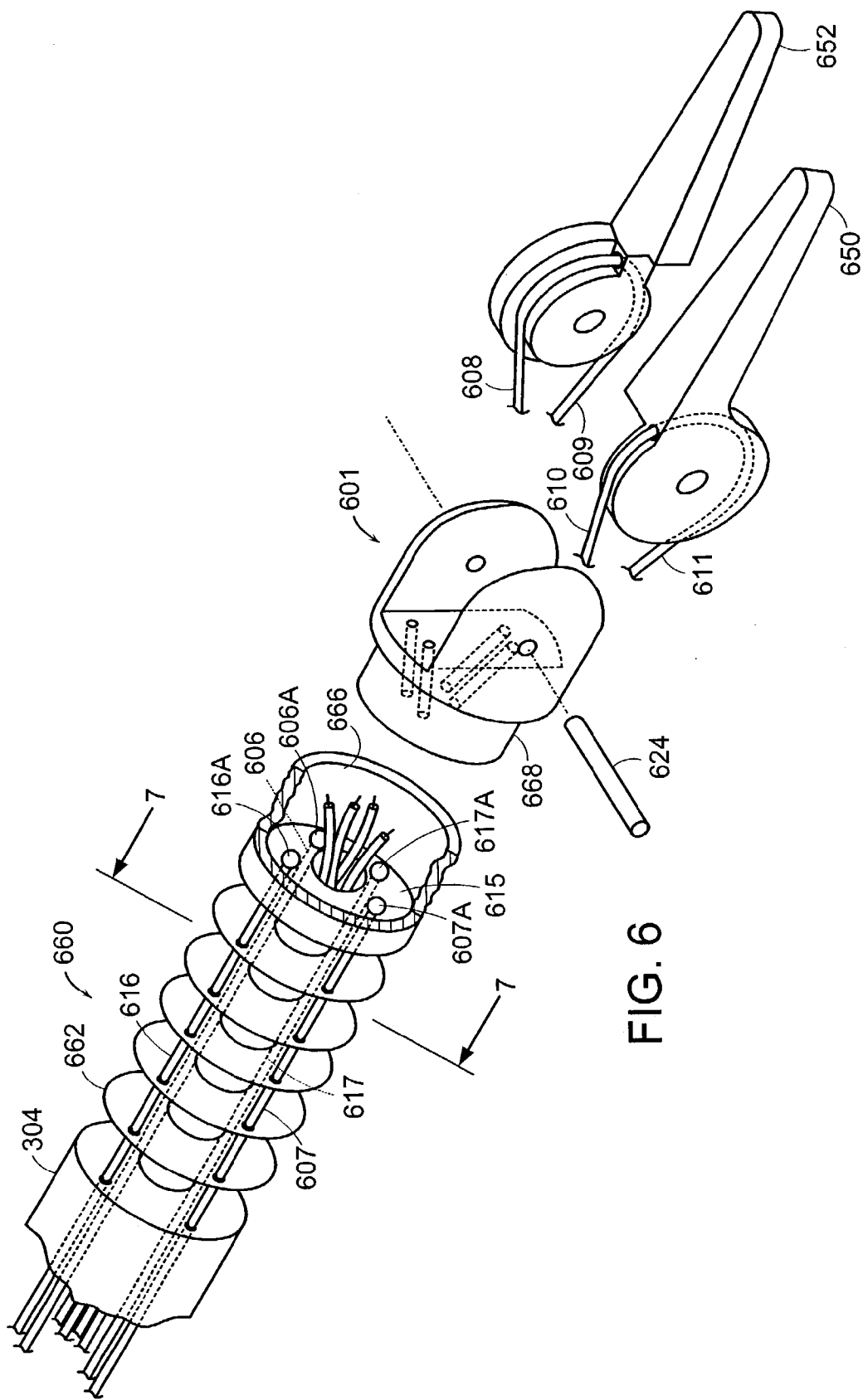


FIG. 6

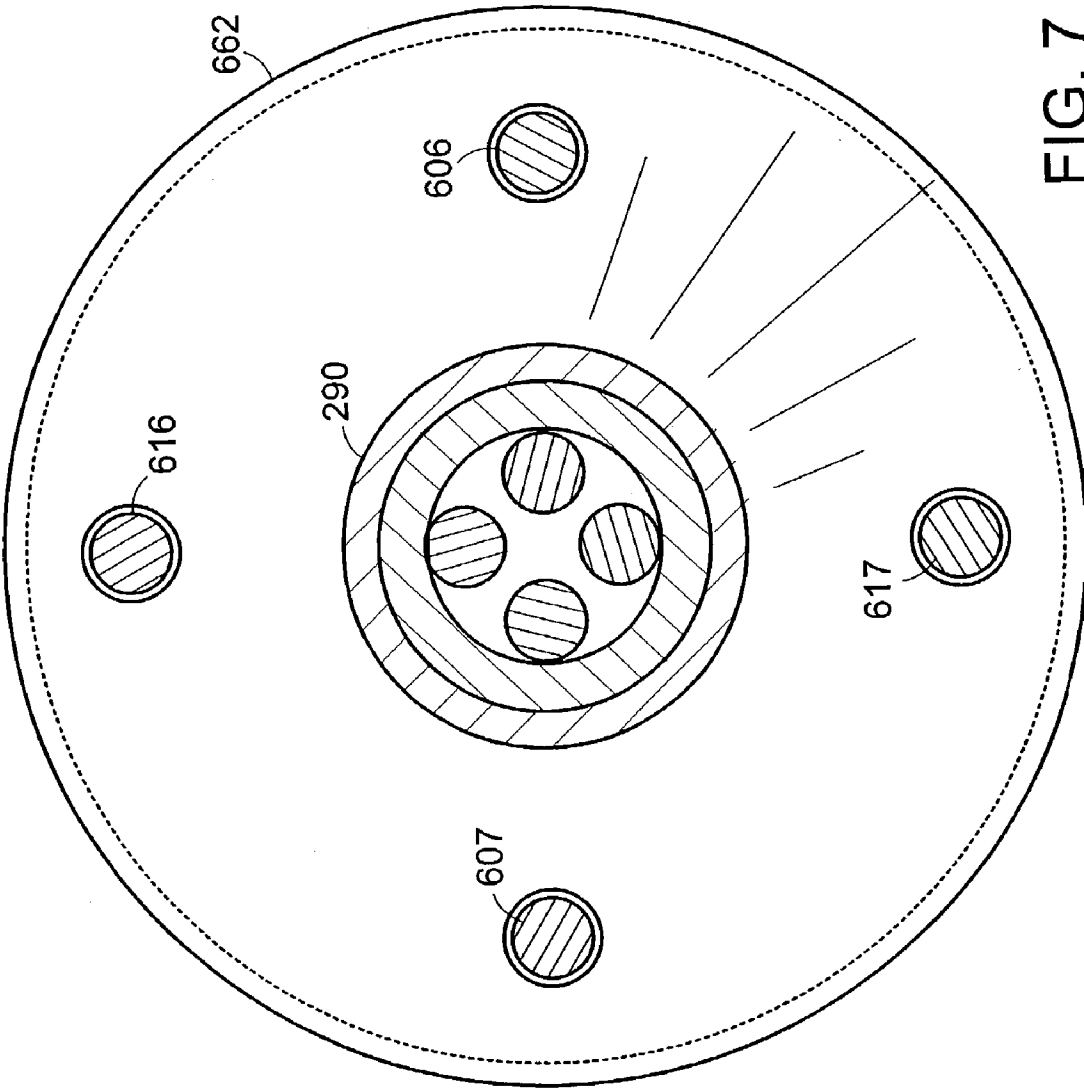
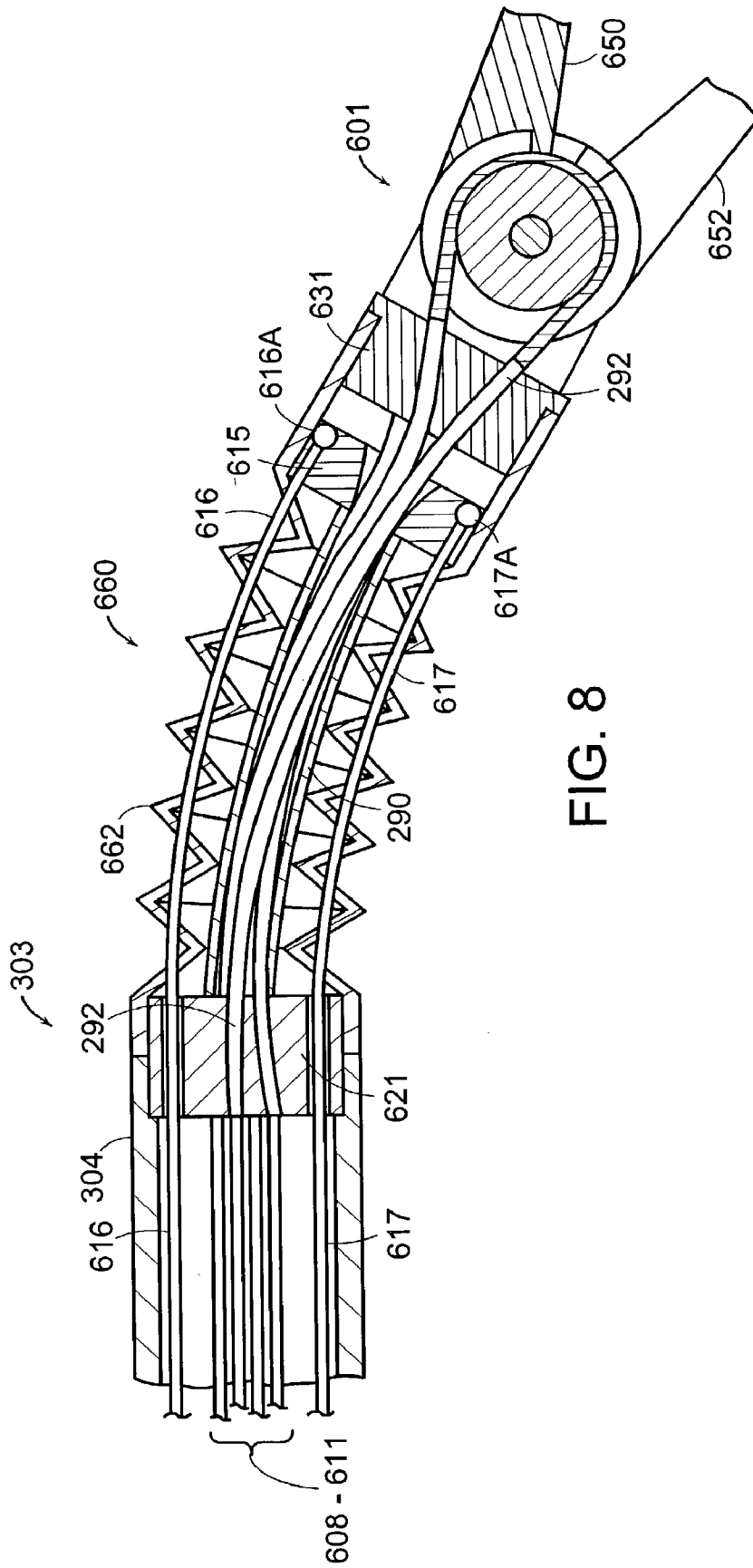
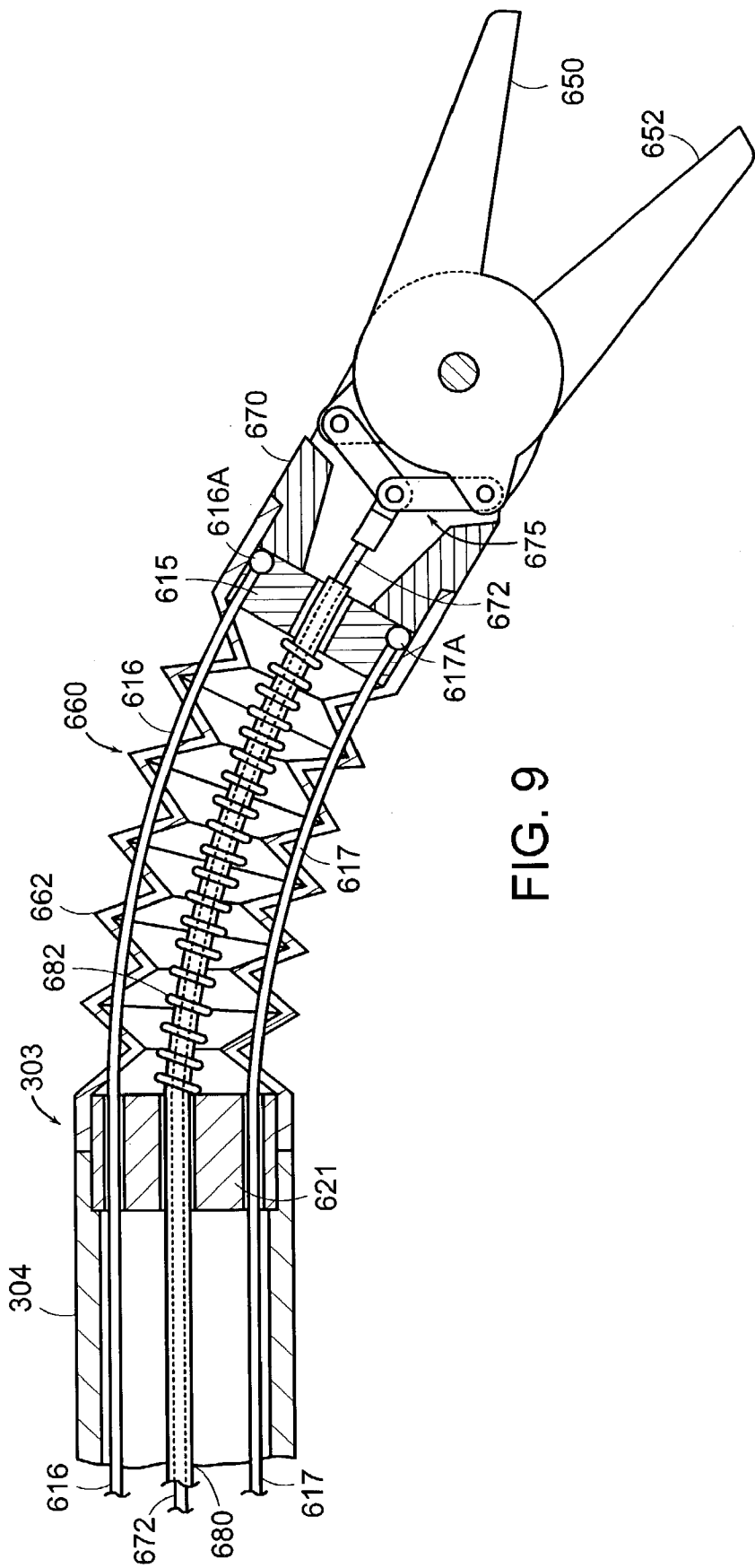
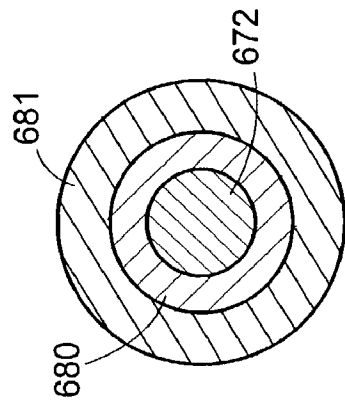
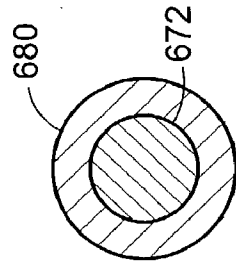
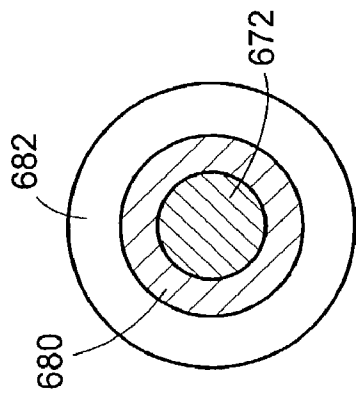
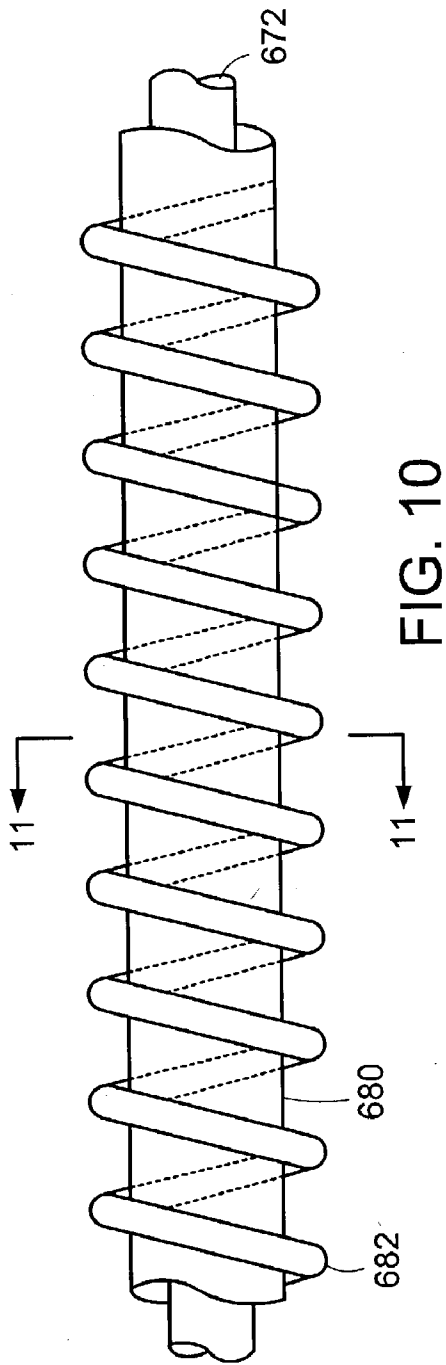
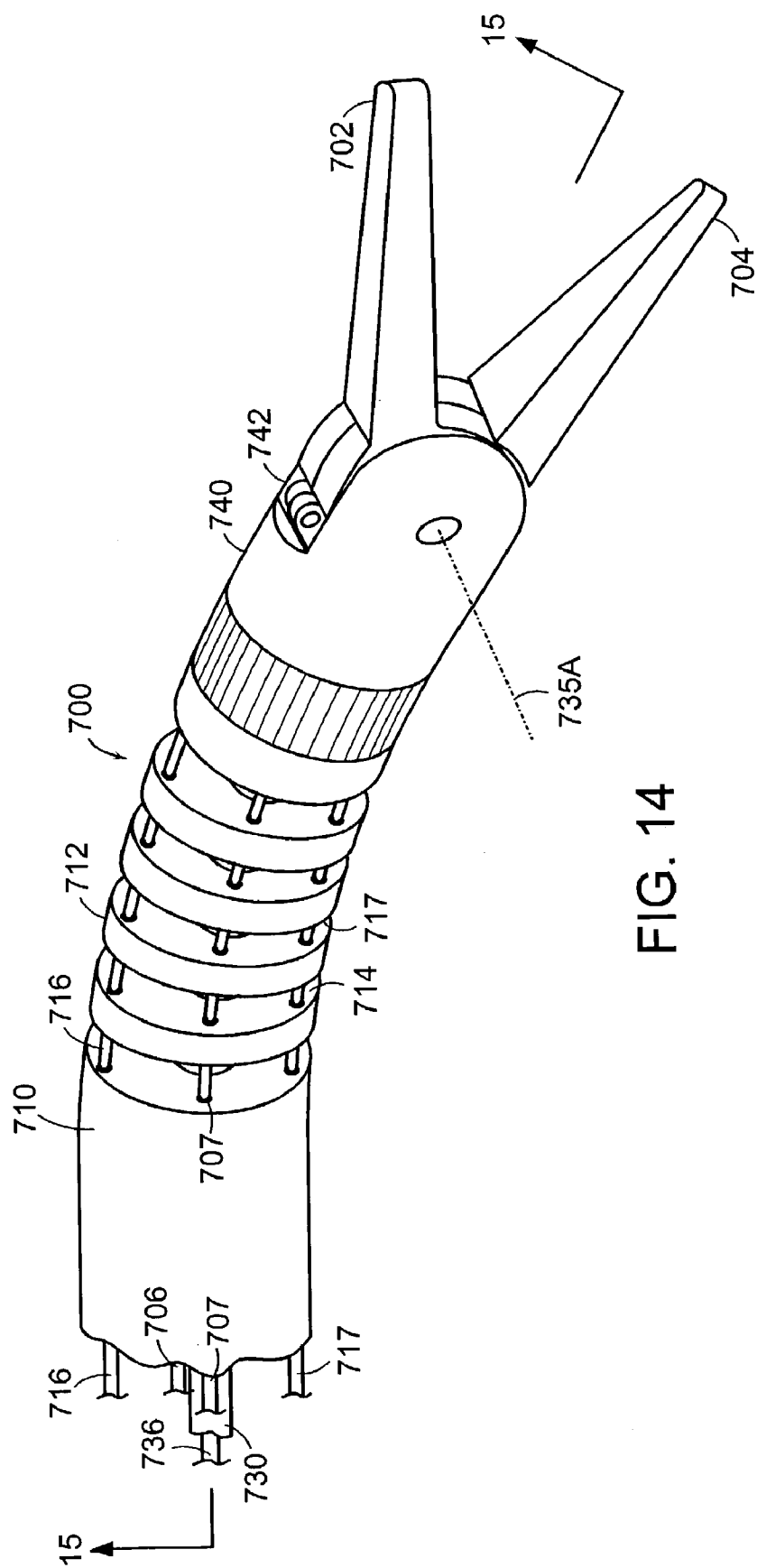


FIG. 7









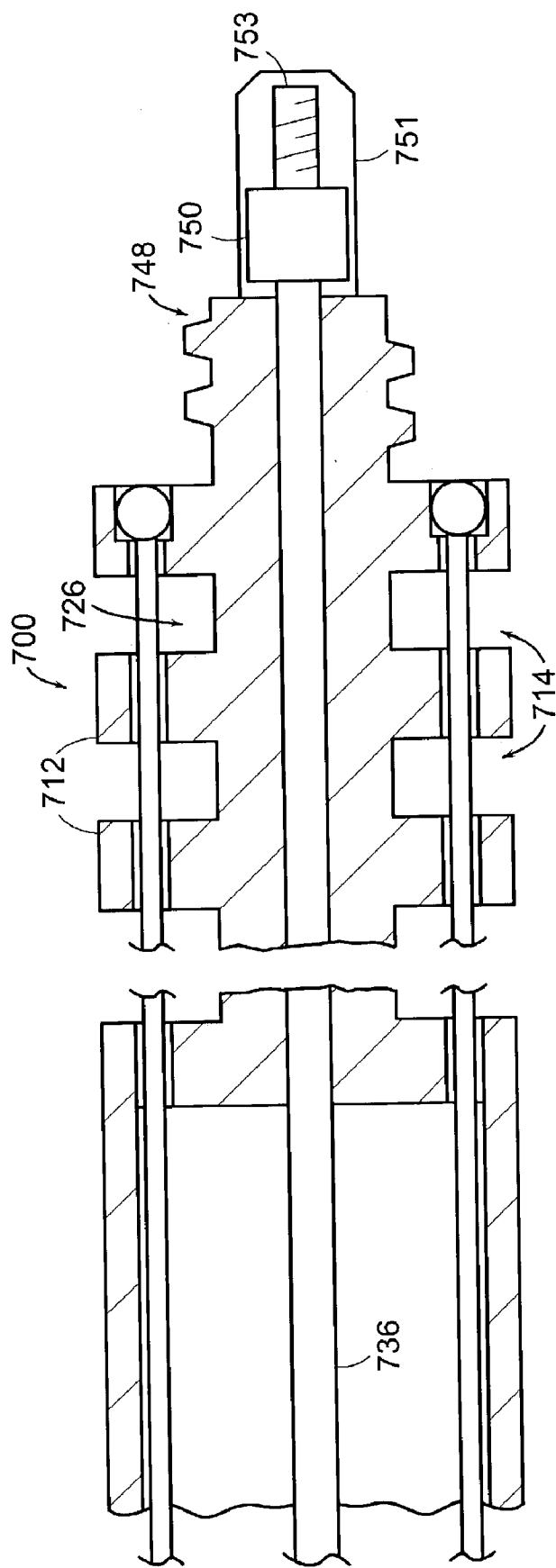


FIG. 15A

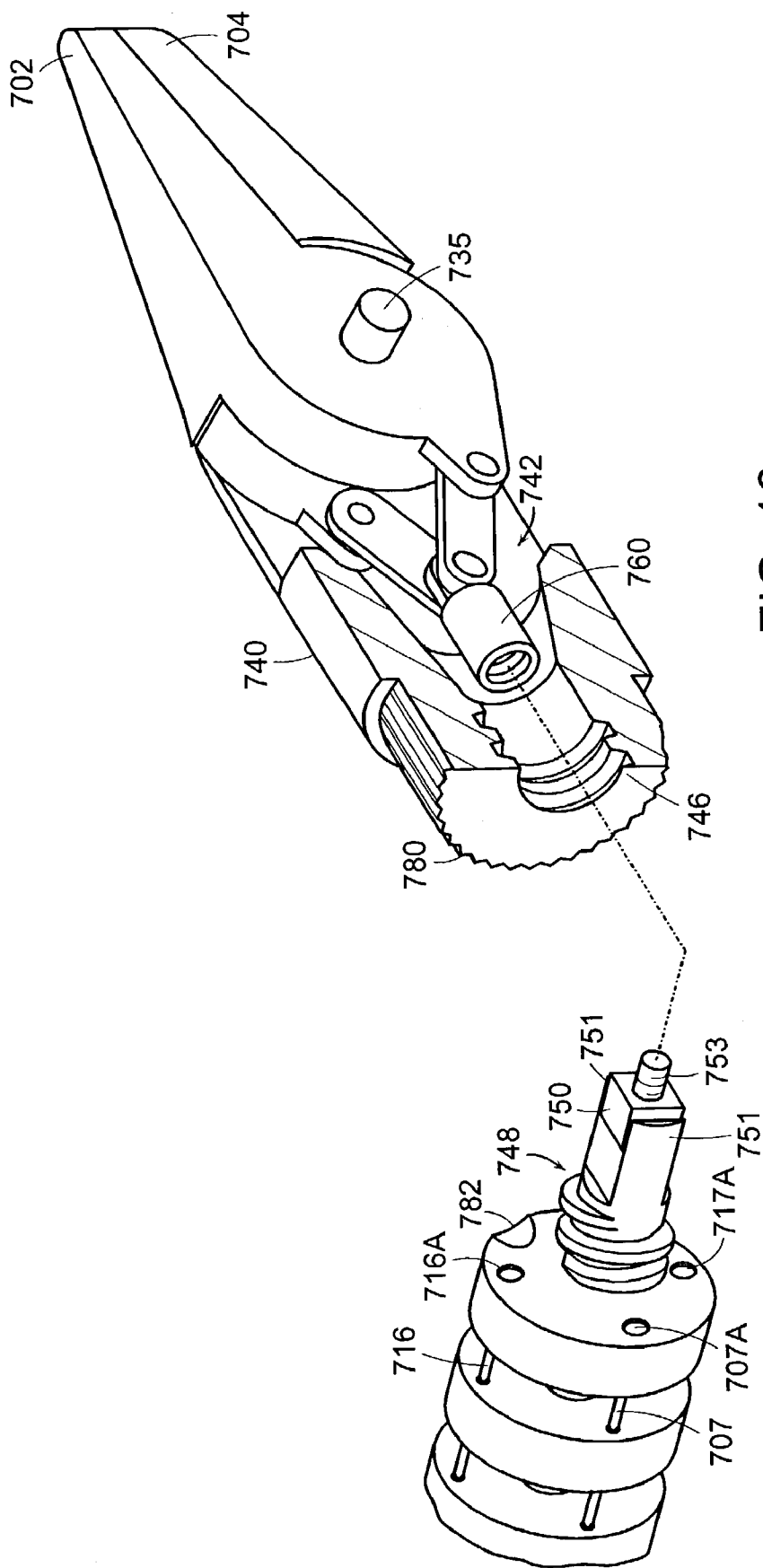
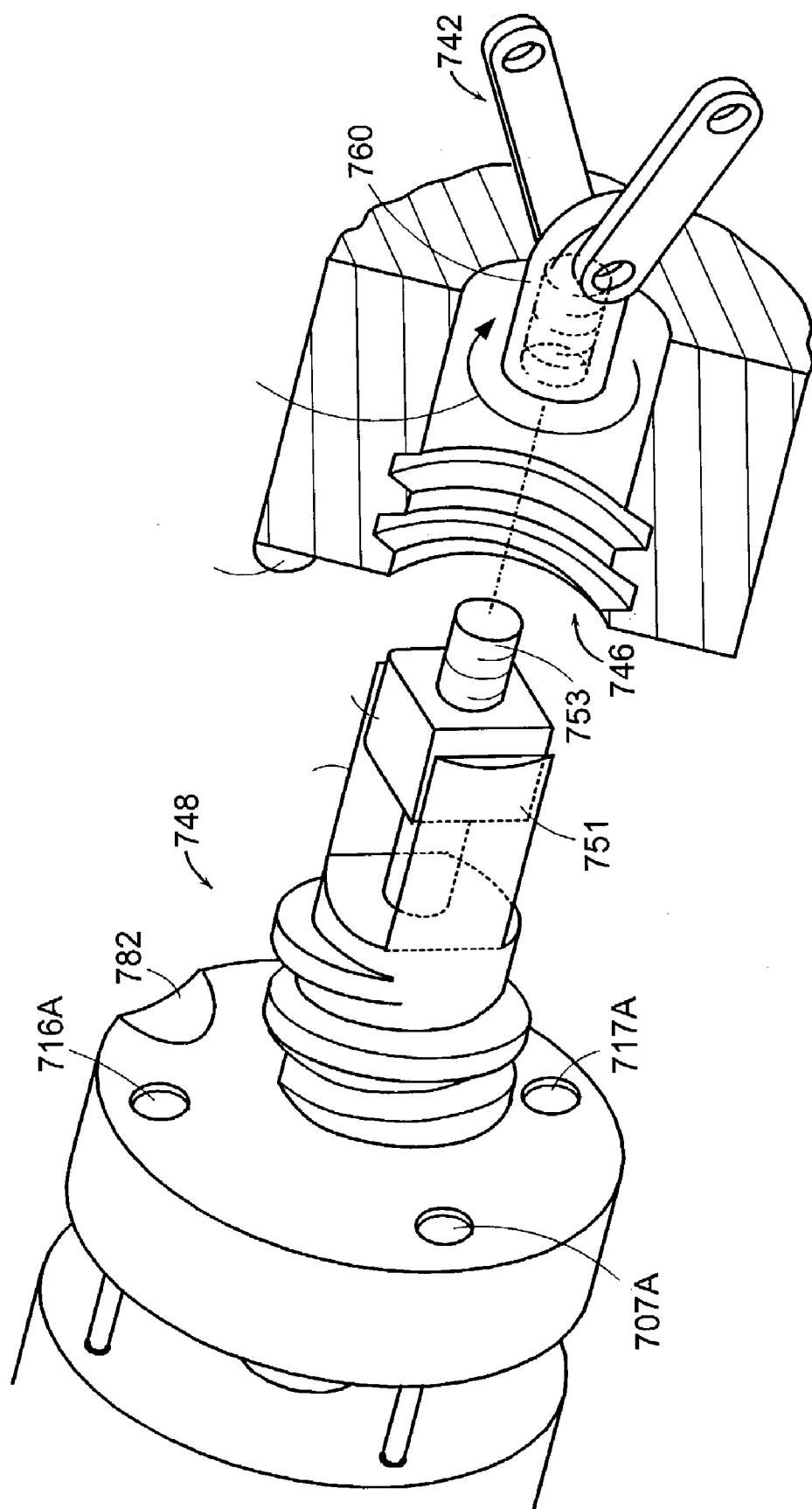


FIG. 16



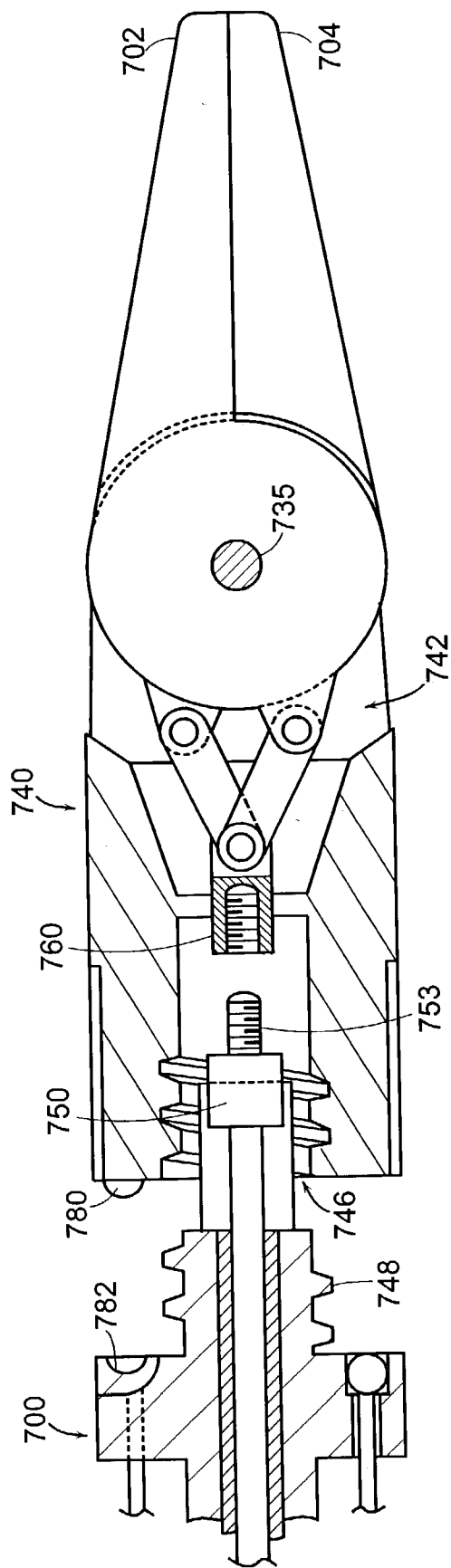


FIG. 18

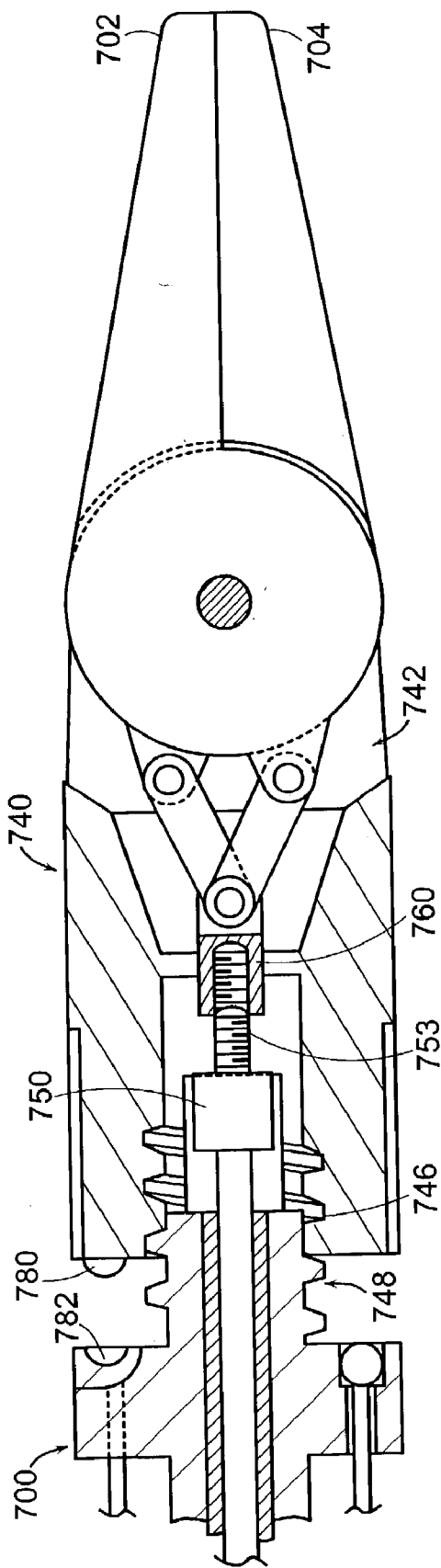


FIG. 19

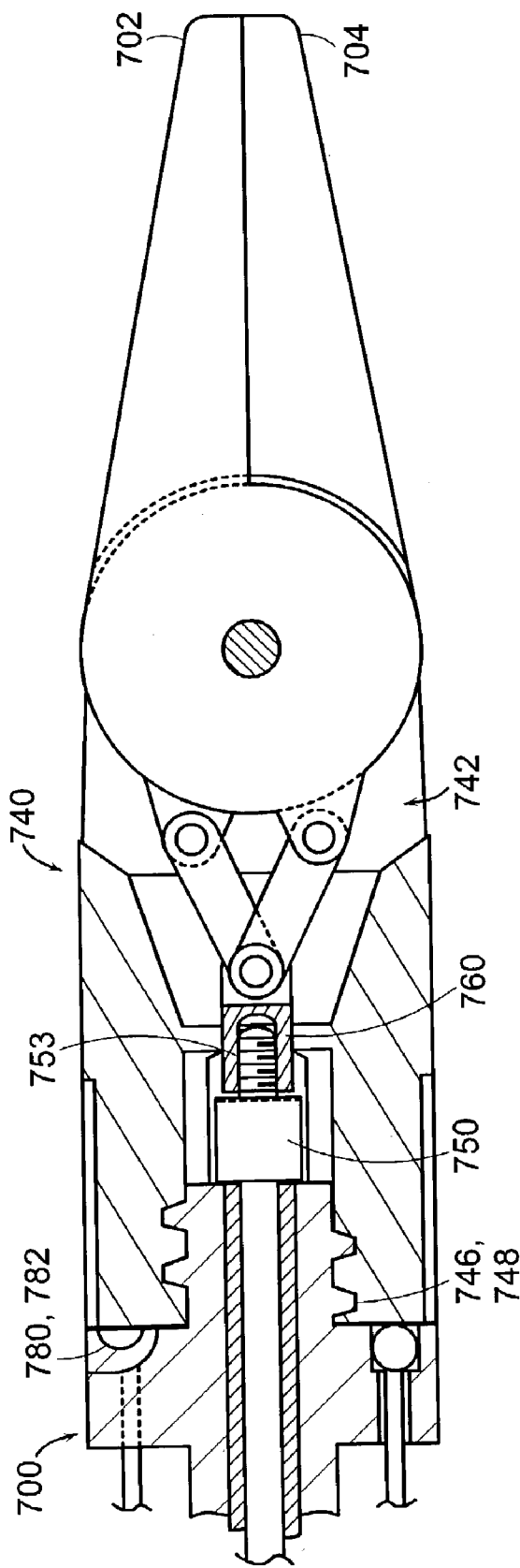
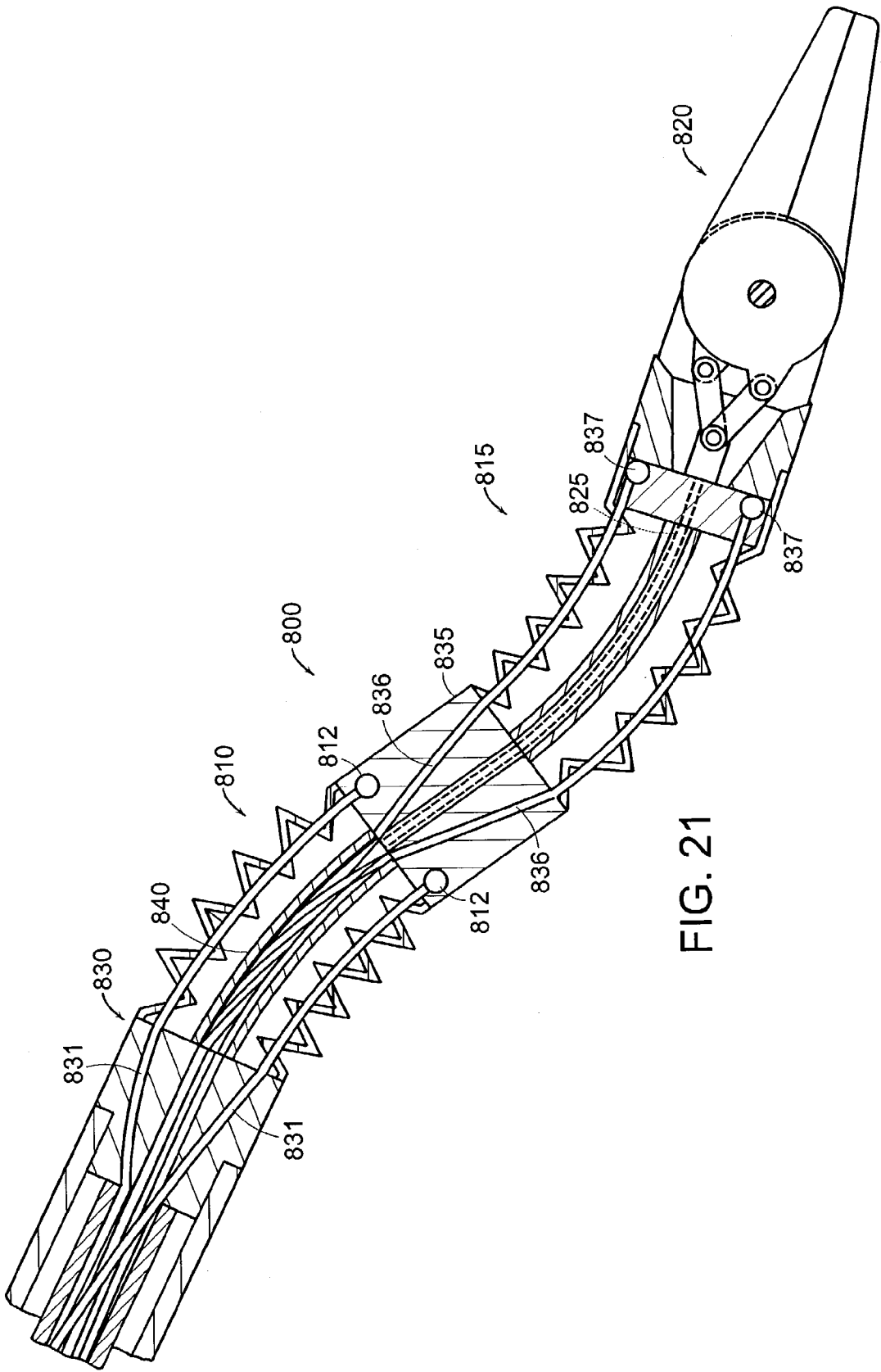


FIG. 20



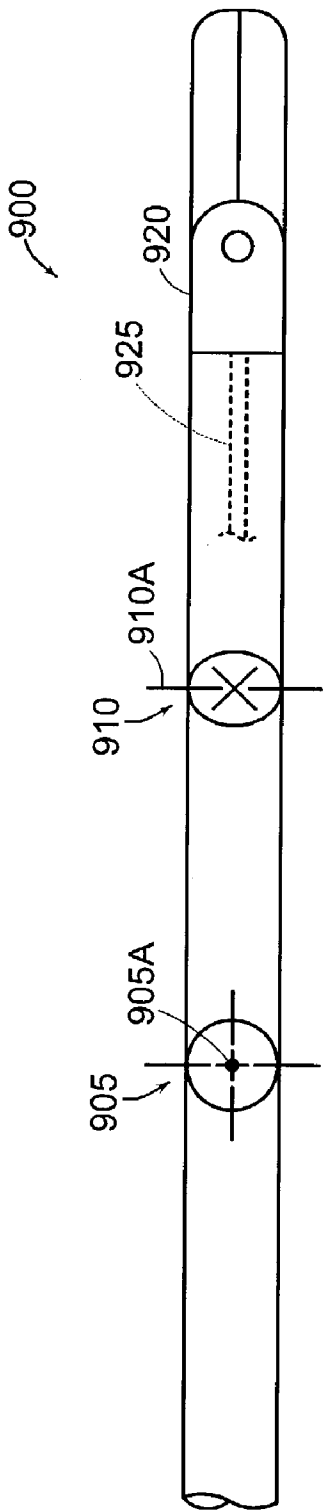


FIG. 22

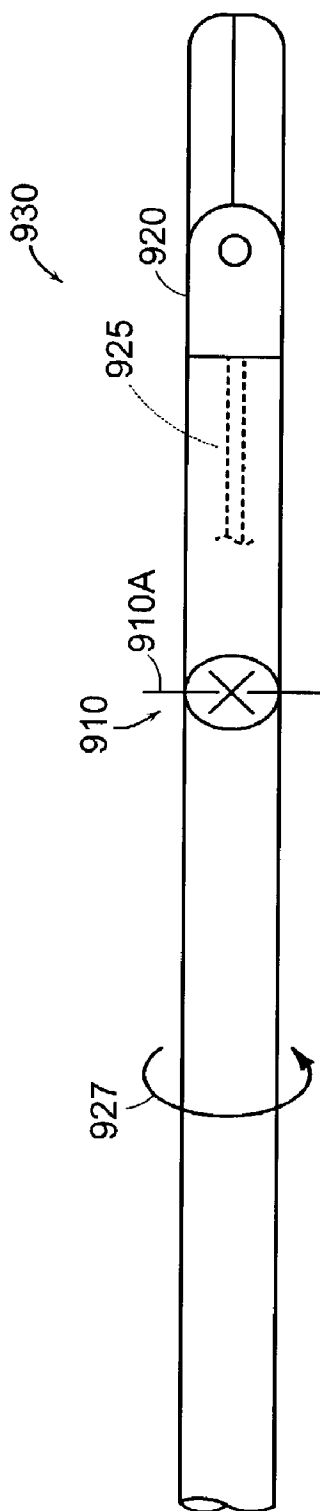
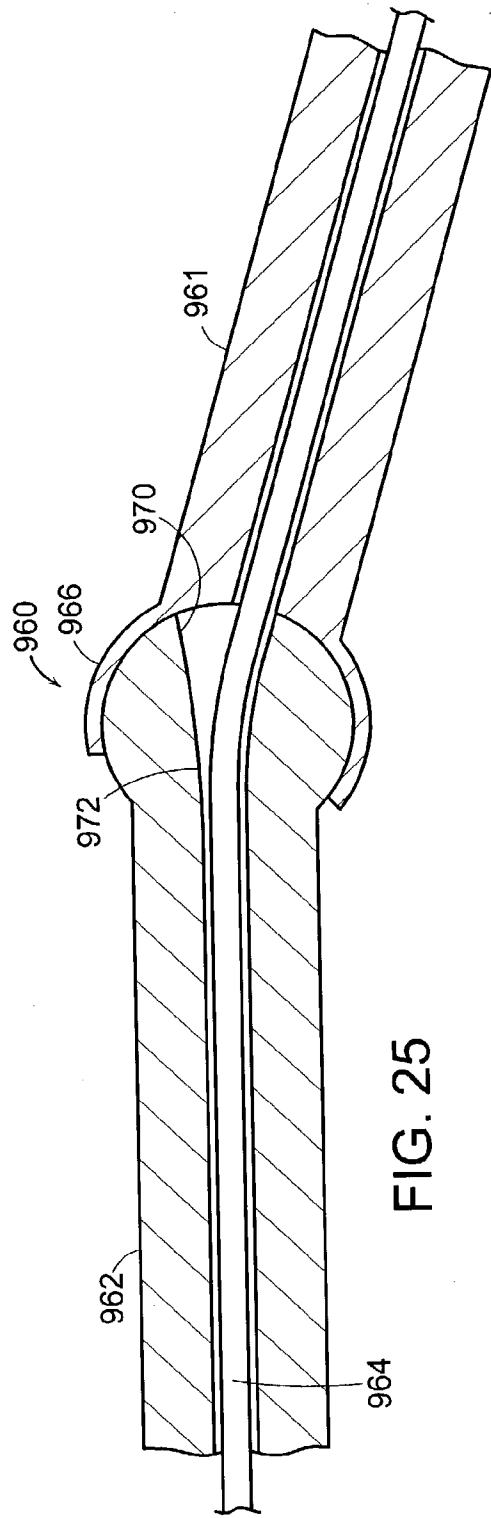
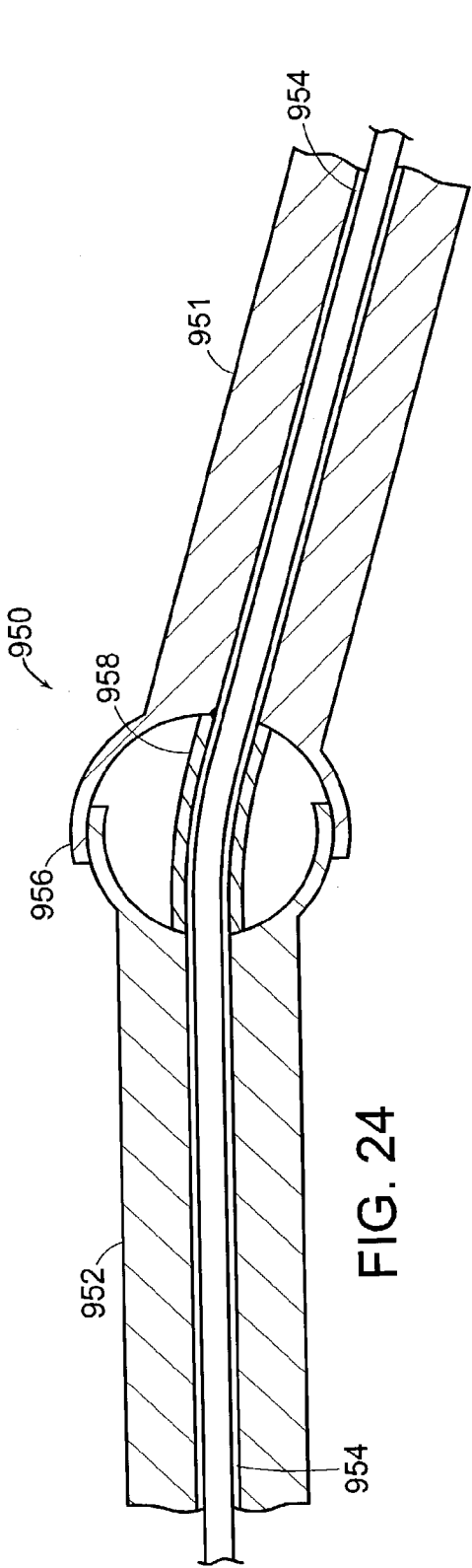
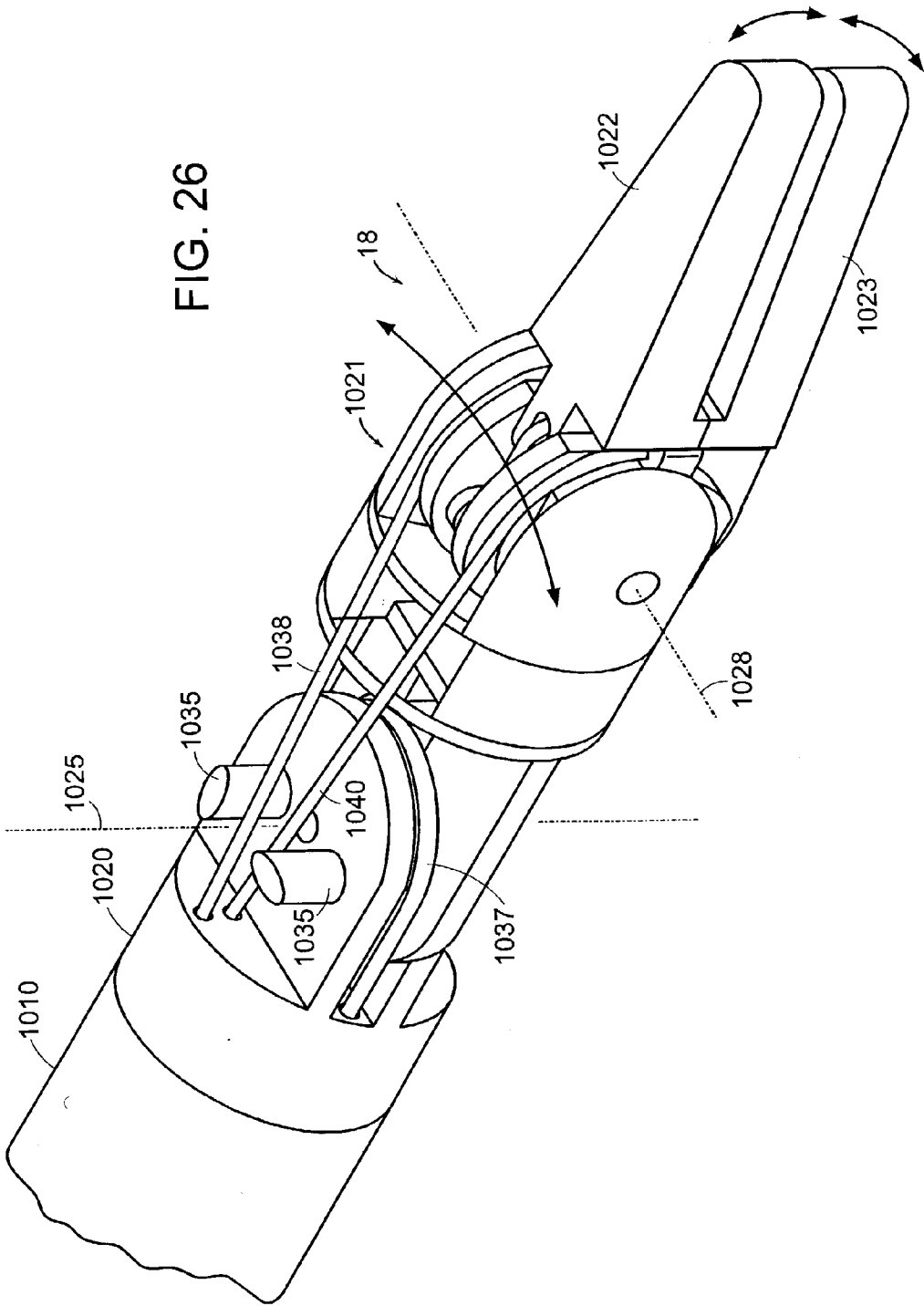
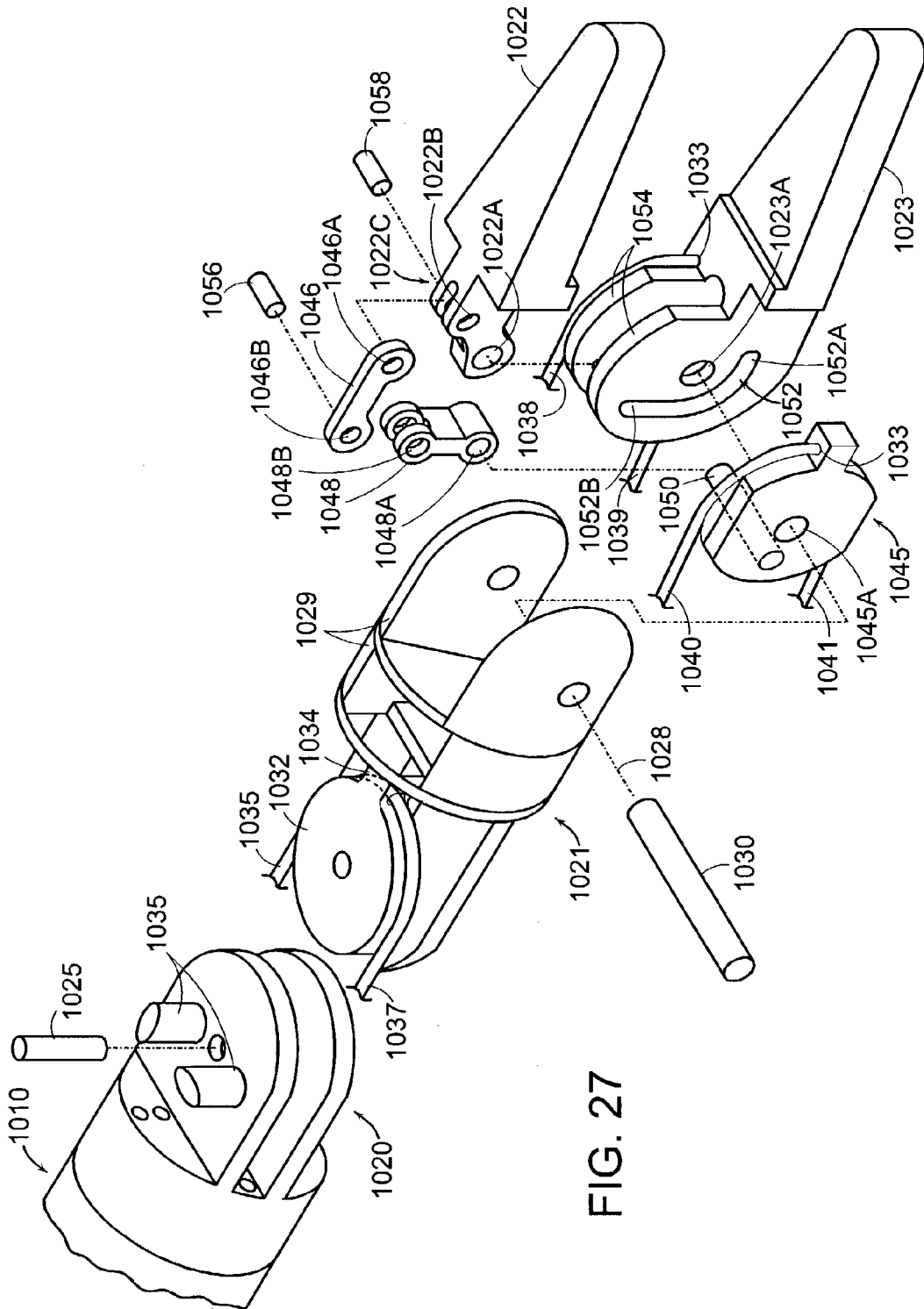


FIG. 23







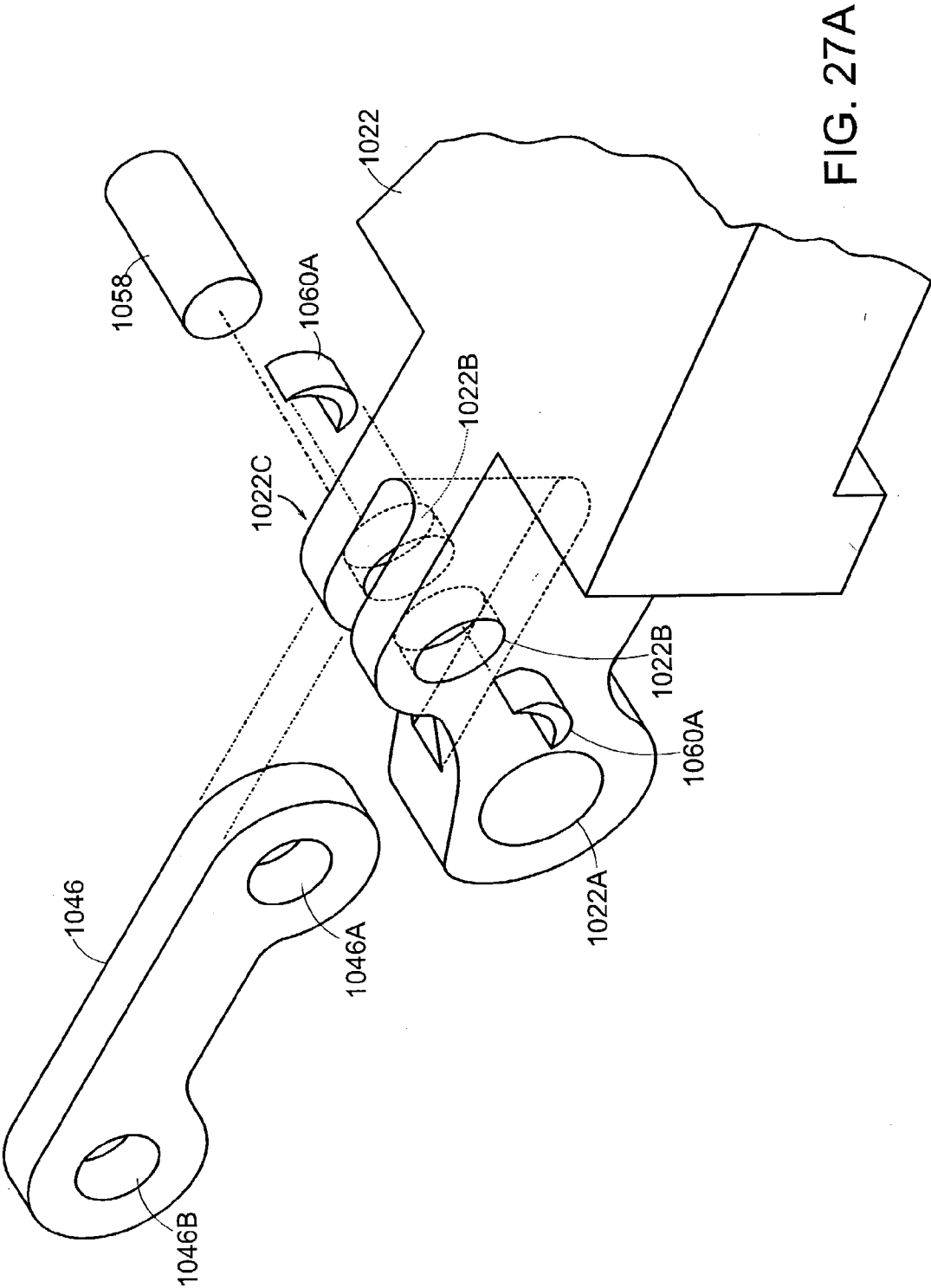


FIG. 27A

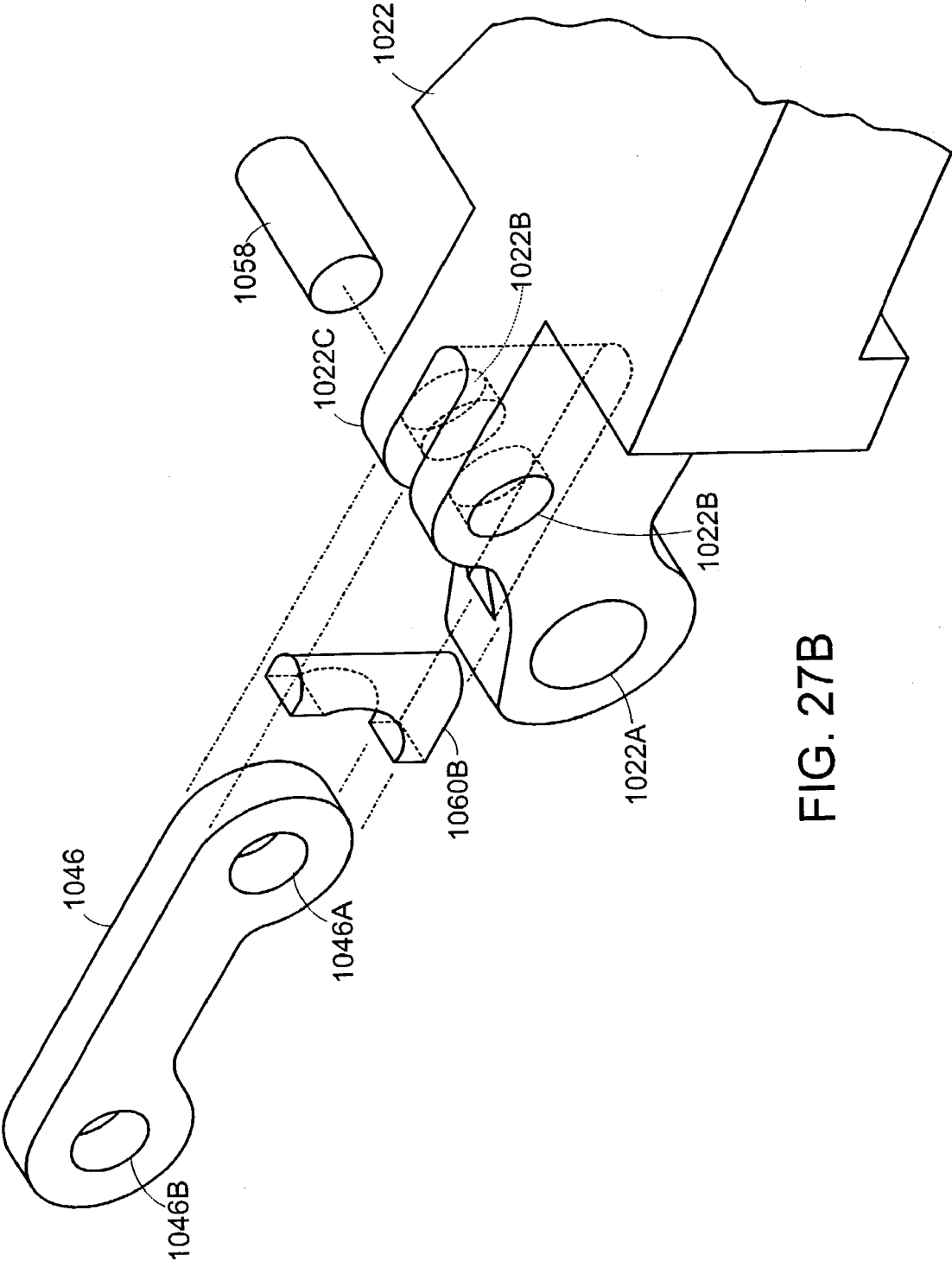


FIG. 27B

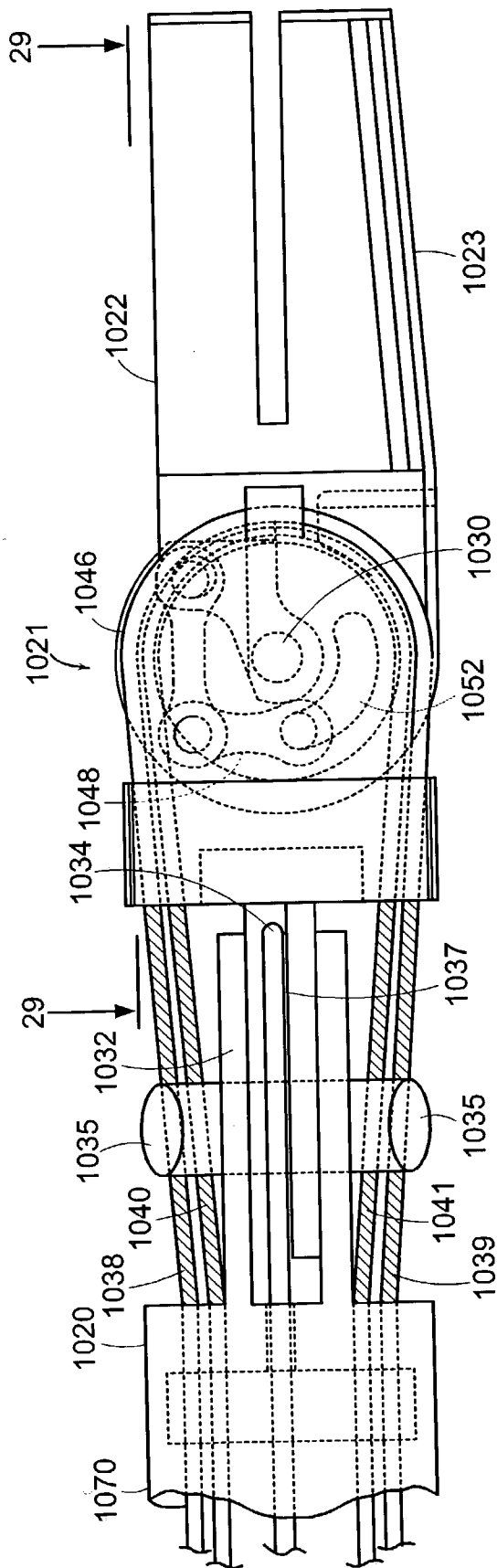


FIG. 28

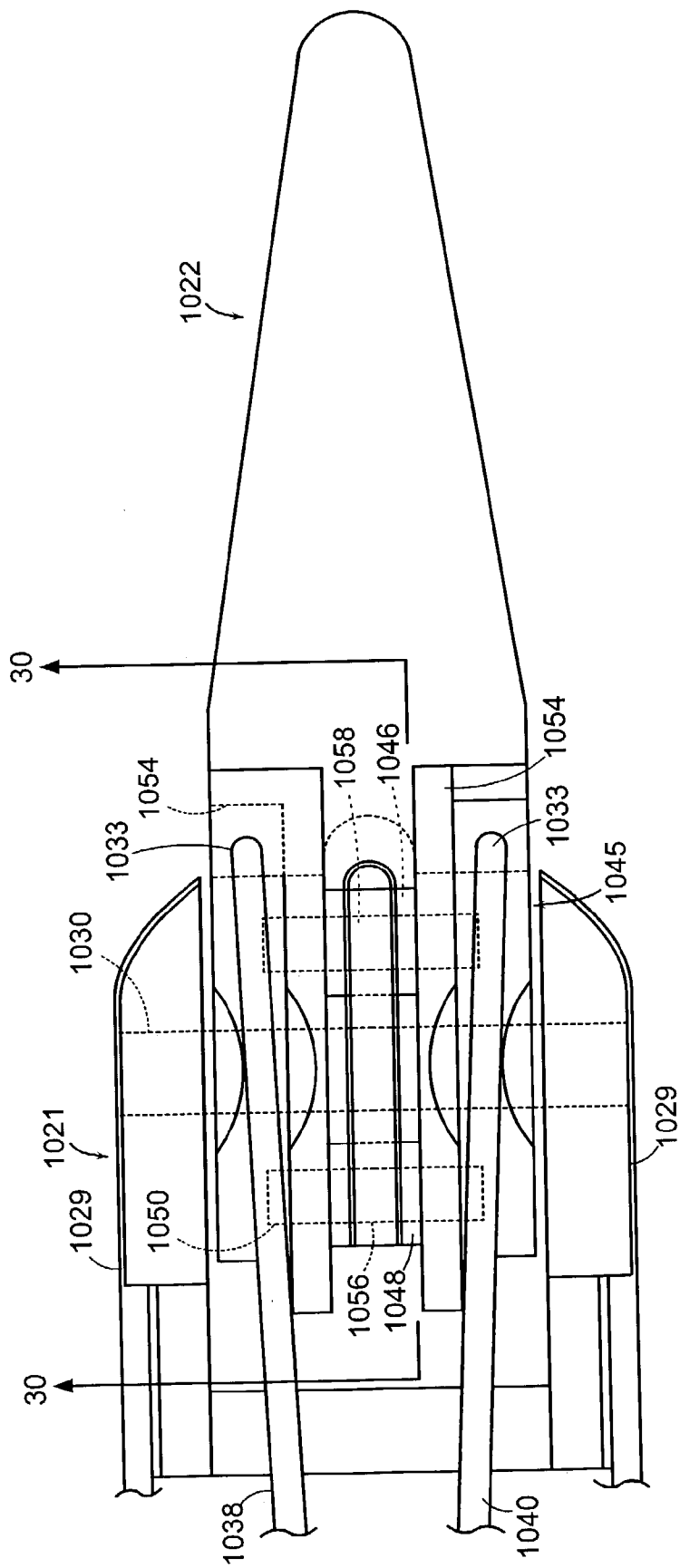


FIG. 29

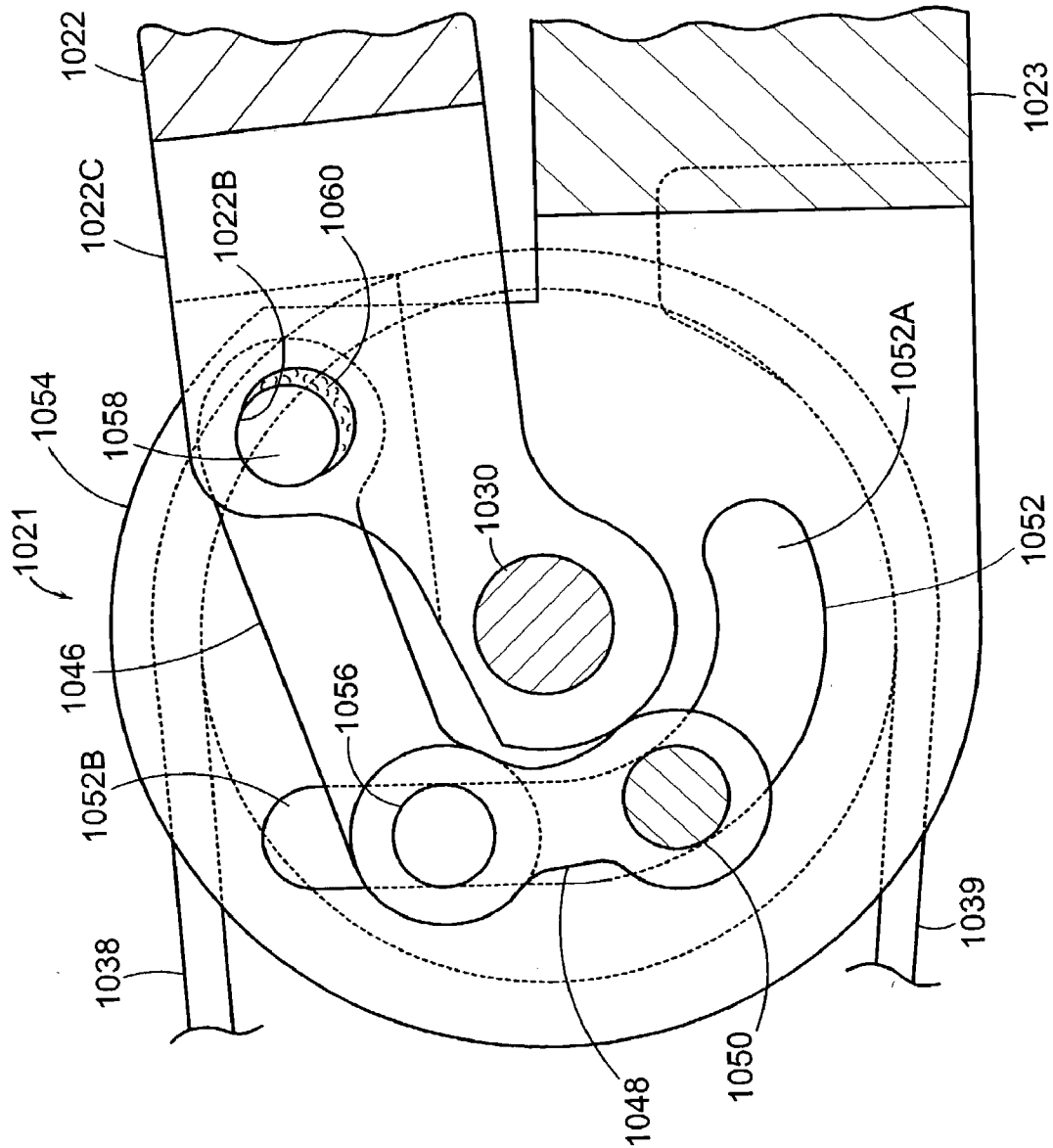


FIG. 30

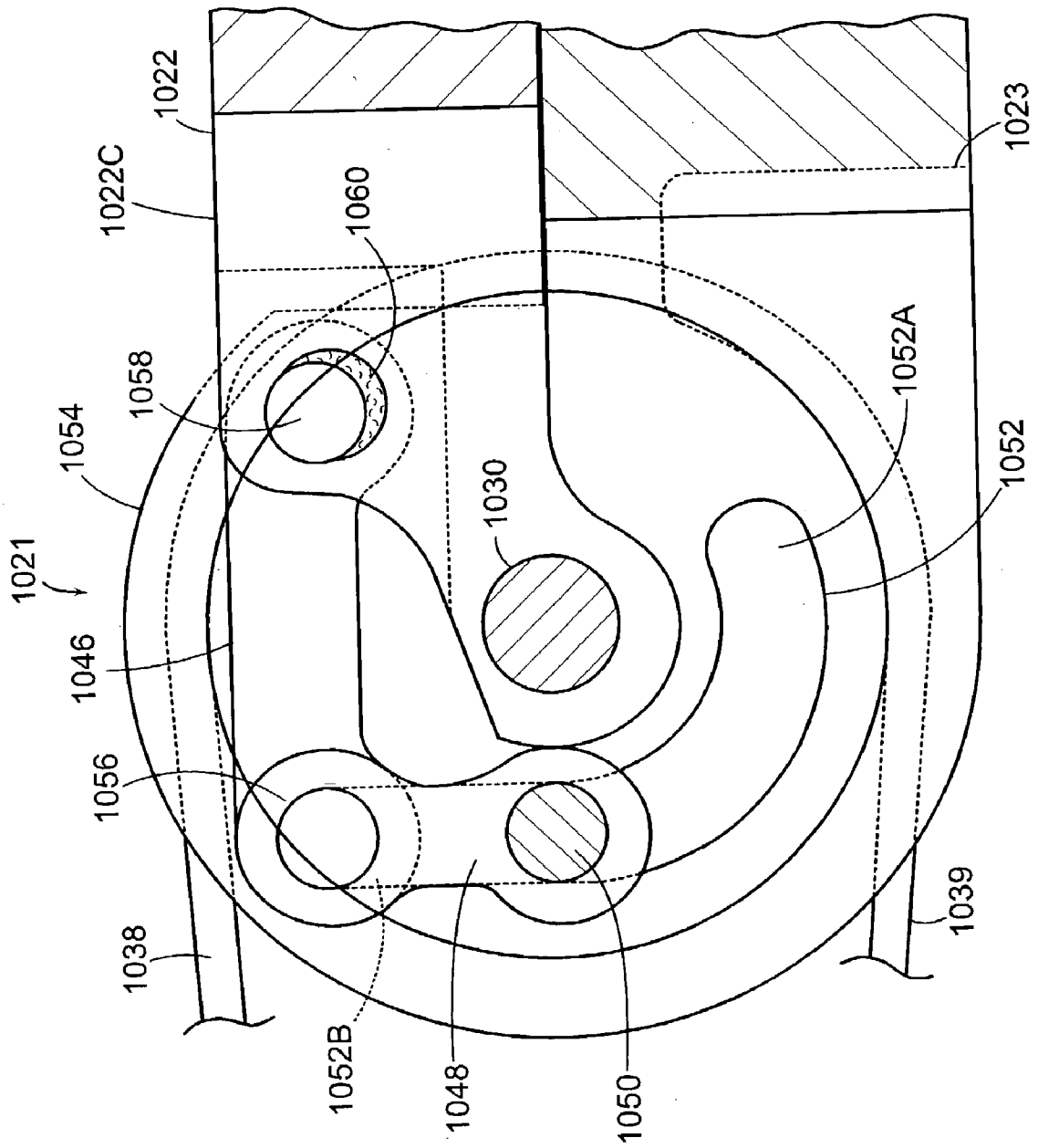


FIG. 31

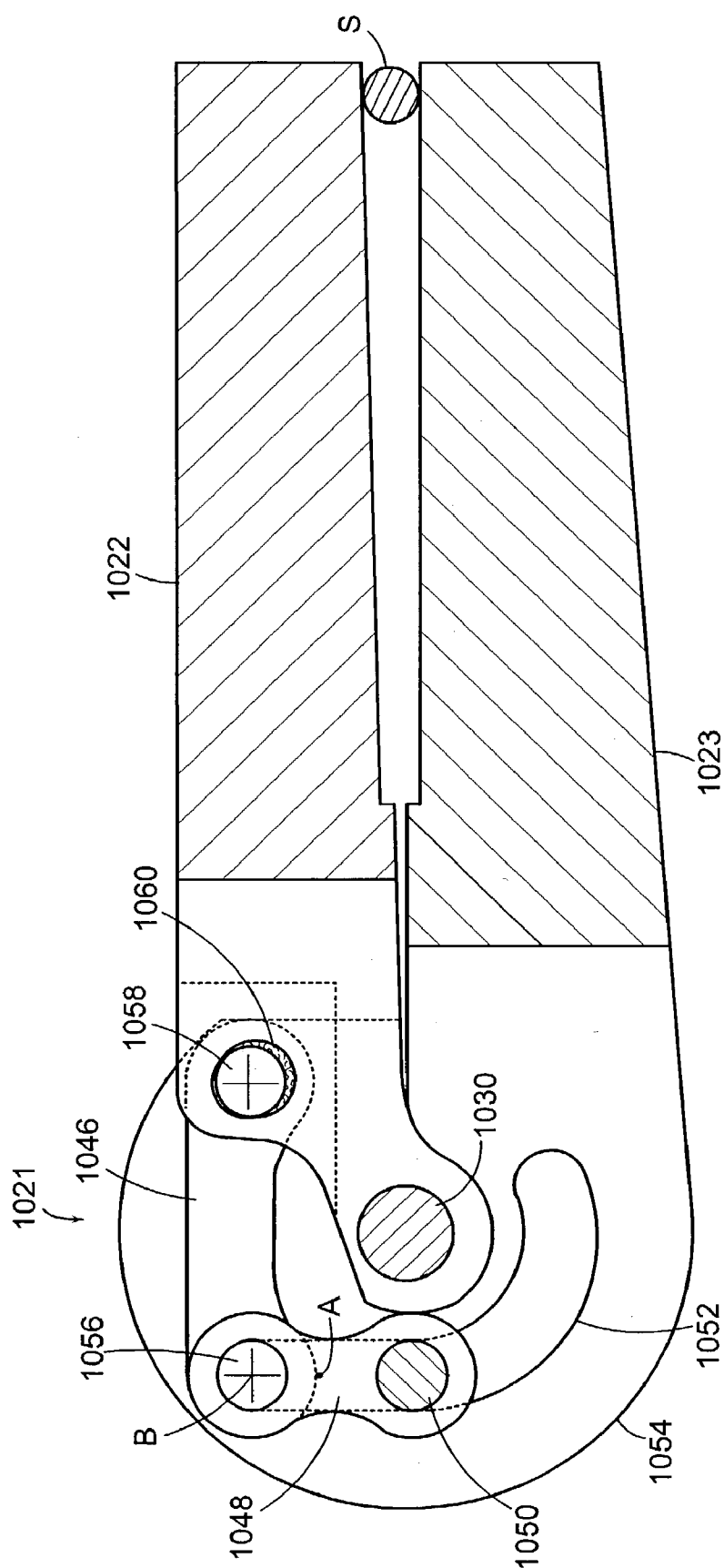


FIG. 32

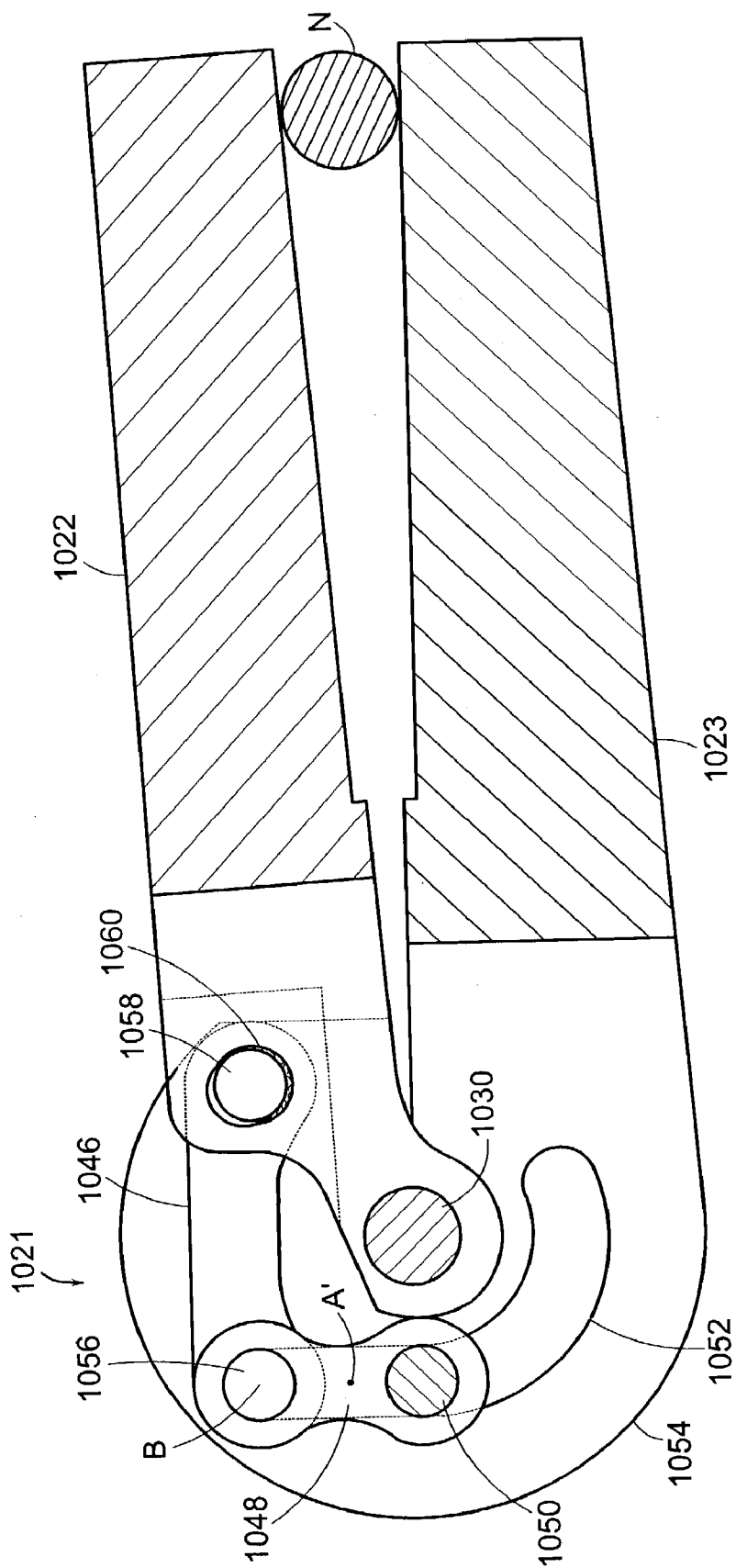


FIG. 33

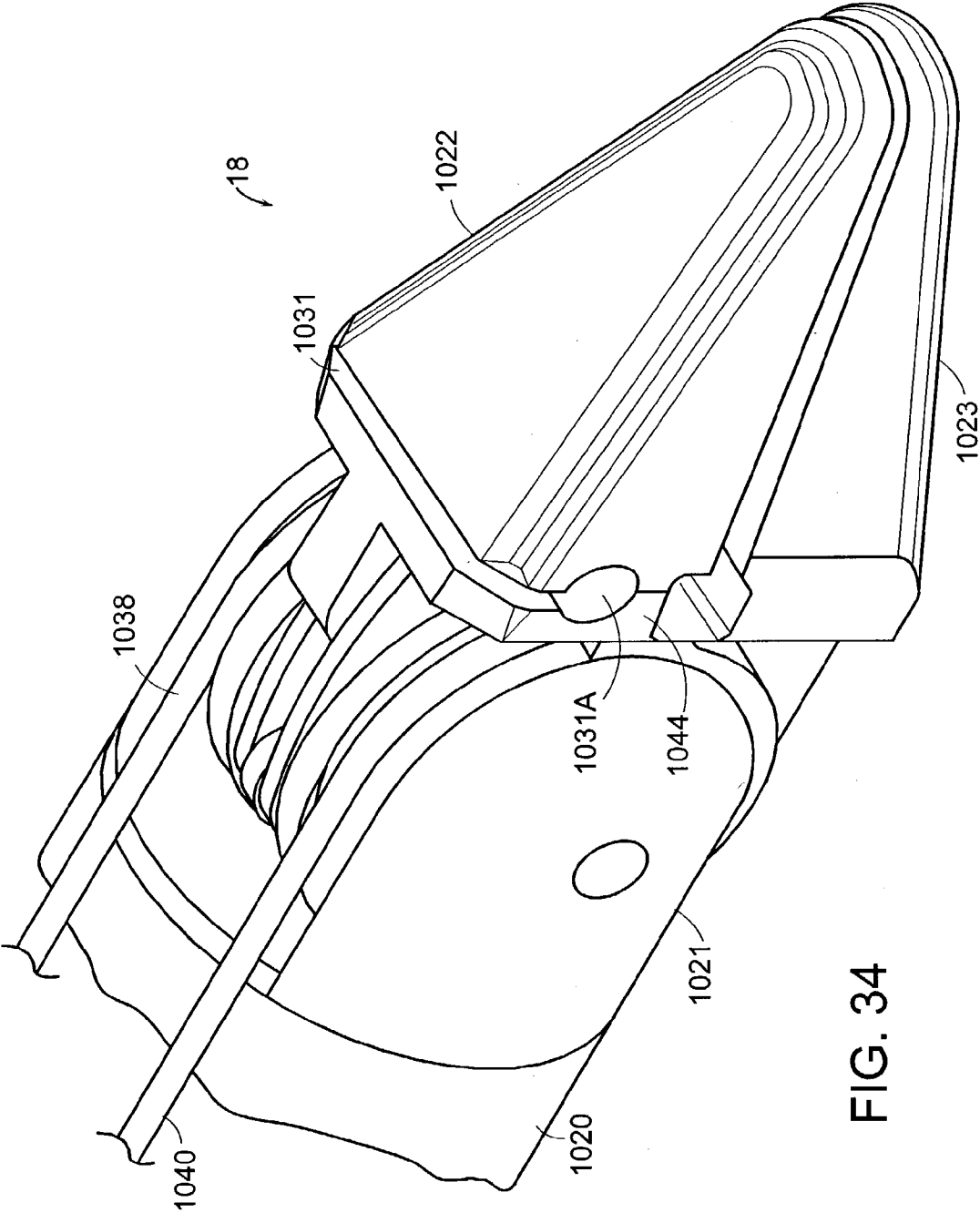


FIG. 34

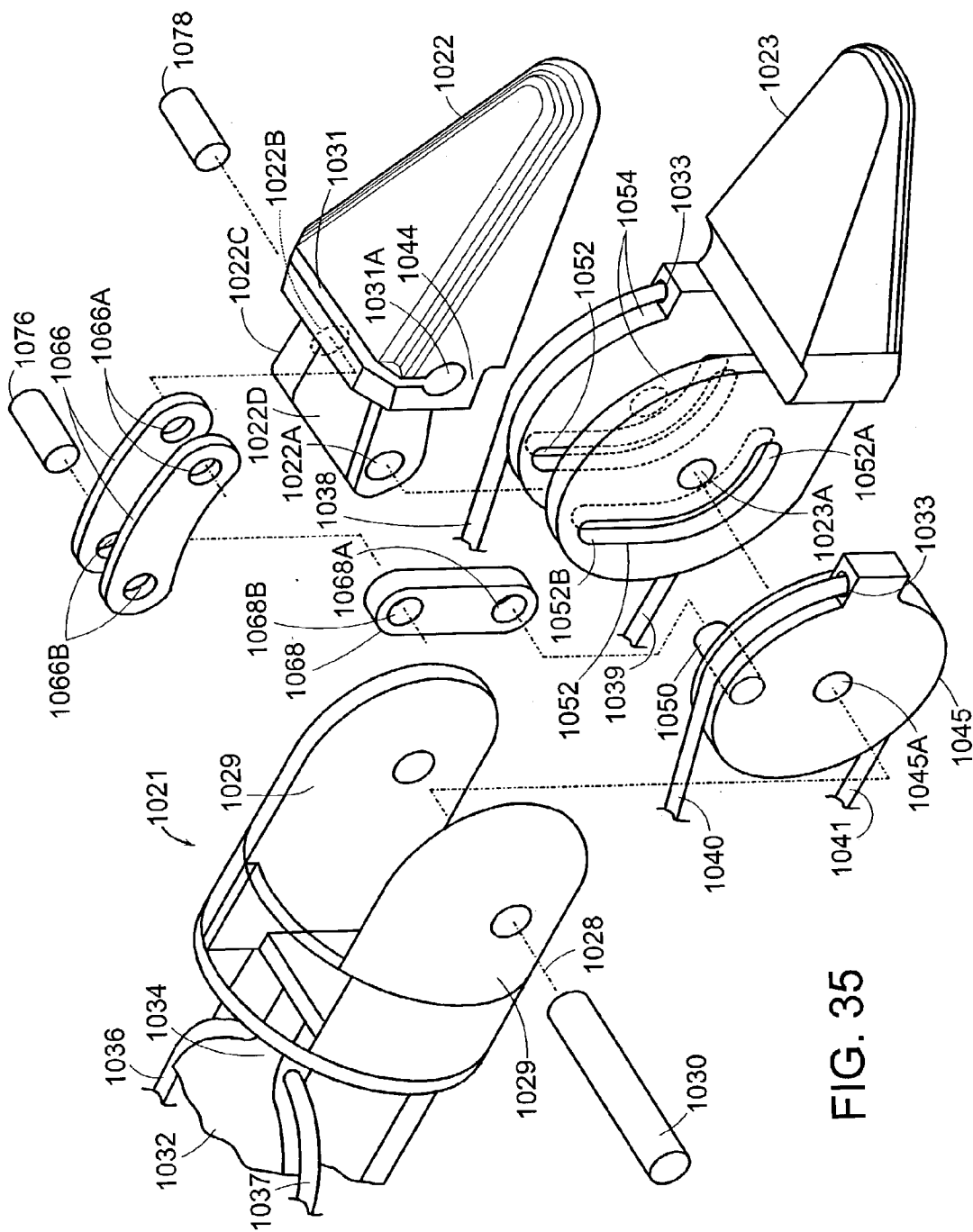


FIG. 35

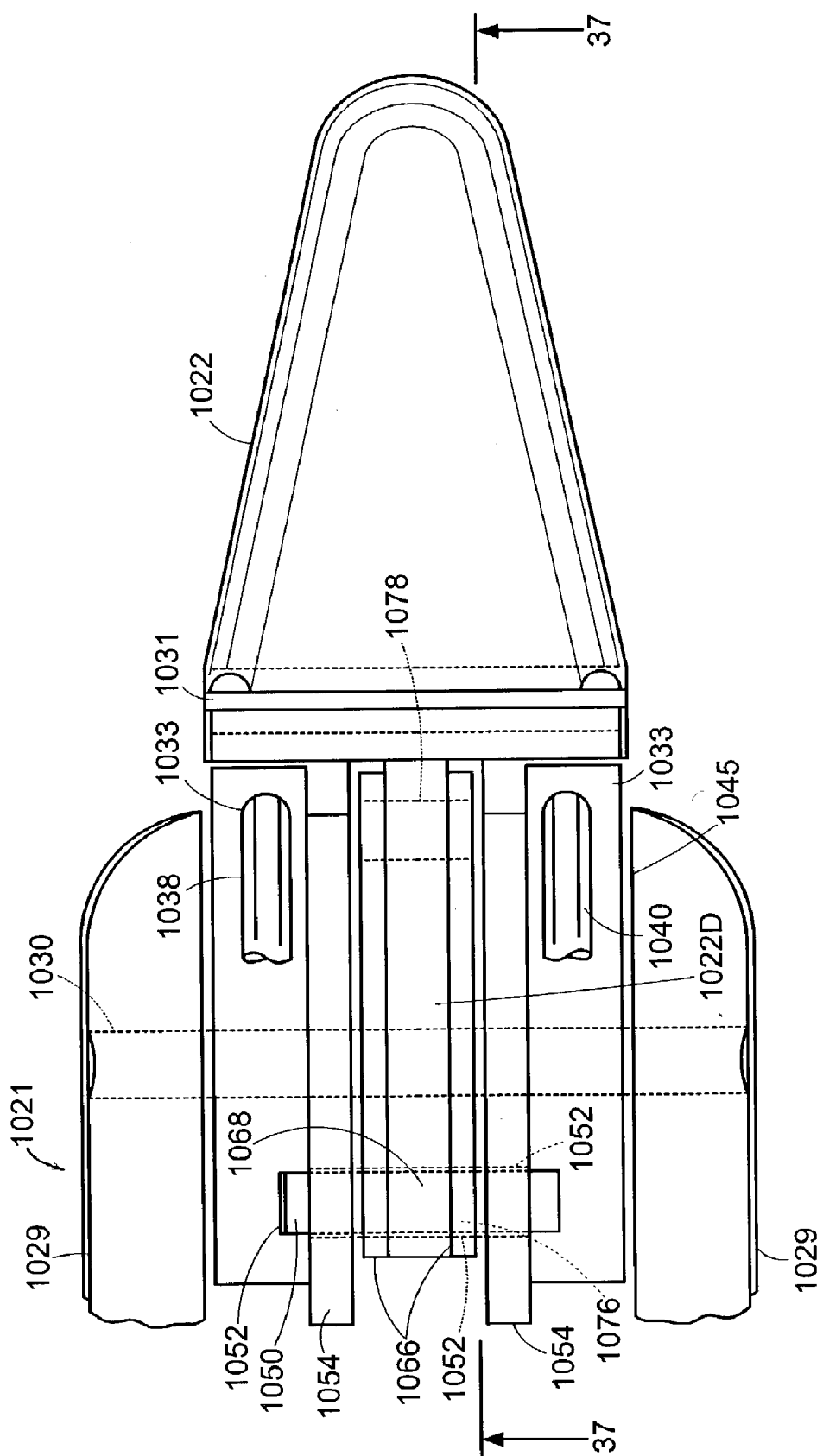


FIG. 36

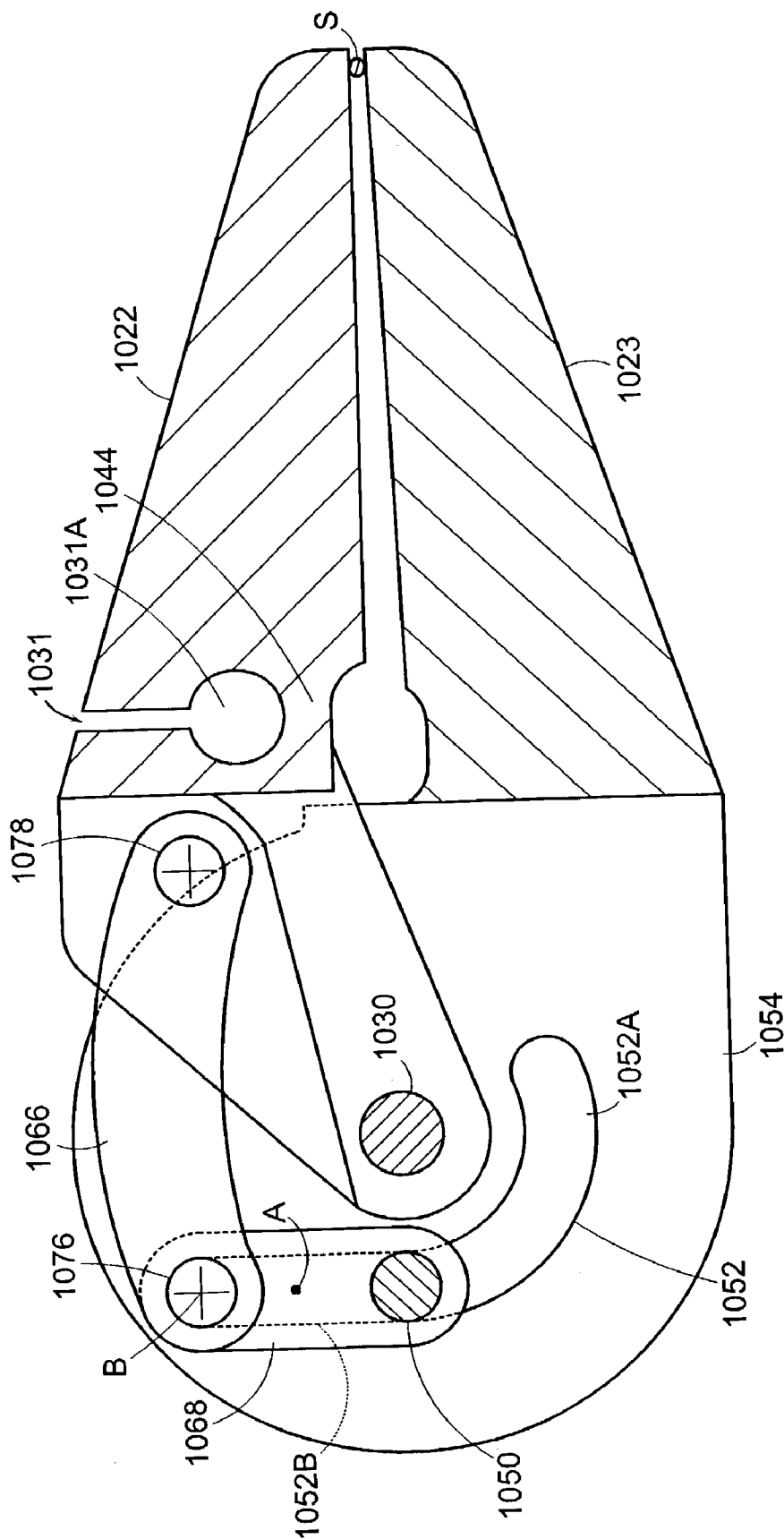


FIG. 37

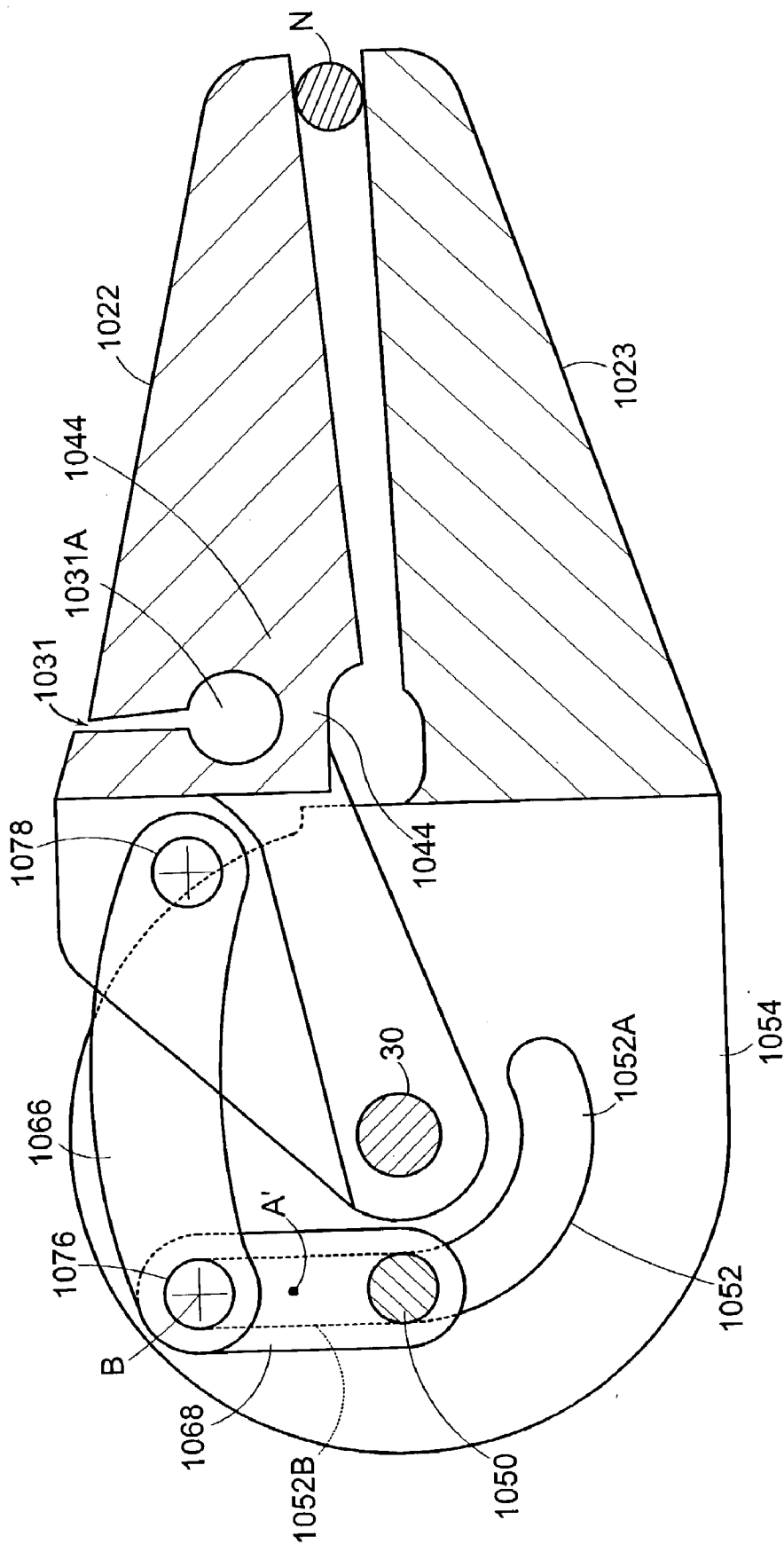


FIG. 38

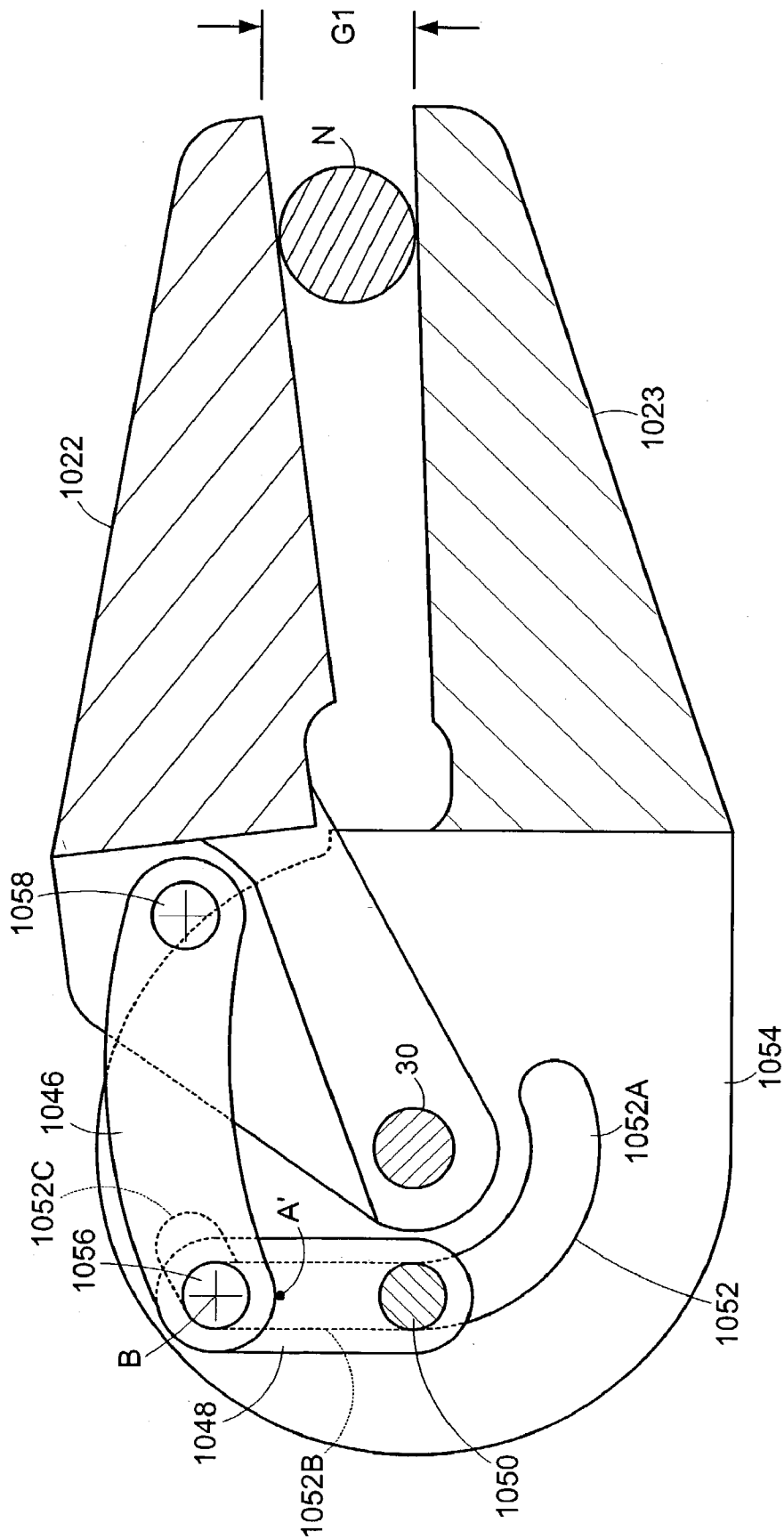


FIG. 39

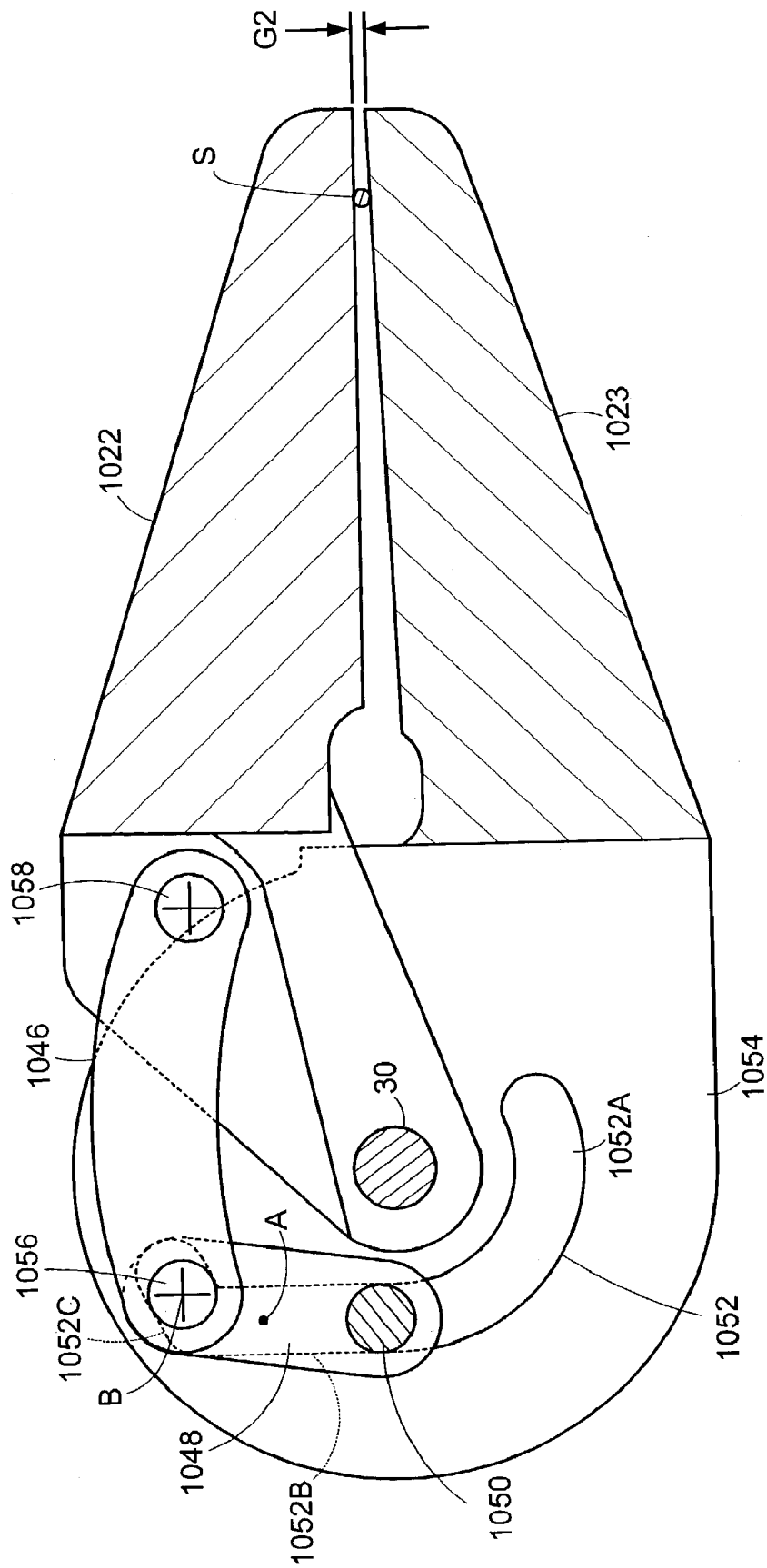
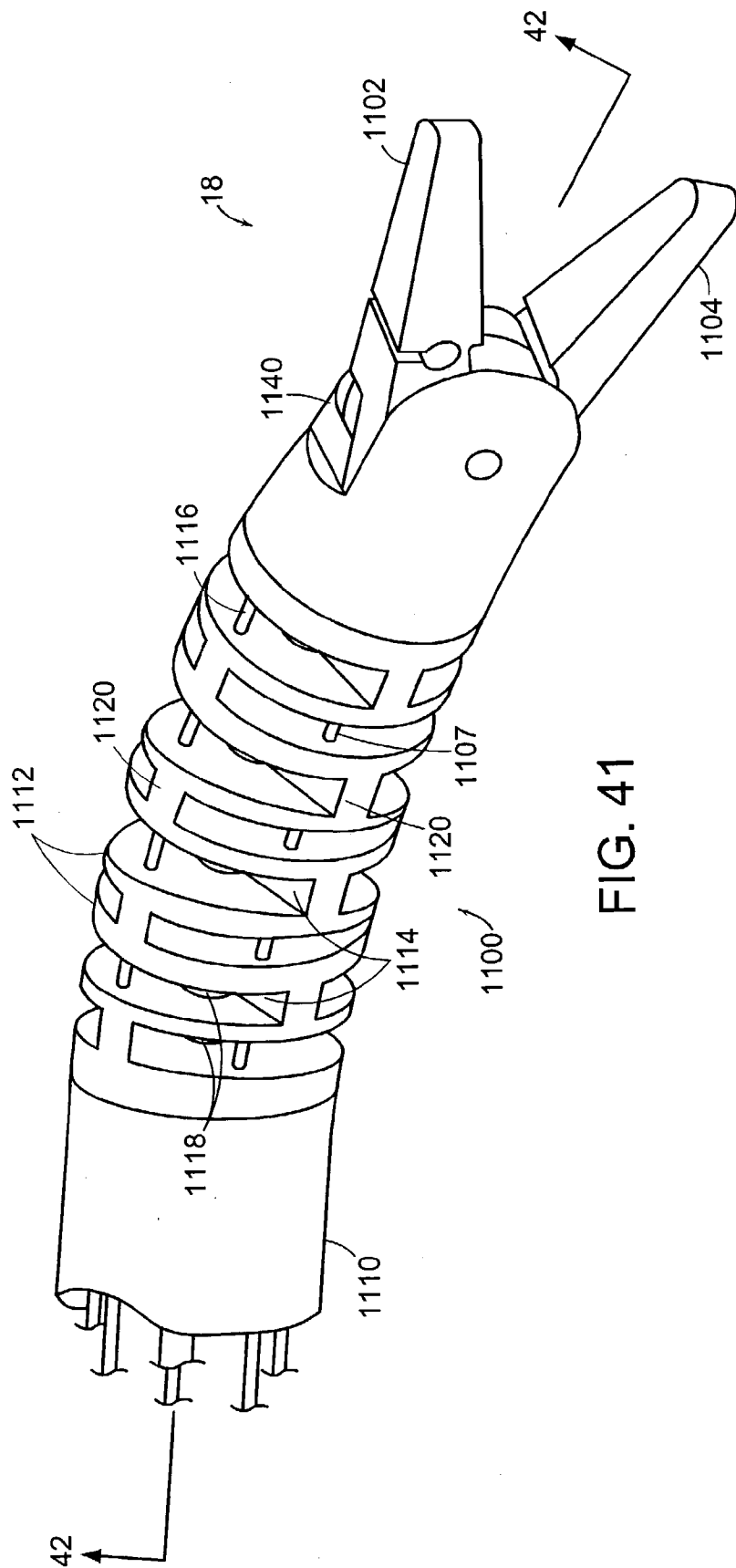


FIG. 40



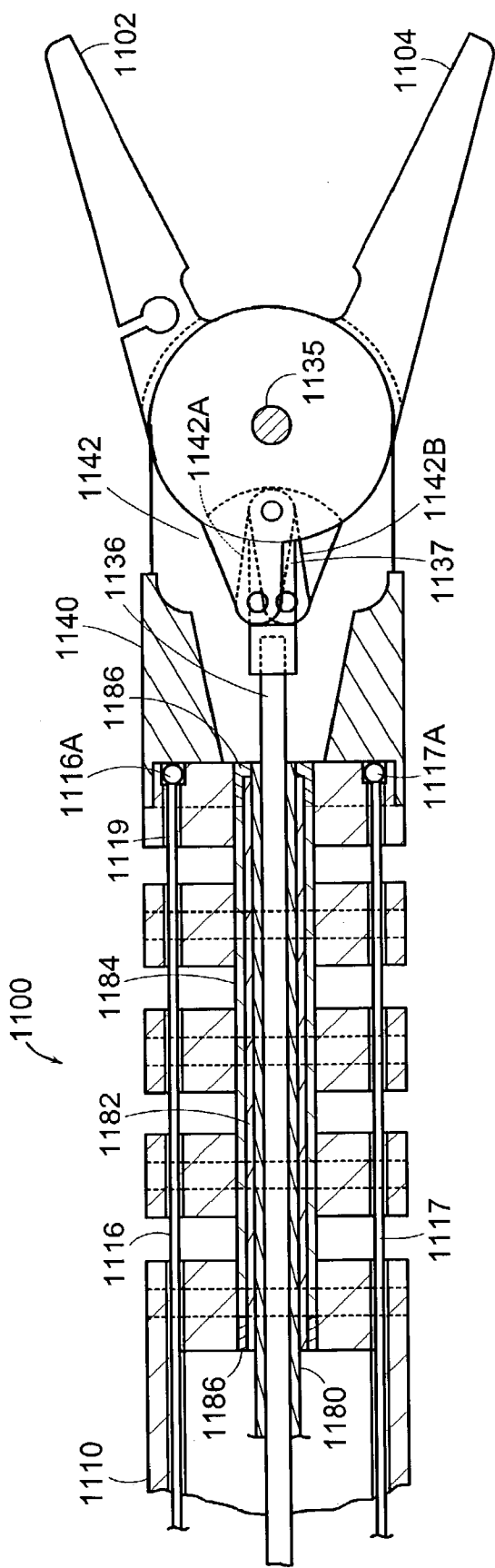


FIG. 42

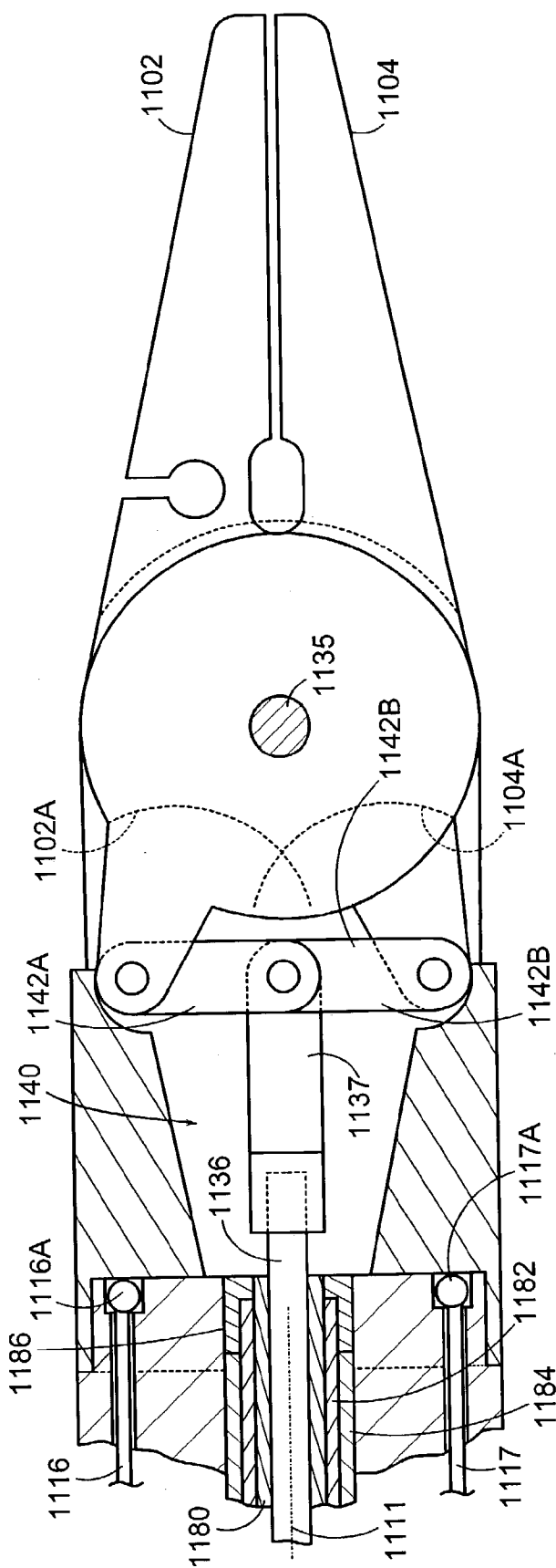


FIG. 43

FIG. 44

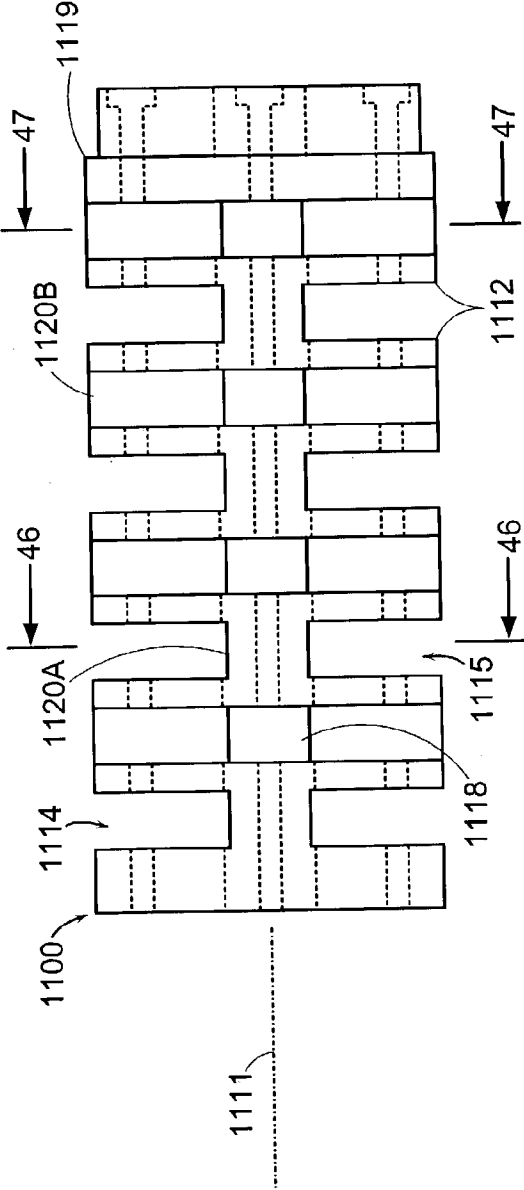


FIG. 45

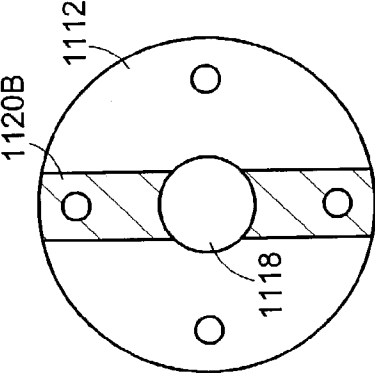


FIG. 47

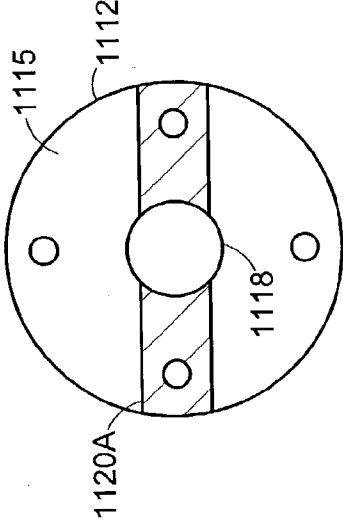


FIG. 46

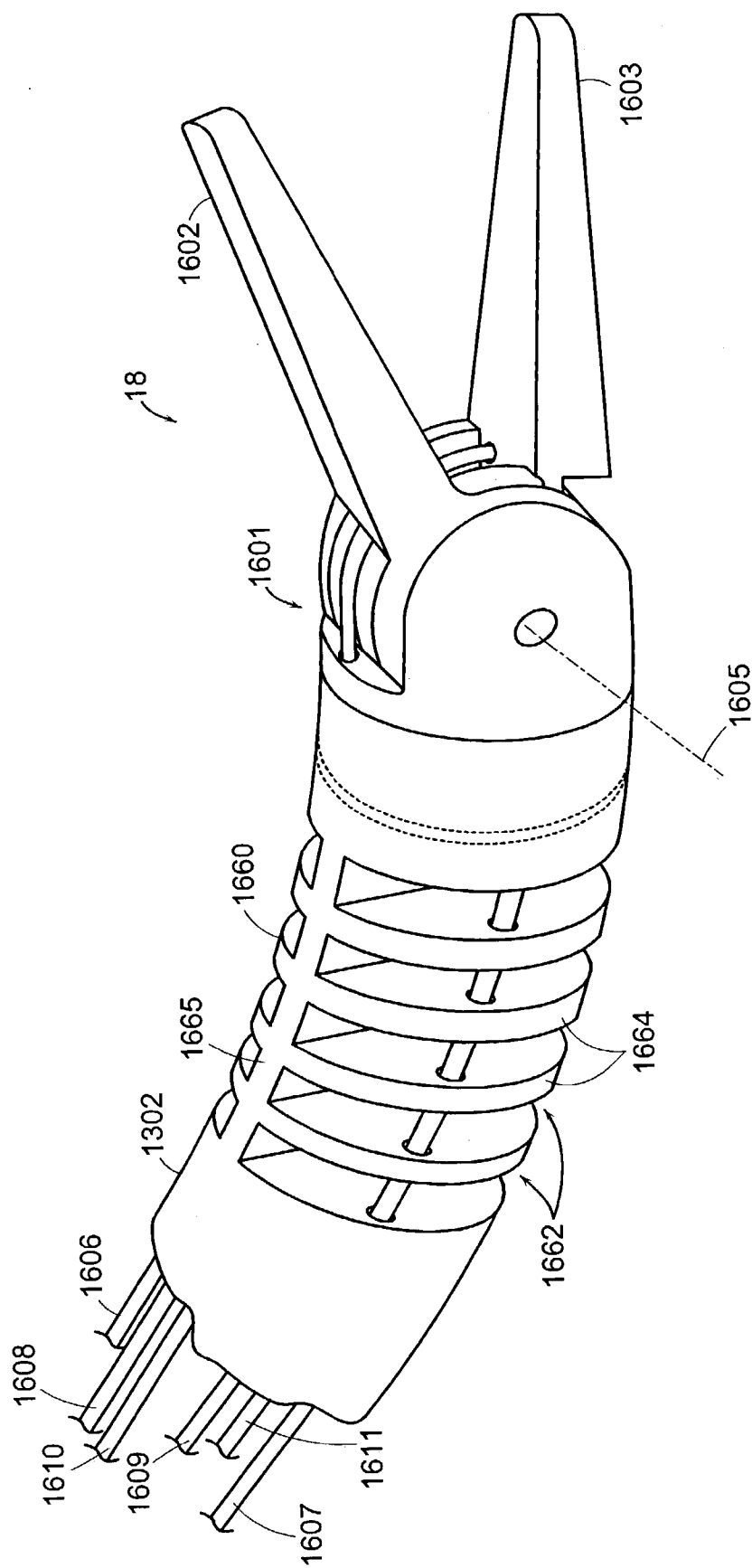


FIG. 48A

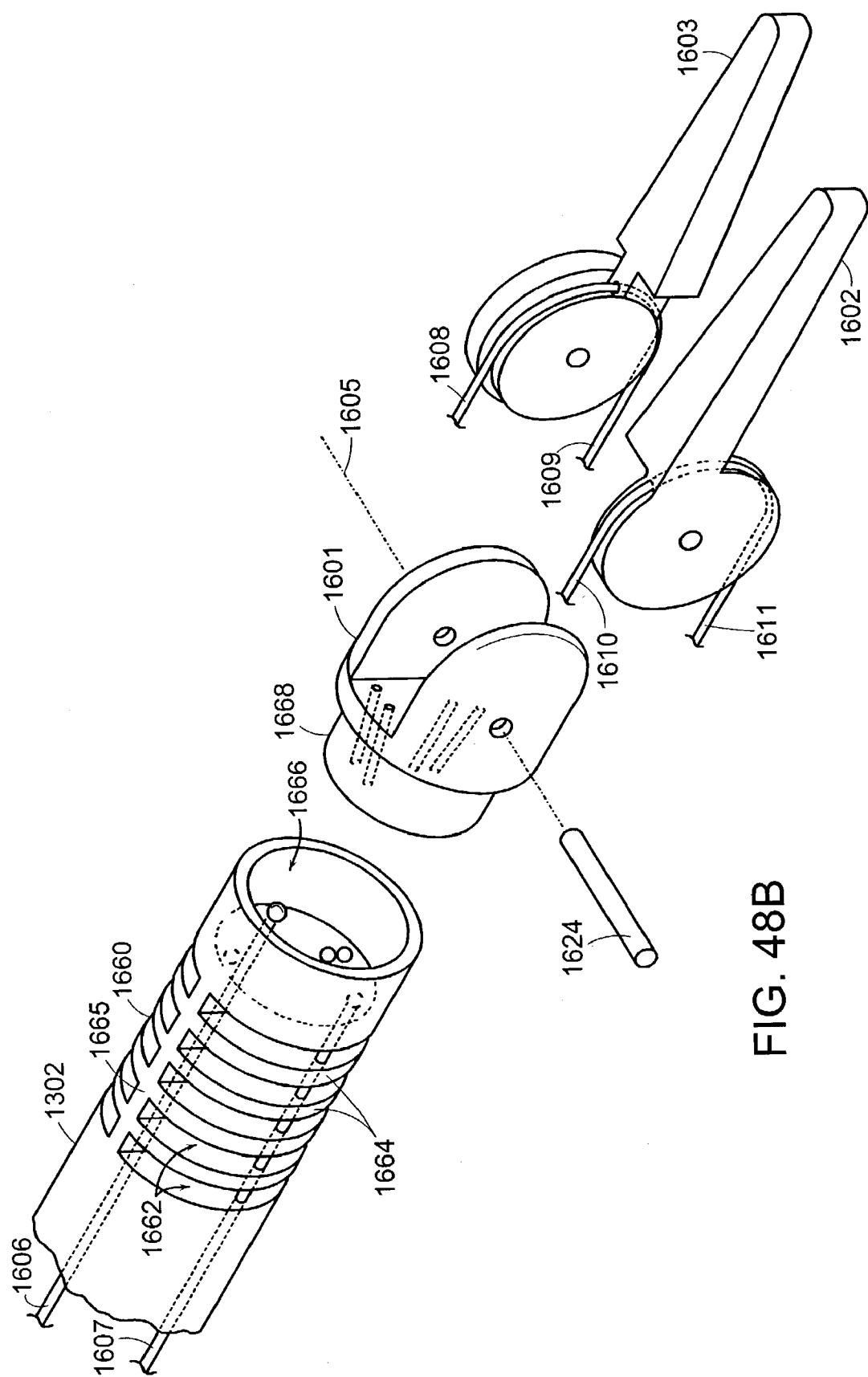


FIG. 48B

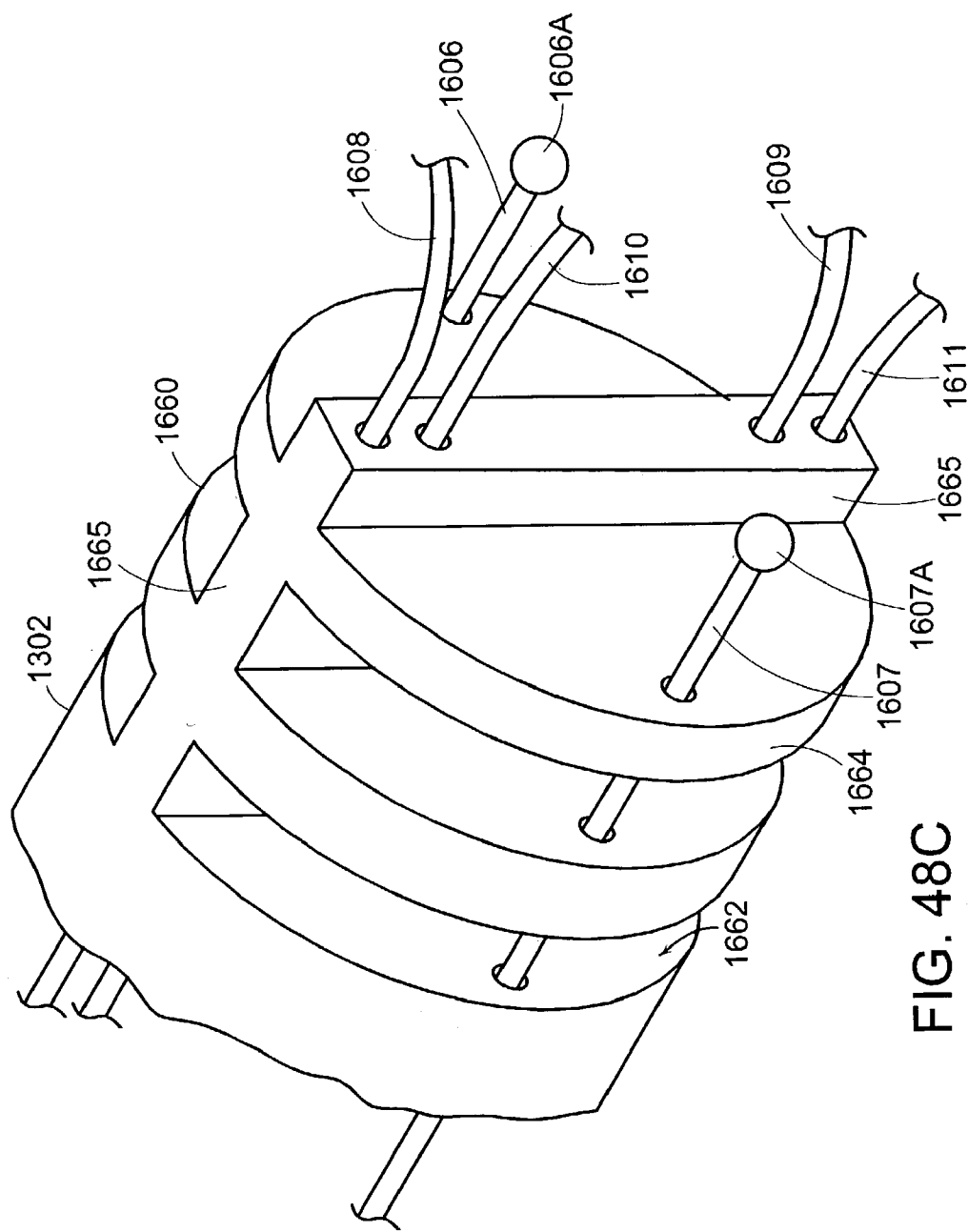


FIG. 48C

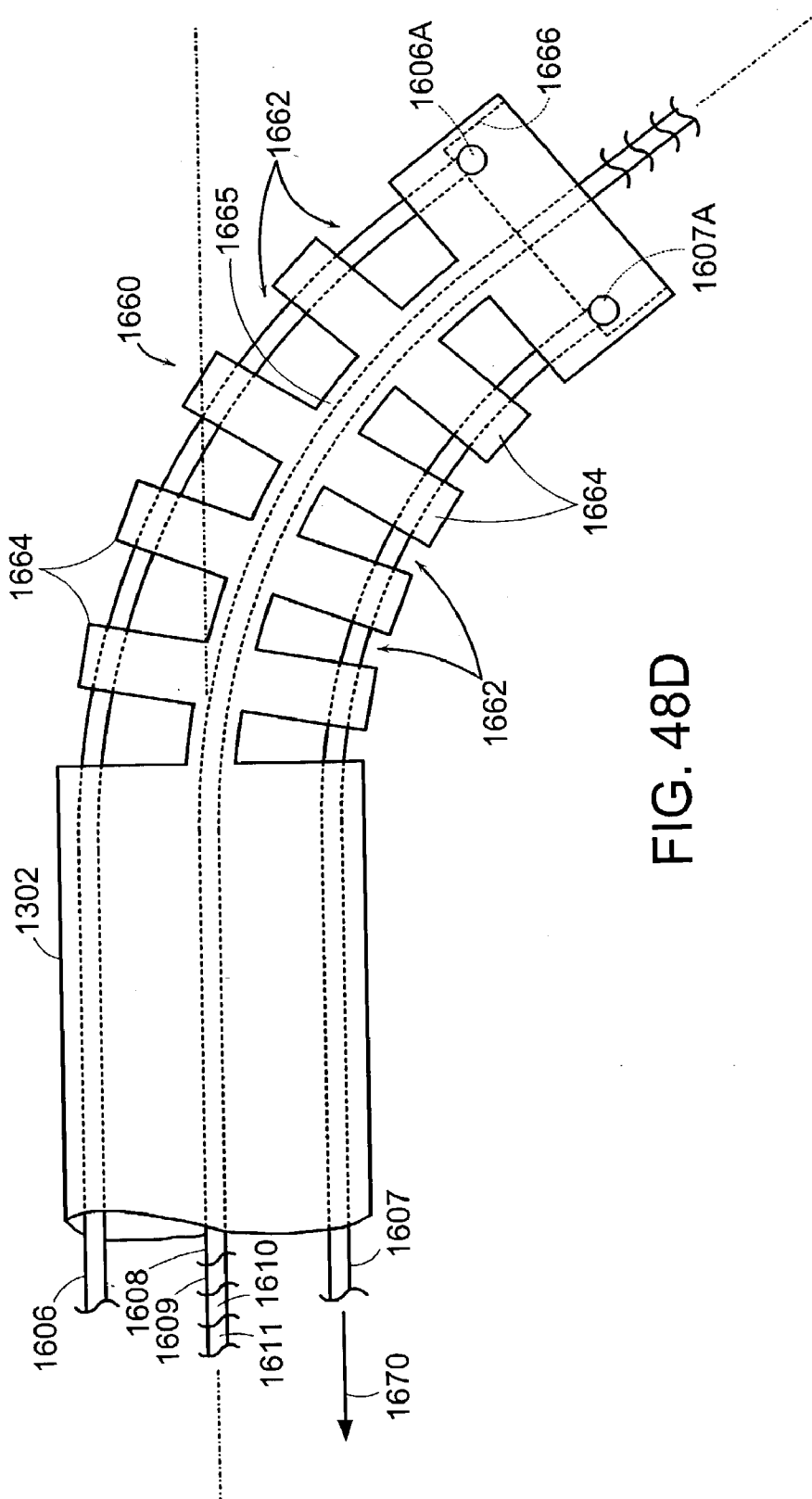
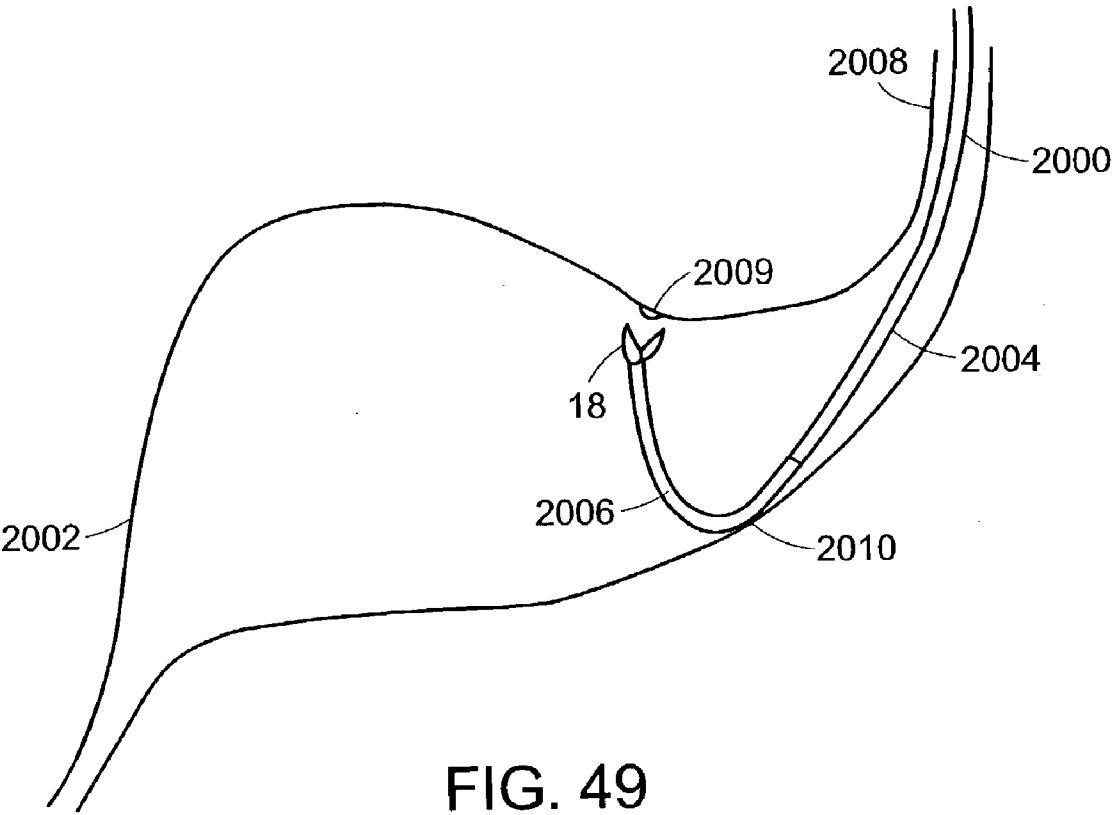


FIG. 48D



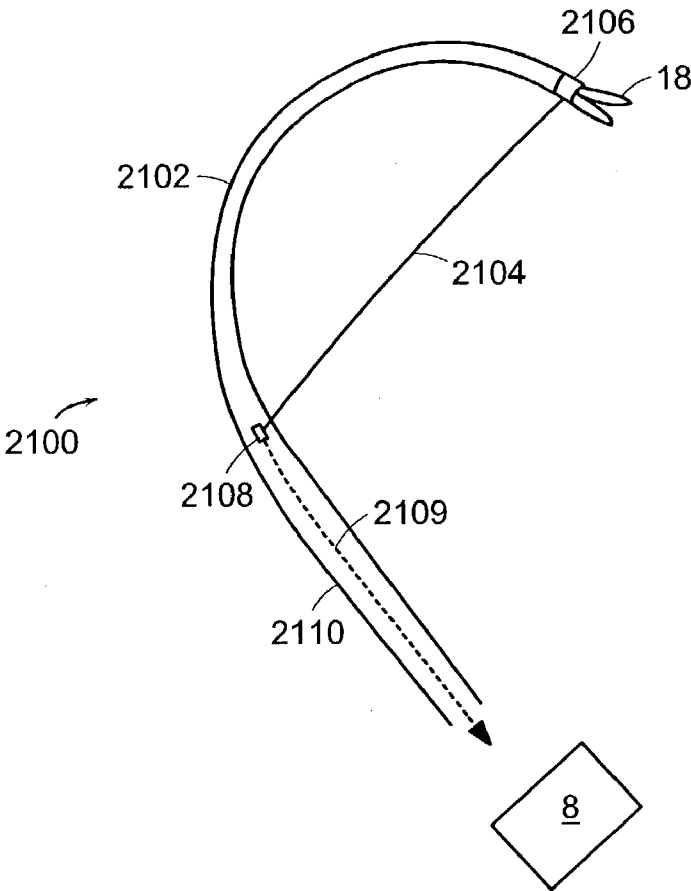


FIG. 50A

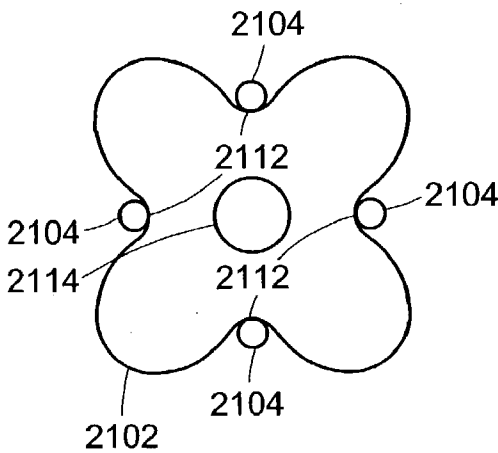


FIG. 50B

ROBOTICALLY CONTROLLED MEDICAL INSTRUMENT WITH A FLEXIBLE SECTION

BACKGROUND

[0001] Various types of instruments are used to perform surgical procedures on living subjects such as human patients. Typically, in the past, the surgeon held the instrument and inserted it into the patient to an internal surgical site. The surgeon then manually manipulated the instrument to perform the operation at the site. These instruments have been used to perform a number of surgical procedures including holding a needle to suture a region of the surgical site, cutting tissue, and grasping tissue and blood vessels.

[0002] Recently, some have proposed using telerobotic surgical systems to perform certain surgical procedures. With these systems, the surgeon sits at a master station remotely located from the patient and surgical instrument, and controls the movements of the surgical instrument with an input device. In some systems, the surgeon manipulates the input device with one or both hands, and the instrument replicates the hand and finger movements of the surgeon. Because these replicated movements can be quite complex, the surgical instrument is controlled to move with multiple degrees-of-freedom.

SUMMARY

[0003] The present invention implements an instrument and methods of using the instrument for performing telerobotic surgical procedures on a patient. The instrument includes a bending section that is bendable with at least one degree-of-freedom.

[0004] An instrument may have a bending section with a unibody construction that is bendable with at least one degree-of-freedom. A tool can be supported at the distal end of the bending section and can be used to perform a medical procedure on a subject such as a human patient. With a unibody construction, bending is by flexure of the unibody rather than by movement of parts relative to each other. The instrument can have two or more bending sections with unibody constructions. The two or more bending sections can be spaced apart or positioned adjacent to each other.

[0005] In one embodiment, the bending section has a unibody bellows construction with alternating peaks and valleys positioned between proximal and distal ends of the bending section.

[0006] The unibody construction may have a series of spaced ribs positioned along the length of the bending section between the proximal and distal ends of the bending section. In certain embodiments, the bending section includes a set of opposed ridges that extend along the length of the bending section. The individual ridges are positioned in a respective slot defined by adjacent ribs. In other embodiments, the bending section includes a first set and a second set of ridges extending along the length of the bending section. The individual ridges of the first set of ridges are positioned in every other slot defined between adjacent ribs, and the individual ridges of the second set of ridges are positioned in respective slots unoccupied by the first set of ridges. The first set of ridges can be positioned at about 90 degrees from the second set of ridges about the longitudinal axis of the bending section. Having the two sets

of ridges positioned in the described manner makes the bending section torsionally stiff. However, the bending section remains flexible and bendable with two degrees-of-freedom.

[0007] Some embodiments of the surgical instrument can include one or more of the following features. The instrument can include a first pair of cables and, optionally, a second pair of cables extending along the length of the bending section. To operate the instrument, tension is applied to at least one of the first pair of cables to bend the bending section with one degree-of-freedom, and to at least one of the second pair of cables to bend the bending section with a second degree-of-freedom.

[0008] In some embodiments, the tool is able to move with two additional degrees-of-freedom. The tool can include a first jaw and a second jaw, connected to the first jaw at a pivot joint, so that the first jaw moves with one of the two additional degrees-of-freedom and the second jaw moves with the other of the two additional degrees-of-freedom.

[0009] In certain embodiments, the instrument includes two additional pairs of cables extending along the length of the bending section and coupled to the first jaw and second jaws, respectively. During the surgical procedure, tension is applied to at least one of the first pair of additional cables to operate the first jaw, and to at least one of the second pair of additional cables to operate the second jaw. The additional pairs of cables can be positioned near the longitudinal axis of the bending section, and can be contained in a sleeve positioned along the longitudinal axis of the bending section so that the additional pairs of cables are able to slide along the sleeve relative to the bending section.

[0010] In some embodiments, the tool includes a first jaw and a second jaw, connected to the first jaw at a pivot joint such that the first and second jaws open and close, and an actuation element extending along the length of the bending section and coupled to the first and second jaws to operate the first and second jaws. The actuation element can be a single cable coupled to the first and second jaws with a pair of linkages. The cable is pulled to close the jaws and pushed to open the jaws. The single cable can be positioned near the longitudinal axis of the bending section, and can be contained in a sleeve positioned along the longitudinal axis of the bending section so that the single cable is able to slide back and forth along the sleeve.

[0011] The operation of the instrument may be controlled with a controller coupled with an input device operated by a user such as the surgeon. In particular, the surgeon can instruct the controller to direct a driver to manipulate the bending section and the tool in a desired manner.

[0012] In some embodiments, a robotically controlled medical instrument system includes an elongated shaft having proximal and distal ends, a tool supported from the distal end of the elongated shaft and useable in performing a medical procedure on a subject, at least one controllably bendable section of the shaft, and an electrical controller for receiving a command from an input device, and for, in turn, controlling the bendable section to provide at least one degree-of-freedom at the bendable section.

[0013] The system may include an actuation element extending with the instrument shaft and operable to control actuation of said tool. The actuation element may be posi-

tioned at least one of a substantially center axis and substantially center plane of the controllably bendable section so as to de-couple motion at the controllable bendable section from tool actuation.

[0014] The distal end of the elongated shaft and the tool may have respective removably engaging portions that are readily engageable for positioning the tool at the distal end of the elongated shaft in operative position relative to the elongated shaft, and readily disengageable for removal of the tool from the distal end of the elongated shaft. The tool may be removably coupled with the distal end of the elongated support shaft.

[0015] In another embodiment, a flexible surgical instrument includes a controllably flexible elongated section having a distal end for positioning at an anatomical site of interest of a subject, and at least one cable attached at or near the distal end of the section. The cable extends from its point of attachment exteriorly of the section through an aperture in the section at a position spaced a selected distance along the length of the section away from the distal end. A proximal end of the cable extends from the aperture through the shaft and is tensionable to controllably bend the flexible section.

[0016] Some embodiments may have one or more of the following advantages. A bending section with a unibody construction is typically made with fewer parts than bending sections made with multiple linkages joined together, for example, with pins. Hence, the unibody construction is less expensive and easier to fabricate. Furthermore, with a unibody construction, there are less parts to retain together during a medical procedure, which reduces the potential of breakage of the bending section, and therefore minimizes parts of the bending section and medical instrument falling apart within the subject's body.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

[0018] FIG. 1 is a perspective view illustrating a telerobotic system with which the concepts of the present invention may be practiced;

[0019] FIG. 2 is a schematic diagram illustrating the degrees-of-freedom associated with the slave station of FIG. 1;

[0020] FIG. 3 is a plan view of the instrument insert of the present invention including the stem section and tool;

[0021] FIG. 4 is a cross-sectional view as taken along line 4-4 of FIG. 3 and illustrating further details of the stem section;

[0022] FIG. 5 is a perspective view of another embodiment of the tool of the present invention employing a flexible wrist section adjacent the tool;

[0023] FIG. 6 is an exploded perspective view of the embodiment of FIG. 5;

[0024] FIG. 7 is a cross-sectional view of the embodiment of FIG. 5 and as taken along line 7-7 of FIG. 6;

[0025] FIG. 8 is a longitudinal cross-sectional view of the embodiment illustrated in FIGS. 5-7 and showing further details at the wrist flexure;

[0026] FIG. 9 is a longitudinal cross-sectional view similar to that shown in FIG. 8 but for still another embodiment of the present invention using a single actuation element;

[0027] FIG. 10 is an enlarged fragmentary view of further details of the actuation element at the center of the wrist section;

[0028] FIG. 11 is a cross-sectional view through the actuation element of FIG. 10 as taken along line 11-11;

[0029] FIG. 12 is a cross-sectional view through still another embodiment of the actuation element;

[0030] FIG. 13 is still a further cross-sectional view of a further embodiment of the actuation element;

[0031] FIG. 14 is a perspective view of yet another embodiment of the present invention employing a slotted flexible wrist section and a detachable and preferably disposable tool;

[0032] FIG. 15 is a cross-sectional view through the embodiment of FIG. 14 as taken along line 15-15 of FIG. 14;

[0033] FIG. 15A is a fragmentary cross-sectional view of an alternate embodiment of the flexible section;

[0034] FIG. 16 is an exploded perspective view of the embodiment of FIG. 14 showing the detached tool in cross-section;

[0035] FIG. 17 is a further perspective view of the embodiment of FIG. 14;

[0036] FIGS. 18-20 illustrate sequential cross-sectional views showing the mating of the tool with the distal end of the instrument;

[0037] FIG. 21 is a schematic diagram illustrating principles of the present invention in a catheter or flexible instrument using multiple controllably bendable sections along the instrument;

[0038] FIG. 22 is a schematic diagram of an embodiment of an instrument with both elbow and wrist pivot joints, as well as a disposable tool;

[0039] FIG. 23 is a schematic diagram of an embodiment of an instrument with just a wrist pivot joint, as well as a disposable tool;

[0040] FIG. 24 is a diagram showing further details of a wrist joint useable with a disposable tool;

[0041] FIG. 25 is a partially cut-away schematic view of another joint construction;

[0042] FIG. 26 is a perspective view of a another embodiment of a tool;

[0043] FIG. 27 is an exploded perspective view of the tool of FIG. 26 illustrating separate components thereof;

[0044] FIG. 27A is an exploded fragmentary view of one form of resilient member used in the embodiment of FIG. 27;

[0045] FIG. 27B is an exploded fragmentary view of another form of resilient member used in the embodiment of FIG. 27;

[0046] FIG. 28 is a side elevation view of the tool depicted in FIGS. 26 and 27;

[0047] FIG. 29 is an enlarged partial top plan view as seen along line 29-29 of FIG. 28 and illustrating further details of the tool;

[0048] FIG. 30 is a cross-sectional view as taken along line 30-30 of FIG. 29 showing the tool of the present invention with the jaws in a partially open position;

[0049] FIG. 31 is a cross-sectional view like that illustrated in FIG. 30 but with the jaws in a fully closed position;

[0050] FIG. 32 is a somewhat schematic cross-sectional view of the first embodiment of the tool with the resilient pad partially compressed in grasping a small diameter item such as a thread or suture;

[0051] FIG. 33 is a somewhat schematic cross-sectional view of the first embodiment of the tool with the resilient pad essentially fully compressed in grasping a larger diameter item such as a needle;

[0052] FIG. 34 is a perspective view of a second embodiment of the invention employing a flexure gap in one of the jaws;

[0053] FIG. 35 is an exploded perspective view of the tool of this second embodiment of the invention;

[0054] FIG. 36 is a plan view of the tool of FIGS. 34 and 35;

[0055] FIG. 37 is a cross-sectional view taken along line 37-37 of FIG. 36 with the jaws having a slight gap at their closed position;

[0056] FIG. 38 is a cross-sectional view like that illustrated in FIG. 37 but with the jaws grasping a needle or the like, and with the flexure gap in a substantially closed position;

[0057] FIG. 39 is a cross-sectional view similar to that depicted in FIGS. 37 and 38, and of yet another embodiment of the invention illustrating the tool in a partially open position;

[0058] FIG. 40 is a cross-sectional view the same as that depicted in the embodiment of FIG. 39 but with the jaws in a more closed position;

[0059] FIG. 41 is a perspective view of an embodiment of a flexible or bendable shaft segment just proximal to the tool;

[0060] FIG. 42 is a cross-sectional view of the embodiment of FIG. 41 as taken along line 17-17 of FIG. 16, and with the jaws in a substantially open position;

[0061] FIG. 43 is an enlarged partial cross-sectional view similar to that shown in FIG. 42 but with the jaws in a closed position;

[0062] FIG. 44 is an exploded perspective view showing the components including the flexible or bendable segment of FIG. 41;

[0063] FIG. 45 is a side elevation view of the flexible or bendable section itself;

[0064] FIG. 46 is a cross-sectional view through the flexible or bendable section as taken along line 46-46 of FIG. 45;

[0065] FIG. 47 is a cross-sectional view through the flexible or bendable section as taken along line 47-47 of FIG. 45;

[0066] FIG. 48A is a perspective view of an alternate embodiment of the tool and flexible section;

[0067] FIG. 48B is an exploded perspective view of the tool and flexible section illustrated in FIG. 48A;

[0068] FIG. 48C is a fragmentary perspective view showing a portion of the flexible section shown in FIG. 48B; and

[0069] FIG. 48D is a plan view of the flexible section illustrated in FIGS. 48A-48C.

[0070] FIG. 49 illustrates a flexible instrument being used in a stomach of a subject in accordance with the invention.

[0071] FIG. 50A is a schematic of a flexible instrument with a pull-type cable to operate the end of the instrument in accordance with the invention.

[0072] FIG. 50B is cross-sectional view of a bendable section of the flexible instrument of FIG. 50A in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0073] A description of preferred embodiments of the invention follows.

[0074] The surgical robotic system of the present invention, as illustrated in the accompanying drawings, although preferably used to perform minimally invasive surgery, can also be used to perform other procedures as well, such as open or endoscopic surgical procedures. FIG. 1 illustrates a surgical instrument system 10 that includes a master station M at which a surgeon 2 manipulates an input device, and a slave station S including a surgical instrument illustrated generally at 14. In FIG. 1 the input device is illustrated at 3 being manipulated by the hand or hands of the surgeon. The surgeon is illustrated as seated in a comfortable chair 4, and the forearms of the surgeon are typically resting upon armrests 5.

[0075] FIG. 1 illustrates a master assembly 7 associated with the master station M and a slave assembly 8, also referred to as a drive unit, associated with the slave station S. Assemblies 7 and 8 are interconnected by cabling 6 with a controller 9, which typically has associated with it one or more displays and a keyboard.

[0076] As shown in FIG. 1, the drive unit 8 is located remotely from the operative site and is preferably positioned a distance away from the sterile field. The drive unit 8 is controlled by a computer system that is part of the controller 9. The master station M may also be referred to as a user interface vis-à-vis the controller 9. The computer translates

the commands issued at the user interface into an electronically driven motion in the drive unit 8, and the surgical instrument, which is tethered to the drive unit through the cabling connections, produces the desired replicated motion. That is, the controller 9 couples the master station M and the slave station S and is operated in accordance with a computer algorithm, to be described in further detail below. The controller 9 receives a command from the input device 3 and controls the movement of the surgical instrument 14 so as to replicate the input manipulation. FIG. 1 also shows a patient P, upon whom the surgical procedure is performed, lying on an operating table T.

[0077] In the embodiment illustrated in FIG. 1, the surgical instrument 14 includes two separate instruments one on either side of an endoscope 13. The endoscope 13 includes a camera to remotely view the operation site. The camera may be mounted on the distal end of the instrument insert, or may be positioned away from the site to provide an additional perspective on the surgical operation. In certain situations, it may be desirable to provide the endoscope through an opening other than the one used by the surgical instrument 14. In this regard, in FIG. 1 three separate incisions are shown in the patient P, two side incisions for accommodating the surgical instruments and a central incision that accommodates the viewing endoscope. A drape covering the patient is also shown with a single opening.

[0078] The surgical instrument 14 also includes a surgical adaptor or guide 15 and an instrument insert or member 16. The surgical adaptor 15 is basically a passive mechanical device, driven by the attached cable array. Although the surgical adaptor 15 can be easily seen in FIG. 1, the instrument member 16 (FIG. 3) is not clearly illustrated as it extends through the adaptor 15. The instrument insert 16 carries at its distal end a tool 18, described in greater detail below.

[0079] Although reference is made herein to a "surgical instrument," it is contemplated that the principles of this invention also apply to other medical instruments, not necessarily for surgery, and including, but not limited to, such other implements as catheters, as well as diagnostic and therapeutic instruments and implements.

[0080] In FIG. 1 there is illustrated cabling 12 coupling the instrument 14 to the drive unit 8. The cabling 12 is preferably detachable from the drive unit 8. Furthermore, the surgical adaptor 15 may be of relatively simple construction. It may thus be designed for particular surgical applications such as abdominal, cardiac, spinal, arthroscopic, sinus, neural, etc. As indicated previously, the instrument insert 16 couples to the adaptor 15, and essentially provides a means for exchanging the instrument tools. The tools may include, for example, forceps, scissors, needle drivers, electrocautery etc.

[0081] During use, a surgeon can manipulate the input device 3 at a surgeon's interface 11, to effect a desired motion of the tool 18 within the patient. The movement of the handle or hand assembly at input device 3 is interpreted by the controller 9 to control the movement of the tool 18.

[0082] The surgical instrument 14 is preferably mounted on a rigid post 19 that is affixed to but removable from the surgical table T. This mounting arrangement permits the instrument to remain fixed relative to the patient even if the

table is repositioned. In accordance with the present invention the concepts can be practiced even with a single surgical instrument, although, in FIG. 1 there are illustrated two such instruments.

[0083] The surgical instruments 14 are connected to the respective drive units 8 with cablings that include two mechanical cable-in-conduit bundles 21 and 22. These cable bundles 21 and 22 may terminate at two connection modules, which removably attach to the drive unit 8. For further details of the connection modules 23 and 24 can be found in the earlier co-pending application No. PCT/US00/12553, the entire contents of which are incorporated herein by reference. Although two cable bundles are described here, it is to be understood that more or fewer cable bundles can be used. Furthermore, although the drive unit 8 is preferably located outside the sterile field, it may be draped with a sterile barrier so that it can be operated within the sterile field.

[0084] In the preferred technique to set up the system, the tool 18 of the surgical instrument 14 is inserted into the patient through an incision or opening, and the instrument 14 is then mounted to the rigid post 19 using a mounting bracket 25. The cable bundles 21 and 22 are then extended away from the operative area to the drive unit 8, and the connection modules of the cable bundles are engaged into the drive unit 8. Instrument inserts 16 (FIG. 3) may then be passed through the surgical adaptor 15, and coupled laterally with the surgical adaptor 15 through an adaptor coupler, as described below in further detail.

[0085] As just mentioned, the instrument 14 is controlled by the input device 3, which is manipulated by the surgeon. Movement of the hand assembly produces proportional movement of the instrument 14 through the coordinating action of the controller 9. It is typical for the movement of a single hand control to control movement of a single instrument. However, FIG. 1 shows a second input device that is used to control an additional instrument. Accordingly, in FIG. 1 two input devices associated with the two instruments are illustrated.

[0086] The surgeon's interface 11 is in electrical communication with the controller 9 primarily by way of the cabling 6 through the master assembly 7. Cabling 6 also couples the controller 9 to the actuation or drive unit 8. While the cabling 6 transmits electrical signals, the actuation or drive unit 8 is in mechanical communication with the instrument 14. The mechanical communication with the instrument allows the electromechanical components to be removed from the operative region, and preferably from the sterile field. The surgical instrument 14 provides a number of independent motions, or degrees-of-freedom, to the tool 18. These degrees-of-freedom are provided by both the surgical adaptor 15 and the instrument insert 16.

[0087] Shown in FIG. 2 is a schematic representation of the joint movements associated with the slave station S. The first joint movement J1 represents a pivoting motion of the instrument about the pivot pin 225 at axis 225A. Also illustrated is the movement relating to joint J2 which is a transitional movement of the carriage 226 on the rails 224 to move the carriage as well as the instrument 14, supported therefrom, in the direction indicated by the arrow 227 in FIG. 2 towards and away from the operative site, OS. The cabling in the bundle 21 controls both the J1 and J21

movements. It is further noted that the distal end of the guide tube **17** extends to the operation site OS. The operation site may be defined as the general area in close proximity to where movement of the tool occurs, usually in the viewing area of the endoscope and away from the incision.

[0088] FIG. 2 also depicts the rotary motion of both the adaptor tube **17** and the instrument stem. These are illustrated in FIG. 2 as respective motions or joints **J3** (adaptor tube rotation) and **J4** (instrument stem rotation). Motion **J5** indicates a wrist pivot or, alternatively, a wrist flexure. Finally, motions **J6** and **J7** represent the end jaw motions of the tool **18**.

[0089] The combination of joints **J4-J7** allows the instrument insert **16** to be actuated with four degrees-of-freedom. When coupled to the surgical adaptor **15**, the insert **16** and adaptor **15** provide the surgical instrument **14** with seven degrees-of-freedom. Although four degrees-of-freedom are described here for the instrument insert **16**, it is to be understood that greater or fewer numbers of degrees-of-freedom are possible with different instrument inserts. For example an energized insert with only one gripper may be useful for electro-surgery applications, while an insert with an additional linear motion may provide stapling capability.

[0090] With regard to the incision point, FIG. 2 shows the incision point along the dashed line **485**, and a cannula **487** that in some surgical procedures is used in combination with a trocar to pierce the skin at the incision. The guide tube **17** is inserted through the flexible cannula **487** so that the tool is at the operative site OS. The cannula typically has a port at which a gas such as carbon dioxide enters for insufflating the patient. The cannula also is usually provided with a switch or button that can be actuated to desufflate. The cannula is used primarily for guiding the instrument, but may include a valve mechanism for preventing escape of gas from the body.

[0091] FIG. 3 is a plan view showing an instrument insert including the tool **18**, and elongated sections including a rigid section **302** and a flexible section **303**, with the tool **18** mounted at the end of the flexible stem section **303**. The coupler **300** includes one or more wheels that laterally engage wheels of the coupler associated with the surgical adaptor. The coupler **300** also includes an axial wheel **306** that also engages a wheel on the adaptor. The axial engagement wheel **306** is fixed to the rigid stem **302**, and is used to rotate the tool axially at the distal end of the flexible stem section **303**.

[0092] FIG. 3 illustrates the base coupler **300** of the instrument insert **16** with wheels **330**, **332**, and **334** that have half-moon construction for engagement with mating like wheels of the adaptor. These wheels are meant to mate with the corresponding wheels of the adaptor. Also illustrated in FIG. 3 are capstans or idler pulleys **340**, **342**, and **344** associated with wheels **330**, **332**, and **334**, respectively.

[0093] Each wheel of the coupler has two cables that are affixed to the wheel and wrapped about opposite sides at its base. The lower cable rides over one of the idler pulleys or capstans, which routes the cables toward the center of the instrument stem **302**. The cables are kept near the center of the instrument stem, since the closer the cables are to the central axis of the stem, the less disturbance the cables experience as the stem section moves (rotates). The cables

may then be routed individually through plastic tubes that may be affixed, respectively, to the proximal end of the rigid stem **302** and the distal end of the flexible stem section **303**. Alternatively, the cables may each be enclosed in separate plastic tubes or sheaths only in the flexible section of the instrument stem (see, e.g., bundle **284** in FIG. 4). The tubes assist in maintaining constant length pathways for the cables as they move longitudinally within the instrument stem.

[0094] As for the coupler **300**, there are six cables that connect to each of the wheels. Two cables connect to each wheel and one of these cables extends about the associated idler pulley or capstan. These are illustrated in FIG. 3 as idler pulleys **340**, **342** and **344**. Thus, six separate cables extend through the rigid stem **302** and down through the flexible stem section **303** to the area of the tool.

[0095] Associated with the wheels **330**, **332**, and **334** are six cables that extend through the sections **302** and **303**, as illustrated in FIG. 4. One set of these cables controls the pivoting, such as the pivoting movement about pin **620**. The other cables control the operation at the gripping jaws. For example, one pair of cables may control the movement of the lower jaw **652**, while another cable pair may control the operation of the upper jaw **650**.

[0096] In FIG. 4 there is shown the rigid section **302** and the flexible section **303** of the instrument insert **16**. A series of six cables, illustrated at arrow **280** in FIG. 4 extend through these sections and may be considered as separated into three sets for controlling the tool **18**, to provide the motions indicated in FIG. 2 as **J5-J7**. To de-couple wrist control from jaw control, the cabling is supported near to the center axis of the rigid and flexible sections. Note that "de-coupling" simply means that any one controlled action associated with the tool, when performed, does not interfere with other controlled actions that may not be selected at the time that the one controlled action is taking place. This may be controlled to some extent by using a retainer block **282** within these sections between the sections **302** and **303**, as depicted in FIG. 4. On the rigid section side of the block **282** the cables may be unsupported as shown or they could be held within a plastic sleeve either individually and/or as a group. Because the cables are maintained in tension and the rigid section is not meant to bend or flex, the cables can be held in position by being supported, as a group, at the center of block **282**.

[0097] From the other side of block **282** the cables extend through in a bundle **284**. Also, each individual cable is preferably held within a cable sleeve, such as illustrated in FIGS. 6 and 8, to be described later in further detail. Also, as shown in FIG. 8 the cables contained in the sleeves **292** are twisted, for example, 180 degrees over say 8 inches. As also shown in FIG. 4, spacers **286** may be spaced along the flexible section **303** to hold the bundle **284** at the center of the section **303**. The individual cable sleeves also define a substantially fixed length pathway for each cable so that even though the instrument may move or rotate, the cable lengths should stay the same within the flexible stem section. The sleeves may be held in fixed position at their ends such as at block **282** at one end and at the tool **18** at the other end. The outer flexible tube **288** may be a pliable plastic preferably having a fluted or bellows-like configuration, as illustrated.

[0098] The limited twisting of the cable bundle prevents the formation of kinks or loops in individual cables that

might occur if the cables were straight and parallel through the flexible section. This twisting also provides the decoupling between motions, so that actuation of one of the degrees-of-freedom (J5-J7) does not cause a responding action at another degree-of-freedom (J5-J7). The twisting essentially occurs between the block 282 and the location where the bundle enters the wrist joint (for example, the entry to base 600). The 180 degree twisting of the bundle ensures that the cable sheathes are neither stretched nor compressed, even as the bendable section is bent or rotated.

[0099] The construction of one form of tool is illustrated in FIGS. 3 and 4. The tool 18 includes the base 600, link 601, upper grip or jaw 650 and lower grip or jaw 652. The base 600 is affixed to the flexible stem section 303. As illustrated in the drawings, this flexible section may be constructed of a ribbed plastic. This flexible section allows the instrument to readily bend through the curved actuator tube 17.

[0100] The link 601 is rotatably connected to the base 600 about an axis 620A represented by pivot pin 620. The upper and lower jaws 650 and 652 are rotatably connected to the link about axis 605, where axis 605 is essentially perpendicular to the wrist axis at pin 620. Another pivot pin defines axis 605.

[0101] Six cables actuate the separate members 600-603 of the tool. The cabling may travel through the instrument insert stem (section 303) and through a hole in the base 600, wrapping around a curved surface on link 601, and then attaches on link 601. Tension on one set of cables rotates the link 601, and tension on other cables operates the upper and lower grips 650 and 652, about axis pin 605. The cabling is provided in pairs to provide an opposing action operation, including opposite routing paths, on the opposite sides of the instrument insert.

[0102] The set of cables that control the jaws travels through the stem 302, 303 and through holes in the base 600. These cables then pass between two fixed posts 621 that constrain the cables so that they pass substantially through an axis 620A, which defines the rotational motion of the link 601. This construction allows free rotation of the link 601 with essentially no length changes in the cables that actuate the jaws. In other words, these cables, which actuate the grips 650 and 652, are effectively decoupled from the motion of link 601. These cables pass over rounded sections and terminate on grips (or jaws) 650 and 652, respectively. Tension on one pair of cables rotate grips 650 and 652 counter-clockwise about axis 605. Another set of cables provides the clockwise motion to grips or jaws 650 and 652, respectively. The ends of the cables can be secured at the jaws 650 and 652 with the use of an adhesive such as epoxy glue, or the cables could be crimped or pinned to the jaw.

[0103] The instrument 16 slides through the guide tube 17 of adaptor 15, and laterally engages the adaptor coupler 230 pivotally mounted to the base piece 234. The base piece 234 is rotationally mounted to the guide tube 17, and is affixed to the linear slider or carriage 226. The carriage 226, in turn, is pivotally mounted at the pivot 225 about the axis 225A.

[0104] The embodiment of the invention illustrated in FIGS. 2-4 employs a fixed wrist pivot. An alternate construction is shown in FIGS. 5-8 in which there is provided, in place of a wrist pivot, a controllable flexing or bending

section. In FIGS. 5-8, similar reference characters are used for many of the parts as they correspond to elements found in FIGS. 2-4. The construction in FIG. 5 may be employed with a stem section such as illustrated in FIGS. 3 and 4 with a curved guide tube.

[0105] In the embodiment illustrated in FIGS. 5-8, the tool 18 includes an upper grip or jaw 650 and a lower grip or jaw 652, supported from a link 601. Each of the jaws 650, 652 as well as the link 601, may be constructed of metal, or alternatively, the link 601 may be constructed of a hard plastic. The link 601 is engaged with the end of the flexible stem section 303. In this regard reference may also be made to FIG. 4 that shows the ribbed or fluted plastic construction of the flexible stem section 303. Alternatively, the section 303 may be smooth, at least at its distal end, as shown at 304 in FIG. 5. In still another embodiment both sections 302 and 303 can be rigid depending upon the particular application.

[0106] FIG. 5 shows only the end of the stem section 303 (at 304), terminating in bending or flexing section 660. Section 660 may be integrally formed with the rest of section 303. This section 660 is controllably bendable or flexible usually from a remote location such as in accordance with the telerobotic system 10 of FIG. 1. The stem section 303 is preferably constructed so as to be flexible and may have either fluted or smooth outer surfaces. Also, at the flexible section 660, flexibility and bending is enhanced by a bellows configuration 662 having saw-tooth shape of peaks and valleys as shown in FIG. 8. The distal end of the bending section 660 terminates with an opening 666 for receiving the end 668 of the link 601. The bellows configuration may be made of a single piece of material. Alternatively, the bellows configuration 662 may be made of segments connected together, for example, by welds. In any case, the bellows configuration 662 is a unibody construction.

[0107] In the embodiment shown in FIGS. 5-8, the bending or flexing section 660 is constructed to have orthogonal bending movements to provide both pitch and yaw movement of the tool. This is accomplished by using four cables separated at 90° intervals. These four cables include the cables 606, 607, 616, and 617. The operation of cables 606 and 607 provides flexing in one degree-of-freedom while an added degree-of-freedom (orthogonal to the just mentioned one degree-of-freedom) is provided by operation of cables 616 and 617. As illustrated in FIG. 8, these cables extend through the bellows about half way between each peak and valley and thus run in parallel but close to the outer periphery of the flexible section 660. Each of the cables 606, 607, 616, and 617 terminate in a respective ball end 606A, 607A, 616A, and 617A, tensioned against an end wall 615. These same cables also are supported by and extend through retainer block 621. Within section 304 these cables also run near the outer wall as shown to the left in FIG. 8 where cables 616 and 617 are illustrated.

[0108] As for the operation of the tool, the cables 608, 609, 610, and 611 extend through the flexible stem section 303 and also through the retainer block 621, flexing section 660, and the wall 615. These cables extend to the respective jaws (650, 652) to control the operation thereof in a manner similar to that described previously in connection with FIGS. 2-4.

[0109] As is apparent from FIGS. 6-8, within the bellows 662, the tool actuation cables extend through the center of

the bellows and are supported and retained between block 621 and wall 615 by the center sheath 290. The center sheath 290 may be constructed of a soft plastic material, and has an inner diameter sufficient to receive the bundle of cables, and an outer diameter that fits with little clearance against the inner diameter of the bellows 662. The sheath 290 extends between the block 621 and the wall 615 and is dimensioned to hold the cables, as a bundle, at the center axis of the bellows section. Keeping the bundle near the center axis provides proper de-coupling between the various degrees-of-freedom.

[0110] Also, within the bellows 662 each of the cables is contained in its own cable sleeve 292. These sleeves are sufficiently stiff to maintain constant cable lengths within the flexible or bendable section. In FIG. 8 these sleeves are shown extending between retainer block 621 and wall 615. As shown in the right most portion of FIG. 8, the cables are shown extending from the sleeve when the cables reach the end tool. FIG. 8 also illustrates the aforementioned twisting of the cables that assists in providing the decoupling action between the tool operation and the controlled flexing or bending. The cables are twisted about 180 degrees between the block 621 and wall 615. The bellows section itself, may have a length of about one to three inches. Also, more than one bellows section may be used to provide controlled bending at more than one location. In that case separate control cabling is used for each section (see, e.g., FIG. 21 described later).

[0111] As with the earlier described embodiment, the limited twisting of the cable bundle prevents the formation of kinks or loops in individual cables that might occur if the cables were left straight and parallel to one another. This twisting also de-couples certain degrees of motions, so that actuation of one of the degrees-of-freedom does not cause a responding action at another degree-of-freedom. The twisting occurs between the block 621 and the location where the bundle enters the wrist joint, i.e. the entry to base 601. By twisting the cables through 180 degrees, the placement of all the cables is displaced from one end of the bundle to the other by 180 degrees. The individual cable sleeves also define a substantially fixed length pathway for each cable so that even though the instrument may move or rotate the cable lengths stay the same within the section 660.

[0112] The cross-sectional view of FIG. 8 gives details of the cabling in bending section 660. The sheath 290 extends essentially between block 621 and wall 615 and houses the twisted cables/sleeves. The individual sleeves 292 can be considered as terminating at respective ends in blocks 621 and 631. Each of the sleeves may be glued or secured in any other appropriate manner in its supporting end block. This prevents the sleeves from moving axially as the cables are activated. The sleeves are preferably constructed of a plastic that is flexible and yet has sufficient rigidity so they do not kink when the cables are activated. The sleeves also define fixed length pathways that do not compress or elongate as the cables are operated.

[0113] The 180 degrees twist in the cables/sleeves occurs essentially between blocks 621 and 631. This "twisting" of the center cables/sleeves allows the section 660 to be controllably bent, while preventing or minimizing any transfer of motion to the tool operating cables. Similarly, this arrangement also prevents cross-coupling from the tool

operation to the bending control, so that the tool operation alone does not cause any undesired bending of the section 660.

[0114] Referring now to FIGS. 9-13 there is shown another embodiment that includes bellows which can be bent or flexed in a controllable manner, for example, through a user interface like that shown in FIG. 1. Similar reference characters are used in FIG. 9 as those used in describing the embodiment of FIG. 5. Unlike the embodiment shown in FIG. 5, the embodiment of FIG. 9 provides a single cable (or rod) actuation that simplifies the instrument construction, particularly at the tool end of the instrument. The single actuation is possible because the flexible section has two degrees-of-freedom to provide both pitch and yaw.

[0115] In the embodiment illustrated in FIGS. 9-13, the tool 18 includes an upper grip or jaw 650 and a lower grip or jaw 652, supported from a housing 670. Each of the jaws 650, 652, as well as the housing 670, may be constructed of metal, or alternatively, the housing 670 may be constructed of a hard plastic. The housing 670 is engaged to the flexible stem section 303 with the bellows 662. The flexible stem section 303 can be a ribbed or fluted plastic construction like that shown in FIG. 4, or alternatively, the section 303 may be smooth as shown at 304 in FIG. 9.

[0116] In FIG. 9 the jaws are operated from a single push/pull cable 672 that extends through the instrument stem and through the bellows 662 of the flexible or bendable section 660. The cable is centered in the various sections as depicted in FIG. 9 so that when the bendable section is activated, no movement is transferred to the tool actuation cable. In essence, the bellows section 662 expands on one side and compresses on the other side, leaving the center portion unchanged in length, and thus not effecting the cable action. The jaws themselves are supported by a link bar arrangement shown at 675 that is appropriately secured at the distal end of the cable 672. In the position shown in FIG. 9 the jaws are open, but by pulling on the cable away from the jaws the proximal end the link bar 675 pivots and closes the jaws 650, 652.

[0117] FIG. 9 shows only the end portion of the stem section 303, i.e., the portion at 304, terminating in bending or flexing section 660. This section 660 is bent or flexed in a controllable manner usually from a remote location as depicted FIG. 1. The stem section 303 is preferably constructed to be flexible and may have either fluted or smooth outer surfaces. Also, at the bending or flexing section 660, flexibility and bending is enhanced by means of constructing this section with a bellows configuration 66 having peaks and valleys in a saw-tooth shape arrangement as illustrated in the cross-sectional view of FIG. 9. The distal end of the bending section 660 has an opening for receiving the end of the housing 670. A wall 615 is positioned at the distal end of the bellows 662.

[0118] In the embodiment shown in FIG. 9, the bending or flexing section 660 can be bent to provide both pitch and yaw degrees of motion to the tool. This is accomplished by using four cables 606, 607, 616, and 617 that are separated at 90° intervals. The operation of cables 606 and 607 provides flexing in one degree-of-freedom while another degree-of-freedom is provided by the operation of cables 616 and 617. As illustrated in FIG. 9, these cables extend through the bellows about half way between each peak and

valley of the respective bellows, and thus are parallel and near the outer periphery of the flexible section 660. Each of the cables 606, 607, 616, and 617 terminates in a respective ball end 606A, 607A, 616A, and 617A, tensioned against the end wall 615. These cables also are supported by and extend through retainer block 621. Within section 304 these cables also run near the inner surface of the outer wall of the section 304, as shown to the left in FIG. 9 where cables 616 and 617 are illustrated.

[0119] As mentioned previously, the single actuation cable 672 provides all the action that is required to operate the tool, which simplifies the construction of the instrument and makes it easier to keep the single cable centered in the instrument. To accomplish this, there is provided a supporting sleeve 680 that receives the cable 672 with a snug fit. The sleeve 680 (FIG. 10) is preferably constructed of a polyethylene plastic such as PEEK which has the flexibility to flex with bending at the section 660, but at the same time is sufficiently rigid to properly retain and hold the supported cable 672 to enable the cable to readily slide within the supporting sleeve 680 when performing its function. Sleeve 680 defines a fixed length for the cable and does not allow any expansion or compression of the cable or sleeve. The sleeve 680 may extend from the wall 615 back through the retainer block 621 and into the flexible section of the instrument, as shown in FIG. 9. Alternatively, the sleeve 680 may extend only through the section 660 and terminate at block 621.

[0120] In addition to the sleeve 680, there is provided, about the sleeve 680, a helical spring 682 having an outer diameter to allow it to fit snugly within the inner diameter of the bellows 662. Note that there is a relatively close fit between the cable 672, sleeve 680, and helical spring 682 within the bellows 662. Opposite ends of the helical spring 682 are located between the block 621 and wall 615. FIG. 10 shows the spring shape and the relationship of the helical spring to the sleeve 680 and the actuation cable 672. In FIG. 10, the coils of the spring are shown spaced apart, but they can be more closely spaced than shown or completely closed.

[0121] The spring 682 may be free-floating about the sleeve 680, and is preferably not engaged in any passage in the end supports, such as the passage in block 621. The sleeve 680, on the other hand receives the cable 672 and is fixed in position relative to block 621 and wall 615. Passages are provided in block 621 and wall 615, and a glue or other securing arrangement is preferably used to hold the sleeve fixed at the block 621 and wall 615. The spring 682 is also used as a filler or spacer between the sleeve 680 and the bellows 662 inner surface. The spring provides a fixed position spacer since it is typically a metal, and thus will maintain the centering of the sleeve/cable, and yet is also flexible enough to bend when the section 660 is bent in a controlled manner. The sleeve itself is preferably made of plastic such as PEEK which has sufficient strength to receive and guide the cable, yet is flexible enough so that it will not kink or distort, and thus keeps the cable in a proper state for activation, and defines a fixed length for the cable.

[0122] By maintaining the sleeve 680 fixed in position at the block 621 and wall 615, the cable length at the center axis of section 660 does not change when the section 660 is bent. That is, the bellows shortens on one side and expands

on the other side while keeping the center axis length unchanged. In this way when bending occurs at section 660 there is no transfer of motion to the cable 672 which could undesirably move the jaws. Hence, the bending motion is de-coupled from the tool operation motion, and vice versa.

[0123] FIG. 11 is a cross-sectional view taken along line 11-11 of FIG. 10 showing the centered cable 672, plastic sleeve 680, and the helical spring 682. FIG. 12 is a similar cross-sectional view but for an alternate embodiment using only the center cable 672 and the sleeve 680. In FIG. 12 the sleeve 680 is larger in outer diameter in comparison to the sleeve shown in FIG. 11 so that there is a proper and close fit between the sleeve and the inside of the bellows.

[0124] FIG. 13 is a cross-sectional view through another embodiment of the cable support. This embodiment also has the center cable 672 contained within the sleeve 680, but in place of the spring 682 there is instead used a spacer 681 made of, for example, plastic, to keep the sleeve and cable centered in the bellows. The spacer 681 may be constructed of a softer plastic than the sleeve 680, or may be made of a plastic foam material.

[0125] One of the benefits of the embodiment of FIG. 9 is that only a single cable is necessary to activate the tool. Recall that the pitch and yaw of the tool is controlled at the flexible wrist section 660 shown in FIG. 9. This arrangement lends itself to making the tool disposable or at the very least detachable from the instrument body so that it can be replaced with a substitute tool. A detachable embodiment of the present invention is illustrated in FIG. 14 and the companion views are shown in FIGS. 15-20. Besides being detachable this arrangement also makes it possible to provide at least a resposable and preferably a disposable instrument tip or tool.

[0126] In FIG. 14 a disposable tip is illustrated in conjunction with a flexible shaft or tube having a remotely controllable bending or flexing section 700. The medical instrument may include an elongated shaft, such as shaft section 710 shown in FIGS. 14 and 15, having proximal and distal ends, and a tool, such as graspers 702 and 704, supported from the distal end of the elongated shaft and useable in performing a medical procedure on a subject. The distal end of the elongated shaft and the tool have respective removably engaging portions that are readily engagable for positioning the tool at the distal end of the elongated shaft, and readily disengagable for removal of the tool from the distal end of the elongated shaft. The tool may be detachable to facilitate substituting another tool, or the tool may be constructed to be readily disposable. The removably engaging portions may be snap-fitted together, or, as illustrated here, may be provided by a screw interlock between the distal end of the instrument shaft and the base or housing of the tool. Also, other forms of detachable engaging portions are considered as falling within the scope of the present invention.

[0127] As shown in FIG. 14, the detachable or disposable tool is used with a flexible controllably bendable section. In another version the disposable tool can be used with a wrist pivot or even a pair of successive wrist pivots that are orthogonal to one another for providing pitch and yaw movement at the tool. The disposable tool in this version is also preferably actuated by a single actuation element, cable or the like.

[0128] In FIGS. 14 and 15, in a manner similar to that shown in FIG. 9, the tool is actuated by a single tendon or cable 736 that extends through the flexible section 700. To provide the pitch and yaw action at the tool, the bending or flexing section 700 is constructed to have orthogonal bending movements by pulling on four cables 706, 707, 716, and 717 separated at about 90° intervals, and by using a center support 726 with ribs 712 extending from the center support 726 and defining slots 714 between adjacent ribs, as depicted in FIG. 15. The ribs 712 extend from a center support 726 that has extending therethrough a passage for receiving the cable 736 positioned within a sheath 730. The ribs 712 also provide a guide structure to the four cables 706, 707, 716, and 717. The bending section 700 is a unibody construction that extends from the end of tube section 710, which itself may be flexible, and it may be smooth as shown, or may be fluted as illustrated in FIG. 4.

[0129] This version enables the bending section to be bent in orthogonal directions by the use of the four cables 706, 707, 716, and 717. The operation of cables 706 and 707 provides flexing in one degree-of-freedom while another orthogonal degree-of-freedom is provided by the operation of cables 716 and 717. Each of the cables 706, 707, 716, and 717 has at their terminating ends respective balls 706A, 707A, 716A, and 717A that may be held in corresponding recesses in a distal end wall 719 of the flexible section 700. Note that in place of the slotted bending section 700, a bellows arrangement such as shown in FIGS. 5 or 9 can be used.

[0130] The structure shown in FIGS. 14-17 preferably includes a plastic stiffener sheath or sleeve 730 that surrounds the cable 736, and that fits closely within the passage of the center support wall 726. The sleeve 730 is preferably constructed of a polyethylene plastic such as PEEK which has enough flexibility to flex with the bending section 700, but at the same time is sufficiently rigid to properly retain, center and hold the supported cable to allow the cable 736 to readily slide within the supporting sleeve 730 in performing its function. The sleeve 730 may extend from the distal end of the flex section 700, back through the passage in the wall 726, and into the shaft section 710 of the instrument, as shown in FIG. 15.

[0131] Referring to FIG. 15A there is shown an alternate embodiment for the bending section 700 in which the sleeve 730 is eliminated. In this case, the passage in the wall 726 is dimensioned to directly and snugly receive the cable 736 with a close tolerance fit but having sufficient clearance to allow the cable to readily slide in the instrument.

[0132] The grippers 702 and 704 are supported for opening and closing by the use of a pivot pin 735 that extends along axis 735A in a housing 740. Referring to FIG. 16 there is shown in partial cross-section the housing 740, pin 735, and grippers 702 and 704. The pin 735 may be supported at its ends on opposite sides of housing 740. The tool also includes a pivot linkage 742 that intercouples the grippers with the actuation cable 736 such that as the linkage is moved in the axial direction by the cable 736 to open or close the jaws (or grippers). In FIG. 15 the linkage and tool are shown in solid outline in the closed position, which corresponds to a "pulling" of the cable in a direction away from the tool. FIG. 15 also shows, in dotted outline, the linkage and grippers in an open position, which corresponds

to a "pushing" of the cable in a direction toward the tool. The grippers themselves are prevented from any axial movement by the support at pin 735, so when the linkage is operated from the cable 736 the resulting action is either opening or closing of the grippers, depending upon the direction of longitudinal translation of the actuating cable 736.

[0133] For the tool shown in FIGS. 14-17 to be detachable there is provided removably engaging portions, which in the illustrated embodiment are formed by mating threaded portions. Further, these mating portions are provided both with respect to the actuation element (cable) as well as the stationary components of the tool and tube. Thus, the tool housing has a threaded portion 746 with female threads, and the distal end of the flexible section 700, as shown in FIG. 16, has a threaded portion 748 with male threads. The end of the actuation cable 736, as shown in FIGS. 16 and 17, is terminated at block 750, passing through a center passage in the threaded portion 748. The block 750, interacting with arms 751, allows longitudinal sliding of the cable 736, but prevents rotation thereof so that the tool can be screwed onto the shaft without rotating the actuation cable. The block 750 supports a male threaded shaft 753 that is adapted to mate with the tool. The threaded portion at 753 may have twice the threads per length as the threaded portion 748. Also, the block 750 interacts with the arms as the tool is fully engaged to compensate for differences in thread pitch between the engaging members.

[0134] As previously indicated, the tool grippers are operated with the linkage 742. FIG. 17 shows the end of this linkage supporting a female threaded piece 760. To engage the tool with the instrument shaft, the female piece 760 is threaded onto the male threaded shaft 753 in the direction indicated by the rotational direction arrow 770.

[0135] Referring to FIGS. 18-20, there is shown the sequence of steps to attach the instrument tip to the shaft of the instrument. These views are somewhat schematic and are for the purpose of merely illustrating the steps taken in attaching the tool to the instrument shaft.

[0136] In FIG. 18 the tool is first illustrated with its housing 740 about to engage at threaded female piece 760 with the corresponding threaded male shaft 753. It is noted that the threads of pieces 760 and shaft 753 are finer than the threaded portions 748 and 746. Also, the threaded piece 760 and shaft 753 are designed such that only about four turns are necessary to fully seat these members together. On the other hand the sections 746 and 748 have coarser threads so that it takes, say, only about two turns to engage the two sections together. When the tool is fully engaged there is a detent arrangement provided between the interlocking members to lock them in their final position. This is shown in the drawings by interlocking tab 780 of housing 740, and recess 782 associated with the flexible section 700.

[0137] FIG. 19 illustrates the positions of the various components after two turns have occurred between threaded shaft 753 and threaded piece 760, and the other outer mating threaded sections are to engage. Next the threaded portions 746 and 748 engage and after two more turns of the tool, the tool is fully engaged with the shaft, as illustrated in FIG. 20. In that position the detents are also engaged so that the tool is, in essence, locked to the instrument shaft and ready for use. It is also noted in FIG. 20 that because of the difference in thread pitch between the fine and course threads, the block 750 is free to move inward away from the tool.

[0138] Referring now to **FIG. 21**, there is shown an embodiment having a detachable and disposable tool, and particularly adapted for application to a flexible instrument including a catheter. Features of the earlier described embodiments may be used with the embodiment of **FIG. 21**. Again, although not necessary, in a preferred embodiment the tool is operated remotely in a telerobotic manner from a user device such as shown in **FIG. 1**. The use of multiple controllably bendable segments as shown in **FIG. 21** is particularly advantageous in a flexible instrument to assist in guidance thereof such as, for example, in vessels or arteries.

[0139] **FIG. 21** shows primarily the distal end of a flexible instrument with the more proximal portions of the instrument being supported and driven in a manner similar to that illustrated in **FIGS. 1 and 2**. Rather than having only one bending or flexing section as described above, the flexible instrument **800** has two bending sections **810** and **815** spaced along the instrument shaft that are remotely actuable. In other configurations, these sections **810** and **815** can be formed directly in series, and more than two controllable segments can be used.

[0140] A tool **820** is positioned at the distal end of the instrument, and is preferably constructed to be disposable and may be substantially the same as the tool illustrated in **FIGS. 14-17** including the interengaging portions for detachability of both the tool body and the tool actuation element. As shown in **FIG. 21**, a cable **825** is used as the actuation element. Also illustrated in **FIG. 21** are instrument transition segments **830** and **835**, which may be similarly constructed as the flexible section **303** shown in **FIG. 4**. Alternatively, one or both of these sections **830, 835** may be rigid.

[0141] In each of the instrument sections shown in **FIG. 21** the actuation elements (cables) that are not used to operate a particular section run preferably through the center of the respective section to provide the proper de-coupling between the various degrees of movement. Thus, the center cable bundle **840** through the section **810** includes the cables to operate section **815** and the tool **820**.

[0142] If the two controllable sections **810** and **815** are controlled with both pitch and yaw movements, then four cables are used to actuate each section. Thus, the actuation of each section is similar to the actuation of the embodiments shown earlier in **FIGS. 5 and 9**. The aforementioned "twisting" concept is also preferably used in each of these sections **810, 815** where multiple cables are running through them, particularly in section **810** where five cables extend along the center of the section (four for actuation of the section **815** and one for tool actuation) similar to that shown in **FIG. 8**.

[0143] Thus, nine cables extend through section **830**, five in the center bundle **840** and four extending through and about the periphery of section **810** to provide the controlled bending of section **810**. **FIG. 21** shows two of these cables terminating at **812** and used to operate and move the section **810** with one degree of freedom. Two other cables (displaced about 90 degrees) also terminate at the same general area and are used to operate the bending section **810** with the other degree-of-freedom.

[0144] Next, in section **835** four cables at **836** branch outwardly and terminate at the end of section **815** at **837** to

control the flexing of section **815**. In section **815** there is thus only the single tool actuation cable **825** contained in a sheath extending through the center of the section. Although **FIG. 21** shows only two of the cables **836** for controlling one of the degrees-of-freedom of movement of the section **815**, there are two other cables (displaced about 90 degrees) that also terminate at the same location for the other degree-of-freedom of control of section **815**. Again, reference to **FIG. 8** can be made for the operation of the bending movement of the sections with the use of the cables.

[0145] The instrument shown in **FIG. 21** may be used for any number of different surgical procedures. Flexible instruments of this general type are shown in co-pending applications that have been incorporated herein by reference in their entirety. Although **FIG. 21** shows four cables that are used to actuate a respective bending section, more or fewer cables can be used in each section. For example, if only one degree-of-freedom is desired in section **810** then only two actuating cables are employed to control bending in only one plane. The instrument may also be controlled for rotation to provide another degree-of-freedom.

[0146] In the embodiment of the invention shown in **FIGS. 14-17**, the tool is readily disposable. By providing a bendable section that can control both pitch and yaw movement of the tool, the tool itself becomes actuable with a single cable or rod. Now, **FIGS. 22 and 23** disclose in a schematic manner this same disposability feature as applies to an instrument, whether flexible or rigid, that employs a wrist pivot or wrist and elbow pivot.

[0147] **FIG. 22** is a schematic diagram of the instrument illustrating both elbow and wrist pivot joints, as well as the disposable tool. **FIG. 23** shows just a wrist pivot joint with a disposable tool. More specific details of portions of the diagrams can be found in earlier embodiments described herein.

[0148] In **FIGS. 22 and 23** like reference characters are used to identify like parts. In **FIG. 22** there is provided an instrument **900** that includes both an elbow joint **905** and a wrist joint **910**. These joints allow for orthogonal motions of the various segments about respective axes **905A** and **910A**. Both of these joints are driven by cabling in a manner as described earlier, such as in the pivot arrangement shown in **FIGS. 3 and 4**. This cabling preferably runs through the center of the instrument as previously described. The instrument **900** also includes an end tool **920** driven from a cable or rod **925**. This tool construction and its actuation element may be the same as described in **FIGS. 14-17**, and would include separate interengagable/disengagable portions as previously described.

[0149] In **FIG. 23** there is shown an instrument **930** that includes only a single wrist joint **910**, along with the tool **920** actuated by means of the actuation element **925**. Again tool **920** is preferably readily detachable in the manner shown in **FIGS. 14-17** and is thus readily disposable. To provide another degree-of-freedom the instrument may be controllably rotated as indicated by the arrow **927** in **FIG. 23**.

[0150] **FIG. 24** illustrates a wrist or other joint that may be used for the joints shown **FIGS. 22 and 23**. **FIG. 24** shows a ball joint **950** with intercoupling sections **951** and **952**. An actuation cable **954** is also illustrated extending through sections **951** and **952** as well as through the middle of the

joint 950. The joint 950 may be of a conventional type using mating outer pieces at 956 that enable the sections 951 and 952 to have relative rotation therebetween. At least within the joint itself, there is provided a sheath 958 that encloses the cable 954, and that is preferably fixed in position at the top and bottom of the joint. The sheath is flexible and yet sufficiently durable so as to define a fixed length for the cable to extend through, even as the joint is actuated to rotate or pivot.

[0151] Appropriate cabling may be provided for control of the joint 950. This type of joint is particularly advantageous in that the center of the joint is open and does not interfere at all with the passing of the actuation cable 954 and sheath 958 through the joint 950. Again, by maintaining the cable at the center of the joint, as illustrated, even as the joint is actuated there is no adverse effect on the actuation cable. In other words as the joint rotates it does not change the length of the cable 954, and thus these separate actions are decoupled from each other.

[0152] Referring now to FIG. 25, a further description of a wrist or other joint is illustrated that may be used for the joints shown in FIGS. 22 and 23. FIG. 25 shows a ball joint 960 intercoupling sections 961 and 962. An actuation cable 964 is also illustrated extending through sections 961 and 962 as well as through the middle of the joint 960. Here again, the joint 960 may be a conventional joint using mating outer pieces at 966 that enable the sections 961 and 962 to have relative rotation therebetween. Within the joint itself, there may be provided a sheath that encloses the cable 964 and that may be preferably fixed in position at the top and bottom of the joint.

[0153] Appropriate cabling may be provided for control of the joint 960. In this particular joint rather than being completely open as in FIG. 24 there is provided a funnel like surface illustrated at 970 that directs the cable to an output orifice 972 where the cable is coupled into the section 962. This funnel surface 970 holds the cable such that as the sections experience relative rotation while the length of the cable within the joint is maintained at a fairly fixed length.

[0154] Other embodiments of the tool 18 are within the scope of the invention, such as that illustrated in FIGS. 26-33. A set of jaws is illustrated in the figures, but it is understood that other types of tool constructions may also be used with the concepts of the present invention. Also, the instrument shaft may be a rigid shaft, a flexible shaft, or combinations thereof.

[0155] The tool 18 includes four basic members including the base 1020, link 1021, upper grip or jaw 1022 and lower grip or jaw 1023. The base 1020 is affixed to the instrument shaft 1010. The instrument shaft 1010 may be rigid or flexible depending upon the particular use. If the shaft 1010 is flexible it may be constructed, for example, of a ribbed plastic material. A flexible shaft or section thereof would, in particular, be used in conjunction with a curved guide tube so that the instrument readily bends through the curved adaptor guide tube.

[0156] In the embodiment of FIGS. 26-33, link 1021 is rotatably connected to the base 1020 about wrist pivot axis 1025 with a wrist pivot pin at 1026. The upper and lower jaws 1022 and 1023 are rotatably connected to the link 1021 about axis 1028 with a pivot pin 1030, where axis 1028 is

essentially perpendicular to axis 1025. The jaws may also be referred to as grippers or graspers.

[0157] Six cables 1036-1041 actuate the wrist, namely the link 1021, as well as the end effector or tool 18. Cable 1036 extends through the instrument shaft and through a hole in the base 1020, wraps around curved surface 1032 on link 1021, and then attaches on link 1021 at 1034. Tension on cable 1036 rotates the link 1021, as well as the upper and lower jaws 1022 and 1023, about axis 1025. Cable 1037 provides the opposing action to cable 1036, and goes through the same routing pathway, but on the opposite side of the instrument shaft. Cable 1037 is also attached to link 1021 generally at 1034.

[0158] Cables 1038 and 1040 also travel through the instrument shaft 1030 and through holes in the base 1020. The cables 1038 and 1040 then pass between two fixed posts 1035. These posts constrain the cables to pass substantially through the axis 1025 about which the link 1021 rotates. This construction allows the link 1021 to rotate freely with minimal length changes in cables 1038-1041. In other words, the cables 1038-1041, which actuate the jaws 1022 and 1023, are essentially decoupled from the motion of link 1021. Cables 1038 and 1040 pass over rounded sections and terminate on jaws 1022 and 1023, respectively. The application of tension on cables 1038 and 1040 rotate jaws 1022 and 1023 counter-clockwise about axis 1028.

[0159] Finally, as shown in FIG. 27, the cables 1039 and 1041 pass through the same routing pathway as cables 1038 and 1040, but on the opposite side of the instrument. These cables 1039 and 1041 provide the clockwise motion to grips or jaws 1022 and 1023, respectively. The ends of cables 1038-1041 maybe secured at 1033 of the jaws 1022 and 1023.

[0160] In addition to the jaws 1022 and 1023, the tool 18 includes a rotation piece 1045, a linkage 1046 and slotted linkage 1048. The rotation piece 1045 has a centrally disposed hole 1045A that is adapted to receive the pivot pin 1030. The pivot pin 1030 also passes through holes 1023A in one jaw member and holes 1022A in the other jaw member. The pin 1030 is secured in respective holes in the arms 1029 of the link 1021 in a well-known manner to rotatably support the jaw members from the link 1021. The rotation piece 1045 also carries an actuation pin 1050 extending in the same direction as the pivot pin 1030, and parallel thereto. The actuation pin 1050 extends into curved J-shaped slots 1052 in respective jaw flanges 1054 of jaw 1023.

[0161] The actuation pin 1050 is also received by the linkage 1048 through the end hole 1048A, and the linkage is supported between the spaced flanges 1054 of the jaw 1023. At the slotted end of the linkage 1048 there is a set of holes 1048B that receive the pin 1056. The linkage 1048 also pivotally attaches with the linkage 1046 by virtue of the pin 1056 passing through the holes 1046B and 1048B. The pin 1056 is also positioned in the slots 1052 of the flanges 1054, and thus moves along the slots to different positions, two of which are illustrated in FIGS. 30 and 31. When the jaws are fully closed, the pin 1056 is at the very top of the slot 1052 as illustrated in FIG. 31. FIG. 30 shows the pin 1056 in a lower position which occurs when the jaws are partially opened. The pin 1050 likewise is in different positions in the slot 52 depending upon the position of the jaws.

[0162] The linkage 1046 is also supported at its other end at hole 1046A by the pin 1058. The pin 1058 also passes through a set of holes 1022B in the base of the jaw 1022. The linkage 1046 fits in a slot at the base of the jaw 1022, and the pin 1058 passes through both the base of the jaw 1022 as well as the linkage 1046. The pin 1058 also preferably has a compliant member such as a set of resilient members disposed about at least a portion thereof, as illustrated in FIGS. 30 and 31, at 1060, in an uncompressed position. FIG. 31 shows the resilient cups 1060 uncompressed, while FIG. 32 shows the resilient cups partially compressed when the jaws are grasping a small diameter member such as a suture S. FIG. 33 shows the cups 1060 essentially fully compressed, when the jaws are grasping a larger diameter member such as a needle N. The cups 1060 may fit about the pin 1058, and be disposed in the base of the jaw 1022. The holes 1022B that receive the cups 1060 are of somewhat elongated shape, such as illustrated in FIGS. 27A, 27B, 30, and 31.

[0163] With further reference to FIGS. 32 and 33, the jaws 1022 and 1023 apply a smaller but sufficient force to hold a smaller diameter item, such as the suture S than when holding a larger item such as a needle N. This force is primarily a function of the resiliency of the cups 1060. Thus, the larger the diameter of the item being held, the larger the corresponding holding force. The tool is constructed so that when the jaws are holding an item the size of a needle N the cups 1060 are essentially fully compressed, and a maximum grasping force is applied to the needle N. This is particularly desirable for important surgery techniques for the securing and controlling of the needle. When the jaws 1022 and 1023 first make contact with an item positioned between them, the pin 1056 is in a contact position A' (FIG. 33) for a larger item such as the needle N, or further up the slot 1052 at a position A (FIG. 32) for a smaller item such as the suture S. When a sufficient force is applied to the item with the jaws, the pin 1056 moves to a locked position B (FIGS. 32 and 33), regardless of the size of the item being grasped.

[0164] Other embodiments of the resilient members are shown in the fragmentary exploded views of FIGS. 27A and 27B. The embodiment of FIG. 27A uses a pair of cups 1060A, while the embodiment of FIG. 27B uses only a single cup. In FIGS. 27A and 27B the same reference characters are used as in FIG. 27 to identify like components. In the embodiment of FIG. 27A the cups 1060A are positioned within respective holes 1022B. They may be positioned with the use of an adhesive. The cups 1060A are thus be located at opposite ends of the pin 1058. When the jaws are in the closed position, these cups 1060A are compressed as the pin 1058 rides downwardly in the somewhat elongated hole or slot 1022B. In the embodiment of FIG. 27B the single cup 1060B is of somewhat larger shape than the cups 1060A and is located between the spaced walls of the base 1022C. The link 1046 is positioned between these walls, as is the cup 1060B. The cup 1060B may also be secured in position by an adhesive. The cup 1060B is engaged by the end of the link 1046. In this embodiment the pin 1058 also rides within the elongated slots 1022B and when the jaws are moved to a closed position the end of link 1046 bears against the cup 1060B. In still another embodiment one may use all three cups to provide additional resiliency.

[0165] The actuation cables for the end effector include the cables 1038-1041. One set of cables actuates the rotation piece 1045, while the other set of cables actuates the jaw 1023. The other jaw 1022 is actuated through the coupling provided from the rotation piece 1045 to the jaw 1022, including pin 1050 and the associated linkages 1046 and 1048 controlled via pins riding in slots 1052. These linkages provide direct drive from the rotation piece 1045 to the base of the jaw 1022, to control the pivoting motion of that jaw, controlled usually from a remote location.

[0166] Another embodiment of the tool 18 is illustrated in FIGS. 34-38, where FIG. 34 is a perspective view of the tool while FIG. 35 is an exploded perspective view showing the separate components of the tool. In this embodiment the same reference characters are used to designate similar components.

[0167] The tool 18 shown in FIGS. 34-38 includes four basic members including a base 1020, a link 1021 attached to the base, an upper grip or jaw 1022, and a lower grip or jaw 1023. The base is affixed to an instrument shaft in a manner similar to that depicted in FIG. 26. As before, the instrument shaft may be rigid or flexible depending upon the particular use.

[0168] In the embodiment shown in FIGS. 34-38, the link 1021 may be rotatably connected to the base about a wrist axis such as the axis 1025 of the just previously described embodiment. The upper and lower jaws 1022 and 1023 are rotatably connected to the link 1021 about axis 1028 with a pin 1030 that is substantially perpendicular to axis 1025.

[0169] Six cables 1036-1041 actuate the wrist, namely the link 1021, as well as the end effector or tool 18. Cable 1036 extends through the instrument shaft and through a hole in the base, wraps around curved surface 1032 on link 1021, and then attaches on link 1021 at 1034 (FIG. 35). Tension on cable 1036 rotates the link 1021, and the upper and lower jaws 1022 and 1023, about the wrist axis. Cable 1037 provides the opposing action to cable 1036, and goes through the same routing pathway, but on the opposite side of the instrument shaft. Cable 1037 is also attached to link 1021 generally at 1034.

[0170] Cables 1038 and 1040 also travel through the instrument shaft and through holes in the base. The cables 1038 and 1040 then pass between two fixed posts that are similar to the posts 1035 in FIG. 26. These posts constrain the cables so that they pass substantially through the wrist axis about which the link 1021 rotates. This construction allows the link 1021 to freely rotate with minimal length changes in cables 1038-1041. Hence, the cables 1038-1041, which actuate the jaws 1022 and 1023, are decoupled from the motion of link 1021. Cables 1038 and 1040 pass over rounded sections and terminate on jaws 1022 and 1023, respectively. The application of tension on cables 1038 and 1040 rotate jaws 1022 and 1023 counter-clockwise about axis 1028.

[0171] Finally, as shown in FIG. 35, the cables 1039 and 1041 pass through the same routing pathway as cables 1038 and 1040, but on the opposite side of the instrument. These cables 1039 and 1041 provide the clockwise motion to jaws 1022 and 1023, respectively. The ends of cables 1038-1041 are secured at 1033 of the jaws 1022 and 1023.

[0172] In addition to the jaws 1022 and 1023, the tool 18 includes the rotation piece 1045, along with linkage pair

1066 and straight linkage **1068**. The rotation piece **1045** has a central hole **1045A** that receives the pivot pin **1030**. The pivot pin **1030** also passes through holes **1023A** in one jaw member and hole **1022A** in the other jaw member. The pin **1030** is secured to respective holes in the arms **1029** of the link **1021** to rotatably support the jaw members from the link **1021**. The rotation piece **1045** also carries an actuation pin **1050** extending in the same direction as the pivot pin **1030**, and parallel thereto. The actuation pin **1050** extends into curved slots **1052** in respective jaw flanges **1054** of jaw **1023**, as shown in **FIGS. 35, 37, and 38**.

[0173] The actuation pin **1050** is also received through an end hole **1068A** of the linkage **1068**, and the linkage is supported between the spaced flanges **1054** of the jaw **1023**. At the other end of the linkage **1068** there is a hole **1068B** that receives the pin **1076**. The linkage **1068** also pivotally attaches with the linkage pair **1066** by virtue of the pin **1076** passing through the holes **1066B** and **1068B**. The pin **1076** is also positioned in the slots **1052** of the flanges **1054**, and thus moves along the slots to different positions, two of which are illustrated in **FIGS. 37 and 38**. When the jaws are in a substantially closed position, the pin **1076** is at the top of the slot **1052** as illustrated in **FIG. 37**. When the jaws are in other positions, the pin **1050** will reside in different positions in the slot **1052**.

[0174] The linkages **1066** are also supported at its other ends at holes **1066A** the pin **1078**. The pin **1078** also passes through a hole **1022B** in the base of the jaw **1022**. At that point the base has a support wall **1022D** in which the hole **1022B** is located. The linkage pair **1066** fits on opposite sides of the wall **1022D**, and the pin **1078** passes through both the base of the jaw **1022** as well as the linkage pair **1066**.

[0175] The actuation cables for the end effector or tool include the cables **1038-1041**. One set of cables actuates the rotation piece **1045**, while the other set of cables actuates the jaw **1023**. The other jaw **1022** is actuated through the coupling provided from the rotation piece **1045** to the jaw **1022**, including pin **1050** and the associated linkages **1046** and **1048** riding in slots **1052**. These linkages provide direct drive from the rotation piece **1045** to the base of the jaw **1022**, to control the pivoting motion of that jaw, typically from a remote location.

[0176] In the embodiment shown in **FIGS. 35-38**, control of the grasping force on an item is provided primarily by means of a slot or gap in one of the jaws. This is illustrated in **FIGS. 34-38** by the gap **1031** located near the base **1022C** in the jaw **1022**. **FIGS. 35, 37, and 38** show in particular the shape and depth of the gap **1031**. The gap **1031** is located above a hinge **1044** where the jaw can deflect when grasping and holding an item, regardless of its size, and with a firm grasping force. The gap **1031** may be terminated in a tubular passage **1031A** to enhance the hinging effect of the hinge **1044**. Hence the hinge **1044** acts as a compliance member similar to the resilient members **1060** described with reference to **FIGS. 27-33**.

[0177] Referring now in particular to **FIGS. 37 and 38**, the jaws **1022, 1023** are shown in a substantially closed position in **FIG. 37** grasping a suture **S**. In that position it is noted that both of the pins **1050** and **1076** are substantially at their top transition locations. **FIG. 38** illustrates the jaws **1022, 1023** grasping an item such as a needle **N** that causes

the jaw **1022** to flex and consequently the gap **31** to close up. This flexure enables the application of a varied grasping force at the tip of the jaws. When the links are at the end of their travel, the jaw **1022** flexes when the jaws **1022, 1023** grasp an item. The amount of flexure depends on the diameter of the item being grasped. Thus, the jaws **1022** flexes to a lesser extent when a smaller diameter item such as a suture **S** is being grasped then when a larger item such as a needle **N** is being held. That is, to grasp a smaller item, the gap **1031** closes to a lesser extent, while the jaws still apply a sufficient holding force to the item. This force is primarily a function of the resiliency at the gap, as defined primarily by the flexure capability at the hinge **1044**. The larger the diameter of the item being held, the larger the corresponding holding force. The tool is constructed so that, for an item the size of a needle, as shown in **FIG. 38**, the gap **1031** is fully closed with the sides of the top of the gap touching, with a maximum grasping force being applied to the needle **N**. This is particularly desirable for the securing and controlling of the needle in important surgery techniques. Here again, the pin **1076** is at a contact position **A'** (**FIG. 38**) when the jaws first make contact with a larger item such as the needle **N**, or further up the slot **1052** at a contact position **A** (**FIG. 37**) when the jaws contact a smaller item such as the suture **S**. Regardless of the size of the item, the pin moves to a locked position **B** (**FIGS. 37 and 38**) when the sufficient force is applied to lock the jaws onto the item.

[0178] In connection with both of the embodiments described in respective **FIG. 26-33**, and **FIGS. 34-38**, there has been described a "locked" position **B** of the pins or jaws. This locked position corresponds to a position wherein the linkages are disposed at right angles to each other. In other words, for example, in **FIG. 31** in that locked position the linkages **1046** and **1048** are disposed at right angles (90 degrees) to each other. This provides virtually infinite grasping force with essentially no back drive at the jaws. Regarding the embodiment in **FIGS. 34-38** it would be the linkages **1066** and **1068** that are disposed at right angles when locked.

[0179] Reference is now made to another embodiment of the invention illustrated in **FIGS. 39 and 40**. This embodiment has a structure very similar to that described in detail in **FIGS. 26-33**. However, in place of the resilient cup **1060** there is provided a modified jaw slot configuration. As indicated previously the slots **1052** in jaw **1023** have a curved segment **1052A**, and a straight segment **1052B**. In this embodiment the J-slots **1052** also have a contiguous end slot **1052C** that extends back toward the tip of the jaw tip. Hence, the overall slot configuration is C-shaped. In **FIG. 39** the jaws are in a substantially open position with a gap **G1** as noted when the jaw members **1022, 1023** are locked onto and the needle **N**, with the pin **1056** located at a locked position **B**. Before the jaws make contact with the needle **N**, the pin **1056** may be out of the end slot **1052C**, and the pins **1050** and **1056** are located at different positions along the slots **1052** depending upon the degree of openness of the jaws. When the jaws contact the needle **N**, the pin **1056** is at a contact position **A'**. In **FIG. 40** the jaws are in a substantially closed position with a small gap **G2** as the jaws grasp a smaller item such as a suture **S**. In this position the pin **1056** now moves further into the end slots **1052C** to the locked position **B**, as the jaws apply a grasping force to an item to lock the suture between the jaws. When contact is first made between the jaws and the suture, the pin **1056** is

located at the contact position A further up the slot 1052 than the contact position A' of FIG. 39. Thus, depending upon the size thereof, the pin 1056 moves to a greater or lesser extent into the slots 1052C.

[0180] To hold a large diameter item such as a needle, the pins 1050 and 1056 are in the position illustrated in FIG. 39 with there being a maximum grasping force applied to the item by virtue of the links 1046 and 1048 being positioned at 90 degrees relative to each other. For smaller diameter items such as a suture, the pins rotate slightly further clockwise with the pin 1056 moving into the slot 1052C as illustrated in FIG. 40. When the pin 1056 moves into the slot 1052C, the jaw and linkages move together as a rigid body while closing against the suture.

[0181] In sum the slots 1052C, like the resilient member 1060 (FIGS. 27-33) and the hinge 1044 (FIGS. 37 and 38), are accommodating mechanisms that allow a closing force to be applied to grasped items of different sizes as the force is applied to the grasped item as the jaws close to a position at which the jaws remain open.

[0182] The accommodating mechanisms described above like the slots 1052C (FIGS. 39 and 40), the resilient member 1060 (FIGS. 27-33), and the hinge 1044 (FIGS. 37 and 38), can be implemented in other types of grasping mechanisms as well, such as those described in U.S. application Ser. No. 09/827,643, filed Apr. 6, 2001, and U.S. application Ser. No. 10/014,143, filed Nov. 16, 2001, the entire contents of which are incorporated herein by reference.

[0183] In each of the aforementioned embodiments described herein the medical instrument includes a jaw or work members controlled by a drive mechanism that is used to open and close the jaws or work members for applying an increased force to an item grasped between the jaws or work members. The accommodating mechanisms described above such as the slots 1052C (FIGS. 39 and 40), the resilient member 1060 (FIGS. 27-33), and the hinge 1044 (FIGS. 37 and 38), each have the characteristic of providing a maximum grasping force at what may be considered a maximum grasping position. This corresponds to the positions illustrated, and discussed previously, in FIGS. 33, 38, and 39. In each of the embodiments the instrument is constructed so that this maximum position corresponds to a predetermined size or diameter items that is to be grasped, usually a needle in this case. For item smaller or larger than this size the grasping force is progressively less. In the instance of the embodiment of FIGS. 26-33, for smaller items such as the suture S, the force is less because the compliant member is compressed less. For the case of an item larger than the needle N, the linkage does not go to the top of the J-slot and thus the applied force is also less in that case, as the linkages are not yet to a maximum force 90 degree position.

[0184] In all three of the described embodiments the accommodating mechanism allows the jaws or work members to be closed beyond this maximum grasping position in order to grasp items of various sizes, particularly smaller size items. Again, this is illustrated by way of example in FIG. 32 where the jaws go past their maximum grasping position, closing to a closer position therebetween, in grasping the suture S. In FIG. 37 this is illustrated by the jaws closing to grasp the suture S with less force being imposed by the flexure at the jaw 1022. This is also illustrated in

FIGS. 39 and 40. In FIG. 39 the jaws are at their maximum grasping position. In FIG. 40 the jaws are closed beyond this maximum grasping position to grasp the smaller size suture S. The accommodating mechanism in this case may be considered as including the slot segment 1052C that enables further rotation of the linkages to the position illustrated in FIG. 40.

[0185] Other embodiments of the flexible or bending segment are within the scope of the invention. For example, there is shown in FIGS. 41-47 another embodiment of a flexible or bending segment with a unibody construction which can be used with any suitable end effector like the tools 18 described above, whether used with a rigid shaft body or a flexible shaft body or combinations thereof. As with some of the embodiments described earlier, one of the benefits of the embodiment shown in FIGS. 41-47 is that only a single cable 1136 needs to be coupled to the tool 18 to actuate it. The pitch and yaw of the tool 18 is controlled at the flexible section 1100 shown in FIG. 41. This arrangement also lends itself to making the tool disposable or at the very least detachable from the instrument body to facilitate substituting another tool. Here again, because of the simplified construction at the tip of the instrument, a tool can be constructed that is readily detachable from the instrument.

[0186] Although the bendable section 1100 is depicted near the tool, the bendable section can be located at other locations further away from the tool. Since the tool 18 of the embodiment shown in FIGS. 41-47 requires only a single actuation cable, it is simpler to operate than the wrist/tool combination shown in FIGS. 26 and 27. Recall, in the wrist arrangement, a pivot axis does not accommodate single cable actuation. Thus, with the wrist unit one has to use a far more complex cabling scheme, such as, by way of example, the cabling arrangement illustrated in U.S. Pat. Nos. 6,312,435 and 6,206,903. Furthermore, the single cable actuation provides a more simplified design that readily lends itself to a variety of tool constructions.

[0187] In order for the various degrees of motions to be decoupled from each other, and for the proper overall functioning of the distal end of the instrument, the instrument has certain preferred characteristics, particularly at the flexible or bendable section of the instrument shaft. These characteristics are listed below but are not in any particular order of significance. Embodiments can employ at least one of these characteristics. Furthermore, although these characteristics are listed with reference to the embodiment described in FIGS. 41-44, one or more of the characteristics can apply as well to any of the other embodiments described earlier.

[0188] A first characteristic is that the actuation element for the tool be centered in the flexible or bendable section. In this way, during any bending operation the center of the flexible or bendable section tends to maintain the same length, even though opposed outer surfaces of the section may, respectively, expand and contract. This, in essence, means that the bending action is not erroneously transferred to the actuation element for the tool, hence, de-coupling the bending operation from the tool actuation, and vice versa.

[0189] A second characteristic is that the flexible or bendable section of the instrument shaft be readily flexible without the application of undue force. This bendable section, in a preferred embodiment, is to have orthogonal

bending characteristics, hence providing two degrees of freedom (DOF) to the distal tool, for example, yaw and pitch. To accomplish this, at a particular bend location, a substantial portion of the flexible or bendable section is located as near to the center neutral axis **1111** of the section as physically possible. This is achieved by the spaced rib construction including the ribs **1112** shown in the drawings. The slots **1114** defined by these ribs **1112** provide void areas, leaving more material near the center neutral axis, as depicted in **FIG. 45**. Reference has been made to a neutral axis **1111** of the bendable section **1100**. In actuality there is for a particular bend direction a neutral plane that during a bend is maintained at a fixed length.

[0190] A third characteristic relates to the torsional nature of the flexible or bendable section. The more stiff the section is torsionally (twisting moment) the less likely there will be an undesired twisting of the bendable section that accompanies controlled rotation thereof. In other words, if the bendable section is torsionally stiff, then upon controlled rotation of the instrument shaft, there is no an undesired twisting action imparted on the shaft particularly at the flexible or bendable section **1100**. To accomplish this, at a particular bend location, a substantial portion of the material forming the flexible or bendable section is located at the periphery of the flexible or bendable section. This may be achieved by having portions of the section extend to an outer surface. In the embodiment described here this is accomplished by providing radial ridges, such as the ridges **1120** shown in the drawings. Furthermore, these ridges are alternated between horizontal and vertical positions to, at the same time, to provide the orthogonal bending or flexing.

[0191] A fourth characteristic is that the flexible or bendable section of the instrument shaft is constructed so that there is little or no end-to-end compression. In other words, the flexible or bendable section maintains a relatively constant length regardless of the motion actuations that occur in the multiple degrees of freedom movement of the instrument. To accomplish this, a stiff member is provided to maintain the ends of the flexible or bendable section at a fixed spacing. This may be achieved by providing the stiff member as a centrally located stiff sleeve that receives and supports the sliding motion of the actuation element for operation of the distal tool. This stiff member is preferably fixed at its opposite ends to the bendable section to maintain the fixed length of the section, thereby preventing end-to-end compression. At least part of this member may include the sleeve **1182** depicted in **FIG. 43**.

[0192] Referring again to **FIG. 41** there is disclosed one embodiment of the tool **18**, used in conjunction with a flexible shaft or tube having a remotely controllable bending or flexing section **1100**. The medical instrument may include an elongated shaft, such as shaft section **1110** shown in **FIGS. 41 and 42**, having proximal and distal ends; and the tool **18** with jaws **102** and **104**, supported from the distal end of the elongated shaft and useable in performing a medical procedure on a subject. In **FIGS. 42 and 43** the tool **18** is actuated preferably by a single tendon or cable **1136** that extends through the flexible section **1100**. In order to provide the pitch and yaw action at the tool, the bending or flexing section **1100** is constructed to bend in orthogonal directions with the use of four cables separated at about 90° intervals and by using a center support with ribs and slots about the entire periphery of the bending section **1100**, as depicted in

FIGS. 42-44. This orthogonal bending may also be referred to as bi-axial bending, meaning bending in separate axes. The ribs **1112** define corresponding slots **1114**, and also define at each of their centers a center support passage **1118** that has the cable **1136** extending through it, as well as other cable support members described in further detail later. The bending section **1100** extends from the end of tube section **1110**, which itself may be flexible, may be smooth as shown, or may be fluted, and may have other controllable bending sections disposed along its length.

[0193] To bend the bending section **1100** in orthogonal directions, use is made of the four cables **1106**, **1107**, **1116** and **1117**. The operation of cables **1106** and **1107** provides flexing in one degree-of-freedom while an added orthogonal degree-of-freedom is provided by operation of cables **1116** and **1117**. Each of the cables **1106**, **1107**, **1116**, and **1117** have at their terminating ends respective balls **1106A**, **1107A**, **1116A**, and **1117A** that may be held in corresponding recesses in a distal end wall **1119** (**FIG. 45**) of the flexible section **1100**.

[0194] The bending section **1100**, as indicated previously, includes a series of spaced ribs **1112** positioned, in parallel, with the plane of each rib extending orthogonal to the neutral axis **1111** of the section **1100**. At the proximal end of the bendable section, an end rib connects to the shaft section **1110**, while at the distal end there is provided the distal end wall **1119** that supports the ends of the cables. Each of the ribs **1112** are held in spaced relationship by means of the alternating ridges **1120**. As depicted in **FIG. 43** these ridges are identified as horizontal ridges **1120A**, alternating with vertical ridges **1120B**. This structure provides support at the center passage for the actuating cable **1136**, while also providing torsional strength to prevent undesired twisting at the shaft section **1100**.

[0195] The jaws **1102** and **1104** are supported for opening and closing by means of a pivot pin **1135** that extends along a pivot axis. These grippers may be supported in link **1140**, and the pin **1135** may be supported at its ends in opposite sides of link **1140**. The tool also includes a pivot linkage **1142** that intercouple between the grippers and the actuation cable **1136**. The pivot linkage **1142** includes linkages **1142A** and **1142B**. At one end, each of the linkages **1142A** and **1142B** connects to respective jaws **1104** and **1102**. At the other end, the linkages **1142A** and **1142B** are pivotally supported at end **1137** of cable **1136**. Opposed pins extend from end **1137** for engagement with the linkages **1142A** and **1142B**. The jaws **1102** and **1104** are shown having recesses **1102A** and **1104A** for accommodating the respective linkages **1142B** and **1142A**.

[0196] In **FIG. 42** the jaws **1102** and **1104** are shown in their open position with the linkages **1142A** and **1142B** shown in a forward pivoted configuration. **FIG. 43** illustrates the jaws **1102** and **1104** in a closed position with the linkages **1142A** and **1142B** shown in an in-line configuration. As the linkage **1142** is moved in an axial direction by the cable **1136**, this action opens and closes the jaws or grippers. This corresponds to a "pushing" of the cable in a direction toward the tool. **FIG. 43**, on the other hand, shows the linkage and grippers in a closed position. This corresponds to a "pulling" of the cable in a direction away from the tool with the specific linkages **1142A** and **1142B** shown in an in-line configuration in their final closed position. The

grippers themselves are prevented from any axial movement by the support at pin 1135, so when the linkage is operated from the cable 1136 the resulting action is either opening or closing of the grippers, depending upon the direction of forward-to-back translation of the actuating cable 1136.

[0197] The structure shown in FIGS. 41-47 preferably also includes a plastic cable sheath 1180, a plastic stiffener sheath or sleeve 1182 that surrounds the cable 1136 and the sheath 1180, and that fits closely in the center passage 1118, and an outer silicon spacer 1184. The sleeve 1182 is preferably constructed of a polyethylene plastic such as PEEK which has flexibility to allow the sleeve 1182 to bend with the section 1100, but at the same time is sufficiently stiff (particularly end-to-end) to properly retain, center and hold the supported cable to enable the cable to readily slide within the sheath 1180 and the supporting sleeve 1182, in performing its function. In FIG. 42 the sleeve 1182 is illustrated extending from the distal end of the bendable section 1100, back through the passage, to the more proximal end of the bendable section 1100.

[0198] Reference has been made previously to the single actuation cable 1136 that provides all the action that is required to operate the tool. This greatly simplifies the construction and makes it easier to keep the single cable centered in the instrument. As indicated previously this centering feature maintains the same length of the actuation element, even though opposed outer surfaces of the section itself may, respectively, expand and contract during bending. This, in essence, means that the bending action is not erroneously transferred to the actuation element, hence, the bending operation is de-coupled from tool actuation, and vice versa.

[0199] FIGS. 42 and 43 also show the use of an adhesive, at 1186, such an epoxy adhesive for anchoring opposite ends of the sheath 1180 and the sleeve 1182 to opposite ends of the bendable section 1100. By maintaining the sheath 1180 and sleeve 1182 fixed in position at their ends, when the section 1100 is controlled to bend, the cable length at the center or neutral axis of section 1100 does not change. Furthermore, at the ribbed bendable section, on one side the section shortens and on the other side it expands while keeping the center or neutral axis length unchanged. In this way when bending occurs at section 1100 there is no transfer of motion to the cable 1136 which could undesirably move the jaws. The bending motion is thus de-coupled from the tool operation motion, and vice versa.

[0200] Other features of the bending section are shown in FIG. 45 in a side elevation view, while FIGS. 46 and 47 illustrate cross-sectional views, with one through one of the ridges 1120A and the other through one of the ridges 1120B. The respective ridges 1120A and 1120B are arranged at about 90 degrees to each other.

[0201] As described earlier, the section 1100 is easily bendable while being torsionally stiff, and has other improved characteristics as well. Details of these characteristics are best described with reference to FIGS. 45-47 by considering a particular cross-section such as the cross-section in FIG. 45 taken along line 46-46. In viewing FIG. 45 it is clear that, at that location and with the orientation of the section 1100 as shown, there is a substantial void created by the slot 1114, so that the majority of the section material is located at the center of the section. This is consistent with

the desired bendability at that location, since, in general, a structure becomes more bendable as its diameter decreases. The void area mentioned is also illustrated in the cross-sectional view of FIG. 46 at 1115.

[0202] To understand how the bending section 1100 can be torsionally stiff while also being bendable, reference is also made to the same location at the line 46-46, but with the section rotated through 90 degrees. This is the same as looking at the cross-sectional view depicted in FIG. 47. In other words, one is thus considering the location through the ridge 1120A. The section 1100 is constructed so that there is preferably a relatively large center passage 1118, leaving more material toward the outer periphery, which is desired for providing enhanced torsional stiffness. Note that this material is the material of the ridge itself. Thus, for torsional stiffness it is desired to have a void near the middle and more material located away from the middle.

[0203] The rib and ridge arrangement shown in the drawings thus provides in a single structure a bendable section that provides two degrees of freedom (biaxial motion) that is also torsionally stiff. The bending characteristics enable the transfer of two degrees of freedom to the tool, rather than just one degree of freedom as with a conventional wrist joint. The torsional stiffness enables direct rotational transfer to the tool through the bendable section and without any twisting at the bendable section.

[0204] Mention has been made previously of the four characteristics of the bendable section described herein. The first characteristic relates to the centering of the actuation element. This is carried out primarily with the use of the center passage and the associated sheath 1180, sleeve 1182, and the spacer 1184. The second characteristic relates to the ease of bending. This is accomplished primarily with the ribbed construction with void peripheral areas. The third characteristic relates to the torsion stiffness that is accomplished primarily by the alternating ridges. Lastly, the fourth characteristic relates to the end-to-end compression. To prevent the bendable section from compressing from end-to-end during an operation, particularly during tool actuation, to facilitate proper tool operation, the center passage is provided with the stiff sleeve 1182, and the opposite ends of the sheath 1180 and sleeve 1182 fixed in place, and the section 1100 has a ridged construction.

[0205] It is noted that FIGS. 41-47 disclose one version of an end effector employing jaws 1102 and 1104, in combination with, linkage 1142. However, other tool constructions are also contemplated as falling within the scope of the present invention including ones that provide a mechanical advantage at the tip of the jaws or other work elements.

[0206] Also, in various embodiments described herein only a single cable is used for tool actuation. (See, for example, FIGS. 9, 15, and 42.) In these embodiments it is preferable to provide at least the opposite ends of the actuation cables with enhanced stiffness, particularly where the cable is unsupported. For example, in FIG. 42 this might be in the distal section of cable 1136 exiting from wall 1119 to the jaws of the tool. This stiffness can be provided by treating the ends of the cable with a harder metal coating, or by other means that will provide a stiffer end section.

[0207] Turning now to FIGS. 48A-48D, there is illustrated yet another embodiment of a flexible section 1660 with a

unibody construction. The tool **18** attached to the distal end of the flexible section **1660** includes an upper grip or jaw **1602** and a lower grip or jaw **603**, supported from a link **1601**. Each of the jaws **1602**, **1603**, as well as the link **1601**, may be constructed of metal, or alternatively, the link **1601** may be constructed of a hard plastic. The link **1601** is engaged with the distal end of the flexible stem section **1302**. FIG. 48C shows the distal end of the stem section **1302**, terminating in a bending or flexing section **1660**. Also, at the flexible section **1660**, flexing and bending is enhanced by the arrangement of diametrically-disposed slots **1662** that define ribs **1664** between the slots. The flexible section **1660** also has a longitudinally extending wall **1665**, through which cabling extends, particularly for the operation of the tool jaws. The wall **1665** can also be thought of as opposed ridges that extend outward from the center of the flexible section **1660**. The very distal end of the bending section **1660** terminates with an opening **1666** for receiving the end **1668** of the link **1601**. The cabling **1608-1611** is preferably at the center of the flex section at wall **1665** to effectively decouple flex or bending motions from tool motions.

[0208] To operate the tool, reference is made to the cables **1608**, **1609**, **1610**, and **1611**. All of these cablings extend through the flexible stem section and also through the wall **1665** as illustrated in FIG. 48C. The cables extend to the respective jaws **1602**, **1603** for controlling operation thereof in a manner similar to that described previously in connection with FIGS. 5-8. FIGS. 48A-48D also show cables **1606** and **1607** which couple through the bending section **1660** and terminate at ball ends **1606A** and **1607A**, respectively, and urge against the end of the bendable section in opening **1666**. When these cables are pulled individually, they can cause a bending of the wrist at the bending or flexing section **1660**. FIG. 48D illustrates the cable **1607** having been pulled in the direction of arrow **1670** so as to flex the section **1660** as depicted in the figure. Pulling on the other cable **1606** causes a bending in the opposite direction.

[0209] By virtue of the slots **1662** forming the ribs **1664**, there is provided a structure that bends quite easily, while the wall or opposed ridges **1665** provide some torsional rigidity to the flexing section **1660**. The wall **1665** bends by compressing at the slots in the manner illustrated in FIG. 48D. This construction eliminates the need for a wrist pin or hinge.

[0210] The embodiment illustrated in FIG. 48B has a separate link **1601**. However, in an alternate embodiment, this link **1601** may be fabricated integrally with, and as part of, the bending section **1660**. For this purpose the link **1601** would then be constructed of a relatively hard plastic rather than the metal link as illustrated in FIG. 48B and would be integral with section **1660**.

[0211] Mention has also been made of various forms of tools that can be used. The tool may include a variety of articulated tools such as: jaws, scissors, graspers, needle holders, micro dissectors, staple appliers, tackers, suction irrigation tools and clip appliers. In addition, the tool may include a non-articulated tool such as: a cutting blade, probe, irrigator, catheter or suction orifice. Moreover, the bending section itself may be non-actuated. As such, even when the bending movements of the bending section are not controlled by a surgeon, the one or more degrees-of-freedom of

movement of the bending section allows it to conform to orifices or lumens within the patient's body as the section is advanced through the body.

[0212] There have been described herein a number of different embodiments of bendable sections such as in FIGS. 5, 14, 21, or 41. These may be used, as illustrated herein, in conjunction with instrument systems as described in, for example, FIG. 1 where the instrument is inserted laparoscopically. Alternatively, these concepts may also be used in flexible instrument systems more like that described in FIG. 21 wherein the bendable sections can be located at various positions along the instrument shaft or body. In this case the bendable section or sections may be used both for guidance toward an operative site, such as for guidance through an anatomic lumen or vessel, or for operation or manipulation at an operative site. In the more rigid system where the instrument is meant to enter the body, for example, through an incision, such as laparoscopically, then it is preferred to have the bendable section located close to but just proximal of the distal end effector or tool. This bendable section positioning provides for proper manipulation of the tool at the operative site. In this case the bendable section preferably has a length in a range on the order of $\frac{3}{4}$ inch to 4 inches. Also, the distance between the tool pivot point and the distal end of the bendable section is preferably equal to or less than the length of the bendable section.

[0213] Referring to FIG. 49, an example of a flexible instrument **2000** is shown in use in a stomach **2002** of a patient. The instrument **2000** includes an elongated portion **2004**, which itself is flexible, and an articulated bendable section **2006**. Any embodiments of the tool **18** described can be mounted at the terminal end of the bendable section **2006**. The bendable section **2006** can be any one of the different embodiments described earlier such as those shown in FIGS. 5, 14, 21, or 41. In operation, the flexible instrument **2000** is inserted through a body lumen such as the esophagus **2008**, and the tool **18** is directed to the operative site **2009**. As shown, the instrument **2000** can lean against some element of the anatomy such as a wall **2010** of the stomach to brace the instrument during the medical procedure, while the bendable section **2006** and the tool **18** are articulated as described above.

[0214] In certain implementations, as shown in FIG. 50A, a flexible instrument **2100** may include a bendable section **2102** that can be operated with one or more pull cables **2104** to manipulate the tip **2106** of the bendable section. The tip **2106** may be provided with an embodiment of the tool **18** described above that is positioned at the operative site to perform a medical procedure. At least one cable **2104** is attached at or near the tip **2106** of the bendable section **2102**, and extends from its point of attachment through an aperture **2108** at a position spaced a selected distance along the length of the bendable section **2102** away from the distal end. The remainder of the cable **2109** extends from the aperture **2108** through a shaft **2110** of the instrument **2100** and is coupled, for example, to a drive unit **8**, like that described earlier, that applies a tension to the cable **2104** to controllably bend the bendable section **2102**.

[0215] The bendable section **2102** may have a circular cross section, or in some embodiments, the bendable section is provided with one or more grooves or valleys **2112** (FIG. 50B) along its length. As such, while the instrument **2100** is

inserted into the patient, the cables **2104** lie along the grooves **2112**, which prevents the cables **2104** from inadvertently catching any body element. As appropriate tension is applied to a particular cable, it effectively “pops” out of the groove **2112** as the tip of the bendable section **2102** is pulled towards the aperture **2108**. For certain embodiments of the tool **18**, the bendable section **2102** is provided with a center tube **2114** through which the actuation element for the tool **18** extends.

[0216] While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims. For example, mention has been made of the bi-axial bending of the bendable section of the instrument. However, the principles of the present invention may also apply to a bendable section that has only one degree-of-freedom, in which case the bendable section would only be controlled by one set of control cables rather than the two sets described earlier.

[0217] This invention can be implemented and combined with other applications, systems, and apparatuses, for example, those discussed in greater detail in U.S. Provisional Application No. 60/332,287, filed Nov. 21, 2001, the entire contents of which are incorporated herein by reference, as well as those discussed in greater detail in each of the following documents, all of which are incorporated herein by reference in their entirety:

[0218] U.S. Pat. Nos. 6,197,017 and 6,432,112, PCT application Serial No. PCT/US00/12553 filed May 9, 2000, and U.S. application Ser. Nos. 09/827,643 filed Apr. 6, 2001, 10/034,871 filed Dec. 21, 2001, 10/270,741 file Oct. 11, 2002, 10/270,743 filed Oct. 11, 2002, 10/270,740 filed Oct. 11, 2002, 10/077,233 filed Feb. 15, 2002, and 10/097,923 filed Mar. 15, 2002.

What is claimed is:

1. A robotically controlled medical instrument comprising:

- a bending section having a unibody construction, and being bendable with at least one degree-of-freedom;
- a tool supported at a distal end of the bending section for performing a medical procedure on a subject; and
- an electronic controller that controls the bending section to provide the at least one degree-of-freedom of movement.

2. The medical instrument of claim 1 further comprising a first pair of cables extending along the length of the bending section, tension being applied to at least one of the first pair of cables to operate the bending section with one degree-of-freedom.

3. The medical instrument of claim 2 further comprising a second pair of cables extending along the length of the bending section, tension being applied to at least one of the second pair of cables to operate the bending section with a second degree-of-freedom.

4. The medical instrument of claim 3 wherein the amount of tension being applied to the respective cables is controlled with the controller coupled with an input device operated by a user.

5. The medical instrument of claim 2 wherein the tool is movable with at least two additional degrees-of-freedom.

6. The medical instrument of claim 5 wherein the tool includes a first jaw and a second jaw connected to the first jaw at a pivot joint, the first jaw being movable with one of the two additional degrees-of-freedom and the second jaw being movable with the other of the two additional degrees-of-freedom.

7. The medical instrument of claim 6 comprising a second pair of cables and a third pair of cables extending along the length of the bending section and coupled to the first jaw and second jaws, respectively, tension being applied to at least one of the second pair of cables to operate the first jaw, and to at least one of the third pair of cables to operate the second jaw.

8. The medical instrument of claim 7 wherein the second and third pair of cables are positioned near the longitudinal axis of the bending section.

9. The medical instrument of claim 8 wherein the second and third pair of cables are contained in a sleeve positioned along the longitudinal axis of the bending section, the second and third pair of cables being able to slide along the sleeve.

10. The medical instrument of claim 7 wherein the amount of tension being applied to the respective cables of the second and third pair of cables is controlled with the controller coupled with an input device operated by a user.

11. The medical instrument of claim 2 wherein the tool includes a first jaw and a second jaw connected to the first jaw at a pivot joint such that the first and second jaws open and close.

12. The medical instrument of claim 11 further comprising an actuation element extending along the length of the bending section and coupled to the first and second jaws to operate the first and second jaws.

13. The medical instrument of claim 12 wherein the actuation element is a single cable, the single cable being coupled to the first and second jaws with a pair of linkages, the first and second jaws being closed by pulling on the single cable and being opened by pushing on the single cable.

14. The medical instrument of claim 13 wherein the single cable is positioned near the longitudinal axis of the bending section.

15. The medical instrument of claim 14 wherein the single cable is contained in a sleeve positioned along the longitudinal axis of the bending section, the single cable being able to slide back and forth along the sleeve.

16. The medical instrument of claim 15 further comprising a helical spring positioned about the sleeve along the length of the bending section to keep the sleeve and single cable near the longitudinal axis of the bending section.

17. The medical instrument of claim 13 wherein the amount of pushing and pulling on the single cable is controlled with the controller coupled with an input device operated by a user.

18. The medical instrument of claim 1 wherein the bending section has a bellows construction with alternating peaks and valleys positioned between proximal and distal ends of the bending section.

19. The medical instrument of claim 1 wherein the bending section has a series of spaced ribs positioned along the length of the bending section between proximal and distal ends of the bending section.

20. The medical instrument of claim 19 wherein the bending section includes a set of opposed ridges extending along the length of the bending section, the individual ridges of the set of ridges being positioned in a respective slot defined by adjacent ribs.

21. The medical instrument of claim 19 wherein the bending section includes a first set of ridges extending along the length of the bending section, the individual ridges of the first set of ridges being positioned in every other slot defined between adjacent ribs, and a second set of ridges, the individual ridges of the second set of ridges being positioned in respective slots unoccupied by the first set of ridges.

22. The medical instrument of claim 21 wherein the first set of ridges is positioned at about 90 degrees from the second set of ridges about the longitudinal axis of the bending section.

23. The medical instrument of claim 1 further comprising a second bending section with a unibody construction, and being bendable with at least one degree-of-freedom.

24. A robotically controlled medical instrument comprising:

- a bending section being bendable with two degrees-of-freedom and having a unibody construction with a series of spaced ribs, the ribs being positioned along the length of the bending between proximal and distal ends of the bending section, the bending section including a first set of ridges extending along the length of the bending section, the individual ridges of the first set of ridges being positioned in every other slot defined between adjacent ribs, and a second set of ridges, the individual ridges of the second set of ridges being positioned in respective slots unoccupied by the first set of ridges;

- a first pair of cables and a second pair of cables extending along the length of the bending section, tension being applied to at least one of the first pair of cables to operate the bending section with one degree-of-freedom, and to at least one of the second pair cables to operate the bending section with a second degree-of-freedom;

- a tool supported at the distal end of the bending section for performing a medical procedure on a subject; and

- an electronic controller that controls the bending section to provide the at least one degree-of-freedom of movement.

25. The medical instrument of claim 24 wherein the tool includes a first jaw and a second jaw connected to the first jaw at a pivot joint such that the first and second jaws open and close.

26. The medical instrument of claim 25 further comprising an actuation element extending along the length of the bending section and coupled to the first and second jaws to operate the first and second jaws.

27. The medical instrument of claim 26 wherein the actuation element is a single cable, the single cable being coupled to the first and second jaws with a pair of linkages, the first and second jaws being closed by pulling on the single cable and being opened by pushing on the single cable.

28. The medical instrument of claim 27 wherein the single cable is contained in a sleeve positioned along the longitudinal axis of the bending section, the single cable being able to slide back and forth along the sleeve.

29. The medical instrument of claim 24 wherein the first set of ridges is positioned at about 90 degrees from the second set of ridges about the longitudinal axis of the bending section.

30. A method of remotely controlling a medical instrument comprising:

- controlling the bending movements of a bending section with a unibody construction having at least one degree-of-freedom with an electronic controller; and

- performing a medical procedure on a subject with a tool supported at a distal end of the bending section.

31. The method of claim 30 wherein the controlling includes applying a tension to at least one of a first pair of cables extending along the length of the bending section to operate the bending section with one degree-of-freedom.

32. The method of claim 31 wherein controlling includes applying a tension to at least one of a second pair cables extending along the length of the bending section to operate the bending section with a second degree-of-freedom.

33. The method of claim 32 wherein the controlling includes controlling with the controller coupled with an input device operated by a user.

34. The method of claim 31 wherein the performing includes applying a tension to at least one of a second pair of cables extending along the length of bending section and coupled to a first jaw of the tool, and applying a tension to at least one of third pair of cables extending along the length of bending section and coupled to a second jaw of the tool.

35. The method of claim 34 wherein the applying includes applying a respective tension to the cables with the controller coupled with an input device operated by a user.

36. The method of claim 31 wherein the performing includes pushing and pulling an actuation element extending along the length of the bending section and coupled to a first jaw and a second jaw connected to the first jaw at a pivot joint, the pushing and pulling causing the jaws to open and close, respectively.

37. The method of claim 36 wherein the pushing and pulling are controlled by the controller coupled with an input device operated by a user.

38. The method of claim 30 further comprising controlling a second bending section with a unibody construction having at least one degree-of-freedom.

39. A method of remotely controlling a medical instrument comprising:

- controlling the bending movements of a bending section with two degrees-of-freedom, the bending section having a unibody construction with a series of spaced ribs, the ribs being positioned along the length of the bending section between proximal and distal ends of the bending section, the bending section including a first set of ridges extending along the length of the bending section, the individual ridges of the first set of ridges being positioned in every other slot defined between adjacent ribs, and a second set of ridges, the individual ridges of the second set of ridges being positioned in respective slots unoccupied by the first set of ridges; and

- performing a medical procedure on a subject with a tool supported at a distal end of the bending section.

40. The method of claim 39 wherein the controlling includes applying a tension to at least one of a first pair of cables extending along the length of the bending section to operate the bending section with one degree-of-freedom, and applying a tension to at least one of a second pair cables extending along the length of the bending section to operate the bending section with a second degree-of-freedom.

41. The method of claim 39 wherein the performing includes pushing and pulling an actuation element extending along the length of the bending section and coupled to a first jaw and a second jaw connected to the first jaw at a pivot joint, the pushing and pulling causing the jaws to open and close, respectively.

42. The method of claim 39 wherein the first set of ridges is positioned at about 90 degrees from the second set of ridges about the longitudinal axis of the bending section.

43. A robotically controlled medical instrument comprising:

a means for supporting a tool;

a means for bending the means for supporting with at least one degree-of-freedom with an electronic controller; and

a means for operating the tool to perform a medical procedure on a subject.

44. A robotically controlled medical instrument system comprising:

an elongated shaft having proximal and distal ends;

a tool supported from the distal end of said elongated shaft and useable in performing a medical procedure on a subject;

at least one controllably bendable section of said shaft; and

an electrical controller for receiving a command from an input device, and for, in turn, controlling said bendable section to provide at least one degree-of-freedom at said bendable section.

45. The instrument system of claim 44 further including a mechanically drivable mechanism at the proximal end of said elongated shaft.

46. The instrument system of claim 2 wherein said mechanically drivable mechanism has at least one coupling tendon extending via said elongated shaft for operating said tool.

47. The instrument system of claim 44 including mechanical cabling comprised of at least one cable for operating said tool and at least another cable for controlling said bendable section.

48. The instrument system of claim 44 wherein said input device is controlled by a medical practitioner that issues commands for also controlling at least one degree-of-freedom of said tool.

49. The instrument system of claim 44 including a drive unit intercoupled with said elongated shaft for controlling the bending action at said bendable section and, via a mechanically drivable portion, actuation of said distally placed tool.

50. The instrument system of claim 44 wherein the bendable section preferably has a length in a range on the order of $\frac{3}{4}$ inch to 4 inches.

51. The instrument system of claim 44 wherein the distance between the tool pivot point and the distal end of

the bendable section is preferably equal to or less than the length of the bendable section.

52. The instrument system of claim 44 further comprising an actuation element extending with said instrument shaft and operable to control actuation of said tool.

53. The instrument system of claim 52 wherein said actuation element is positioned at at least one of a substantially center axis and substantially center plane of said controllably bendable section so as to de-couple motion at said controllable bendable section from tool actuation.

54. A method of remotely controlling an instrument, comprising:

providing an instrument shaft of the instrument that has supported at its distal end a tool that is usable in performing a medical procedure or application;

providing a controllably bendable section along said instrument shaft;

inserting the shaft into a patient's body so as to dispose the tool at an internal operative site; and

controlling, from a remote location, an input device that effects bending of the controllably bendable section to thereby effect positioning of the tool at the operative site.

55. A method as set forth in claim 54 wherein the step of controlling also includes controlling, from the input device, the operation of said tool.

56. A method as set forth in claim 54 wherein said input device is controlled by a medical practitioner that issues commands for also controlling at least one degree-of-freedom of said tool.

57. A method as set forth in claim 54 wherein the step of inserting includes inserting through an incision.

58. A method as set forth in claim 54 wherein the step of inserting includes inserting through a natural body orifice.

59. A method as set forth in claim 54 wherein the step of inserting includes inserting percutaneously.

60. A robotically controlled medical instrument comprising:

an elongated shaft having proximal and distal ends;

a tool supported from the distal end of said elongated shaft and useable in performing a medical procedure on a subject;

at least one controllably bendable section of said shaft disposed proximally of said tool; and

an actuation element extending with said instrument shaft and operable to control actuation of said tool;

said actuation element positioned at at least one of a substantially center axis and substantially center plane of said controllably bendable section so as to de-couple motion at said controllable bendable section from tool actuation.

61. The medical instrument of claim 60 further comprising a first pair of cables extending along a length of the bendable section, tension being applied to at least one of the first pair of cables to operate the bendable section with one degree-of-freedom.

62. The medical instrument of claim 61 further comprising a second pair of cables extending along the length of the

bendable section, tension being applied to at least one of the second pair of cables to operate the bendable section with a second degree-of-freedom.

63. The medical instrument of claim 60 further including an electrical controller coupled with an input device operated by a user for remote control of at least said tool.

64. The medical instrument of claim 60 wherein the tool is movable with at least two additional degrees-of-freedom.

65. The medical instrument of claim 64 wherein the tool includes a first jaw and a second jaw connected to the first jaw at a pivot joint, the first jaw being movable with one of the two additional degrees-of-freedom and the second jaw being movable with the other of the two additional degrees-of-freedom.

66. The medical instrument of claim 65 comprising a second pair of cables and a third pair of cables extending along the length of the bendable section and coupled to the first jaw and second jaws, respectively, tension being applied to at least one of the second pair of cables to operate the first jaw, and to at least one of the third pair of cables to operate the second jaw.

67. The medical instrument of claim 66 wherein the second and third pair of cables are positioned near the longitudinal axis of the bendable section.

68. The medical instrument of claim 67 wherein the second and third pair of cables are contained in a sleeve positioned along the longitudinal axis of the bendable section, the second and third pair of cables being able to slide along the sleeve.

69. The medical instrument of claim 66 wherein the amount of tension being applied to the respective cables of the second and third pair of cables is controlled with a controller coupled with an input device operated by a user.

70. The medical instrument of claim 60 wherein the tool includes a first jaw and a second jaw connected to the first jaw at a pivot joint such that the first and second jaws open and close.

71. The medical instrument of claim 70 wherein the actuation element extends along the length of the bendable section and couples to the first and second jaws to operate the first and second jaws.

72. The medical instrument of claim 71 wherein the actuation element is a single cable, the single cable being coupled to the first and second jaws with a pair of linkages, the first and second jaws being closed by pulling on the single cable and being opened by pushing on the single cable.

73. The medical instrument of claim 72 wherein the single cable is positioned near the longitudinal axis of the bendable section.

74. The medical instrument of claim 73 wherein the single cable is contained in a sleeve positioned along the longitudinal axis of the bendable section, the single cable being able to slide back and forth along the sleeve.

75. The medical instrument of claim 74 further comprising a helical spring positioned about the sleeve along the length of the bendable section to keep the sleeve and single cable near the longitudinal axis of the bendable section.

76. The medical instrument of claim 72 wherein the amount of pushing and pulling on the single cable is controlled with a controller coupled with an input device operated by a user.

77. The medical instrument of claim 60 wherein the bendable section has a bellows construction with alternating peaks and valleys positioned between proximal and distal ends of the bendable section.

78. The medical instrument of claim 60 wherein the bendable section has a series of spaced ribs positioned along the length of the bendable section between proximal and distal ends of the bendable section.

79. The medical instrument of claim 78 wherein the bendable section includes a set of opposed ridges extending along the length of the bendable section, the individual ridges of the set of ridges being positioned in a respective slot defined by adjacent ribs.

80. The medical instrument of claim 78 wherein the bendable section includes a first set of ridges extending along the length of the bendable section, the individual ridges of the first set of ridges being positioned in every other slot defined between adjacent ribs, and a second set of ridges, the individual ridges of the second set of ridges being positioned in respective slots unoccupied by the first set of ridges.

81. The medical instrument of claim 80 wherein the first set of ridges is positioned at about 90 degrees from the second set of ridges about the longitudinal axis of the bendable section.

82. The medical instrument of claim 60 further comprising a second bendable section with a unibody construction, and being bendable with at least one degree-of-freedom.

83. A method of operating a medical instrument comprising:

controlling the bending movements of a bending section with a unibody construction having at least one degree-of-freedom; and

performing a medical procedure on a subject with a tool supported at a distal end of the bending section;

said step of controlling including controlling the one degree-of-freedom, from a remote location via an electrical controller with an input device that effects bending of the controllably bendable section to thereby effect positioning of the tool at the operative site.

84. The method of claim 83 wherein the controlling includes applying a tension to at least one of a first pair of cables extending along the length of the bending section to operate the bending section with one degree-of-freedom.

85. The method of claim 84 wherein controlling includes applying a tension to at least one of a second pair of cables extending along the length of the bending section to operate the bending section with a second degree-of-freedom.

86. The method of claim 83 further including controlling actuation of the tool by means of at least one actuation element.

87. The method of claim 86 wherein said actuation element is positioned at at least one of a substantially center axis and substantially center plane of said controllably bendable section so as to de-couple motion at said controllable bendable section from tool actuation.

88. The method of claim 83 further comprising controlling a second bendable section with a unibody construction having at least one degree-of-freedom.

89. A robotically controlled medical instrument comprising:

a means for supporting a tool;

a means of bending the means for supporting with at least one degree-of-freedom;

a means for operating the tool to perform a medical procedure on a subject;

an actuation means operable to control actuation of said tool;

said actuation means positioned at least one of a substantially center axis and substantially center plane of said means for bending so as to de-couple motion at said means for bending from tool actuation.

90. A robotically controlled medical instrument comprising:

an elongated shaft having proximal and distal ends;

a tool supported from the distal end of said elongated shaft and useable in performing a medical procedure on a subject;

the distal end of said elongated shaft and the tool having respective removably engaging portions that are readily engagable for positioning the tool at the distal end of said elongated shaft in operative position relative to said elongated shaft, and readily disengagable for removal of said tool from the distal end of said elongated shaft.

91. The medical instrument of claim 90 further including a mechanically drivable mechanism at the proximal end of said elongated shaft.

92. The medical instrument of claim 91 wherein said mechanically drivable mechanism, elongated shaft, and tool comprise a single piece disposable unit.

93. The medical instrument of claim 91 wherein said mechanically drivable mechanism has at least one coupling tendon extending via said elongated shaft for operating said tool.

94. The medical instrument of claim 93 wherein said tool is controlled remotely from an electrical controller.

95. The medical instrument of claim 94 wherein said electrical controller couples from a user interface controlled by an operator to remotely and telerobotically control said tool.

96. The medical instrument of claim 90 wherein said tool is disposable.

97. The medical instrument of claim 90 wherein said tool is readily disengagable to allow the substitution of a different tool at the distal end of said elongated shaft.

98. The medical instrument of claim 90 wherein said elongated shaft has a segment thereof that is controllably bendable.

99. The medical instrument of claim 90 wherein said engaging portions include mating threaded portions.

100. The medical instrument of claim 90 including at least one actuation element extending via said elongated shaft and for control of said tool.

101. The medical instrument of claim 100 wherein said actuation element and said tool have removably engaging sections that are readily engagable to provide mechanical drive from the actuation element to the tool, and readily disengagable for removal of said tool from said actuation element.

102. The medical instrument of claim 100 wherein said actuation element includes a tendon that is sufficiently rigid to enable linear translation relative to said tool for actuation and deactuation of said tool.

103. A robotically controlled medical instrument comprising:

an elongated support shaft having proximal and distal ends; and

a tool supported from the distal end of said elongated support shaft and controllable in performing a medical procedure on a subject;

said tool being removably coupled with the distal end of said elongated support shaft.

104. The medical instrument of claim 103 wherein said disposable tool is readily attachable to and detachable from said elongated support shaft.

105. The medical instrument of claim 103 further including a mechanically drivable mechanism disposed at the proximal end of the elongated support shaft and having extending therefrom at least one control tendon coupling to said tool for operation thereof.

106. The medical instrument of claim 103 wherein said tool is actuated remotely via a computer from a user interface device.

107. A flexible surgical instrument comprising a controllably flexible elongated section having a distal end for positioning at an anatomical site of interest of a subject, and at least one cable attached at or near the distal end of the section, the cable extending from its point of attachment exteriorly of the section through an aperture in the section at a position spaced a selected distance along the length of the section away from the distal end, a proximal end of the cable extending from the aperture through the shaft and being tensionable to controllably bend the flexible section.

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