



(51) International Patent Classification:

A61B 34/30 (2016.01) *A61B 17/32* (2006.01)
A61B 17/285 (2006.01) *A61B 17/04* (2006.01)

(21) International Application Number:

PCT/US2016/014979

(22) International Filing Date:

26 January 2016 (26.01.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/107,809 26 January 2015 (26.01.2015) US

(71) Applicant: INTUITIVE SURGICAL OPERATIONS, INC. [US/US]; Patent Department, 1020 Kifer Rd, Sunnyvale, California 94086 (US).

(72) Inventors: GRAMES, Clayton; Brigham Young University, 3760 Harold B. Lee Library, Provo, Utah 84602 (US). STEGER, John Ryan; 270 Hazelton Avenue, Sunnyvale,

California 94085 (US). **HOWELL, Larry L.**; Brigham Young University, 3760 Harold B. Lee Library, Provo, Utah 84602 (US). **JENSEN, Brian D.**; Brigham Young University, 3760 Harold B. Lee Library, Provo, Utah 84602 (US). **MAGLEBY, Spencer**; Brigham Young University, 3760 Harold B. Lee Library, Provo, Utah 84602 (US). **TANNER, Jordan**; Brigham Young University, 3760 Harold B. Lee Library, Provo, Utah 84602 (US).

(74) Agent: **MILLS, John**; Intuitive Surgical Operations, Inc., Patent Department, 1020 Kifer Rd, Sunnyvale, California 94086 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,

[Continued on next page]

(54) Title: ROLLING-CONTACT JOINT MECHANISMS AND METHODS

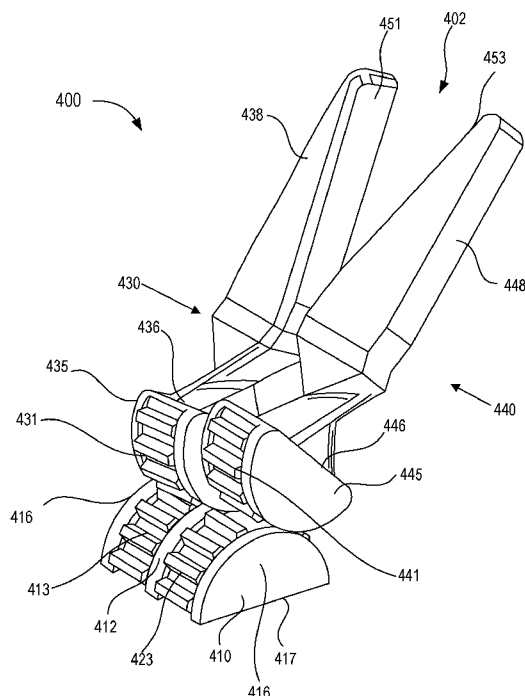


FIG. 10

(57) Abstract: The embodiments described herein can advantageously be used in a wide variety of grasping, cutting, and manipulating operations. In some embodiments, an apparatus includes a first tool member, a second tool member, a base, and an actuator assembly. The first tool member has a first convex surface, and the second tool member has a second convex surface. The first tool member is positioned to rotate relative to the base, and the second tool member is positioned to rotate relative to the base. The base includes a base convex surface. The actuator assembly is configured to maintain the first convex surface in rolling contact with a first portion of the base convex surface. The actuator assembly is configured to maintain the second convex surface in rolling contact with a second portion of the base convex surface. Guide surfaces are added to limit disengagement between the base and a tool member.



SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

ROLLING-CONTACT JOINT MECHANISMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

[1001] This application claims priority to and benefit of U.S. Provisional Application No. 62/107,809, entitled “A Novel Meso-Scale Rolling-Contact Gripping Mechanism for Robotic Surgery,” filed January 26, 2015, the entire disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

[1002] The embodiments described herein relate to joint mechanisms for use in surgical applications. More particularly, the embodiments described herein relate to devices having a split rolling joint having at least two degrees of freedom that is coupled to a tool portion for use in surgical applications.

[1003] Minimally Invasive Surgery (MIS) is a growing field, and known techniques employ tools to manipulate tissue that are both manually controlled or robotically controlled. Such known tools and mechanisms include, for example, kinematic chains including wrist mechanisms, steerable segments, grippers, cutting tools, or the like. Known methods include accessing a target work site inside a patient by at least partially following a natural lumen, such as the digestive tract, blood-carrying lumens, bronchi, or other lumens, of the patient. Following a natural lumen, for example, can allow a surgeon to operate at a work site while making fewer and/or smaller incisions through healthy tissue, although an incision may be needed at locations where the surgical device enters or leaves a natural lumen. In other MIS aspects, a surgical site is accessed without following a body lumen. Access may be via one or more incisions through the patient's body wall or via a natural orifice.

[1004] Surgeons and engineers are making continual efforts to mitigate the negative effects of surgery on patients. Reducing the size and/or the operating footprint of the surgical instruments is one method pursued in this effort. For example, when the instruments approach approximately 3 mm in diameter, they also approach a threshold where the entry incisions can be small enough so that little or no visible scar is left on the patient. But, some known tools having a diameter less than 3 mm lack the desired flexibility and may include mechanisms that produce an undesirably large swept volume inside the patient (e.g., operating footprint). For example, some known tools may lack wrist

articulation and typically have one mechanical Degree of Freedom (DoF), such as grip performed by jaws. Other known tools have a relatively large throw distance from the tool shaft axis to the end effector tip when a wrist orients the end effector away from the tool shaft, so that more volume is needed at a surgical site for effective tissue manipulation. Thus, in general, there is a tradeoff between the benefits of small instrument size and larger numbers of instrument and surgical end effector DoFs.

[1005] Referring to FIG. 1, known tool designs can be categorized in four quadrants. The first three quadrants are represented by a variety of designs: large instruments (6-10 mm diameter) with 1-2 DoF in quadrant I; small instruments (10 μ m–3 mm diameter) with 1-2 DoF in quadrant II; and large instruments with 3 or more DoF in quadrant III. Quadrant IV, defined by meso-scale instruments (e.g., having one or more dimensions between about 100 μ m and about 5 mm) with articulating wrists, is largely unpopulated. Many challenges are present in this area that may not be as pertinent as found within instruments categorized in the other quadrants. For example, manufacturing techniques used in the 5-10 mm range can be less reliable when used to produce smaller than approximately 3 mm diameter instruments. The differences in manufacturing techniques between quadrants I and II are evidence of this. In addition to manufacturing, assembly of individual parts, and maintaining the integrity of the assembly, at this size range is challenging.

[1006] Some known instruments employ joint assemblies (e.g., for grippers) that include a pin-in-slot joint to allow one portion of the tool (e.g., a gripper) to rotate relative to a second part of the tool (e.g., a base). Such known joint mechanisms are referred to as “non-compliant” revolute joints. Such known joints can be subject to undesirable levels of friction, wear, and undesirable motion, all of which that leads to a decline in performance.

[1007] Thus, a need exists for improved joint mechanisms for surgical instruments and methods of assembly and use of improved joint mechanisms.

SUMMARY

[1008] This summary introduces certain aspects of the embodiments described herein to provide a basic understanding. This summary is not an extensive overview of the inventive subject matter, and it is not intended to identify key or critical elements or to delineate the scope of the inventive subject matter. In some embodiments, an apparatus includes a first tool member, a second tool member, a base and an actuator assembly. The first tool member

has a first convex surface, and the second tool member has a second convex surface. The first tool member is positioned to rotate relative to the base, and the second tool member is positioned to rotate relative to the base. The base includes a base convex surface. The actuator assembly is configured to maintain the first convex surface in rolling contact with a first portion of the base convex surface. The actuator assembly configured to maintain the second convex surface in rolling contact with a second portion of the base convex surface.

[1009] In some embodiments, an apparatus includes a tool member having a tool convex surface and a jaw portion. The apparatus includes a base having a base convex surface and jaw portion. The base convex surface is in rolling contact with the tool convex surface such that jaw portion of tool member rotates relative to the base about a first axis to contact the jaw portion of the base. The base has a guide surface positioned to limit movement of the tool member relative to the base about a second axis that is nonparallel to and/or different from the first axis.

BRIEF DESCRIPTION OF THE DRAWINGS

[1010] FIG. 1 is a graph illustrating categories of existing surgical instruments.

[1011] FIG. 2 is a schematic illustration of a joint assembly embodiment.

[1012] FIGS. 3 and 4 are front and side schematic illustrations, respectively, of a joint assembly embodiment.

[1013] FIGS. 5A and 5B are geometric schematic illustration and a schematic illustration, respectively, of a joint assembly embodiment. FIGS. 5A and 5B show the geometry and parameters used in deriving equations of motion and force output for the joint assembly.

[1014] FIG. 6 is a graph depicting the calculated input force for a range of motion of a joint assembly illustrated in FIGS. 5A and 5B.

[1015] FIG. 7 is a graph depicting the calculated mechanical advantage for a range of motion of a joint assembly illustrated in FIGS. 5A and 5B.

[1016] FIGS. 8A and 8B are perspective and front view schematic illustrations, respectively, of a joint assembly embodiment. FIGS. 8A and 8B show the geometry and

parameters used to determine the stress states caused by the contact between the upper and lower segments of the joint assembly.

[1017] FIG. 9 is a graph plotting the stress states at the contact point of the joint assembly illustrated in FIGS. 8A and 8B.

[1018] FIGS. 10 and 11 are perspective views of a joint assembly embodiment.

[1019] FIG. 12 is a schematic illustration of an actuator assembly used in conjunction with the joint assembly shown in FIGS. 10 and 11.

[1020] FIG. 13 shows a model of a half cylinder illustrating a segmented spring constant calculation according to an embodiment.

[1021] FIG. 14 shows a spring model of a joint assembly, according to an embodiment.

[1022] FIGS. 15A-15D are various illustrative embodiments of a base.

[1023] FIGS. 16A and 16B are front views of a portion of a joint assembly embodiment to illustrate parameters associated with a lateral tipping analysis.

[1024] FIG. 17 is a perspective view of the joint assembly embodiment shown in FIGS. 16A and 16B to illustrate parameters associated with a torque (twisting) analysis.

[1025] FIGS. 18A-18D are various views of a test fixture embodiment used to conduct tests of a joint assembly.

[1026] FIG. 19 is a graph showing the sum of cable length changes for a joint assembly embodiment, illustrating the non-conservative nature of the assembly.

[1027] FIGS. 20A and 20B show a front view and a side view, respectively, of a tool member of the joint assembly shown in FIGS. 16A and 16B to illustrate the bending stress analysis.

[1028] FIGS. 21A and 21B are cross-sectional views of the tool member taken along the lines X₁-X₁ and X₂-X₂, respectively, in FIG. 20B.

[1029] FIG. 22 is a side view of a tool member of the joint assembly embodiment shown in FIGS. 16A and 16B to illustrate the buckling analysis.

[1030] FIGS. 23A-23C are perspective views of devices including joint assemblies according to various embodiments.

[1031] FIG. 24 is a perspective view of devices, one of which includes a joint assembly according to an embodiment, manipulating a suture.

[1032] FIG. 25 is a flow diagram of a method of assembly according to an embodiment.

DETAILED DESCRIPTION

[1033] The embodiments described herein can advantageously be used in a wide variety of grasping, cutting, and manipulating operations. In particular, the rolling element joints described herein can allow control of an angle of an end effector tool with respect to a mounting shaft. The rolling element joint is placed at the end of the shaft, before the end effector tool (e.g., shears or grasper) to improve the dexterity of the tool. In some embodiments, a joint assembly is a Compliant Rolling-Contact Element (CORE) joint that includes two half cylinders. The embodiments described herein include joints having an end effector tool (e.g., shears or grasper) with two degrees of freedom that minimizes or reduces friction. The embodiments described herein have mechanisms providing relatively low friction at the meso-scale level. The embodiments described herein include at least a two-degree-of-freedom tool at small scales that has a minimum or reduced number of parts. In other embodiments, however, a tool, a joint assembly, or both, has only one degree-of-freedom.

[1034] In some embodiments, an apparatus includes a first end effector tool member, a second end effector tool member, a base, and an end effector actuator assembly. The first tool member has a first convex surface, and the second tool member has a second convex surface. The first tool member is positioned to rotate relative to the base, and the second tool member is positioned to rotate relative to the base. The base includes a base convex surface. The actuator assembly is configured to maintain the first convex surface in rolling contact with a first portion of the base convex surface, and to roll the first tool member with reference to the base. The actuator assembly is configured to maintain the second convex surface in rolling contact with a second portion of the base convex surface, and to roll the second tool member with reference to the base. The first and second end effector tool members are separate pieces, and so rolling contact between the first convex surface and the base and rolling contact between the second convex surface and the base are independent of one

another. The base has one or more optional guide surfaces positioned to limit movement of the tool members relative to the base.

[1035] In some embodiments, an apparatus includes an end effector tool member having a tool member convex surface, a base, and an actuator assembly. The base includes a base convex surface, and the tool member is configured to rotate relative to the base. The base has an optional guide surface positioned to limit movement of the tool member relative to the base. The actuator assembly is configured to maintain the tool convex surface in rolling contact with the base convex surface, and to roll the tool member with reference to the base. The actuator assembly includes a flexible member coupled to the tool member. The base convex surface is disposed between a first end portion of the flexible member and a second end portion of the flexible member.

[1036] In some embodiments, an apparatus includes an end effector tool member having a tool member convex surface and a jaw portion. The apparatus includes a base having a base convex surface and jaw portion. The base convex surface is in rolling contact with the tool convex surface such that jaw portion of tool member rotates relative to the base about a first axis to contact the jaw portion of the base. The base has an optional guide surface positioned to limit movement of the tool member relative to the base about a second axis that is nonparallel to and/or different from the first axis.

[1037] Methods of manufacturing and using a joint assembly are also described herein. In some embodiments, a method includes coupling an end effector actuator assembly to an end effector tool member. The actuator assembly includes at least one flexible member, and the tool member has a tool convex surface. The tool convex surface is placed into rolling contact with a base convex surface of a base such that when the actuator assembly applies an actuation force to the tool member, the tool member rotates relative to the base. The method further includes applying a preload force to the flexible member to maintain the tool convex surface in contact with the base convex surface. In some embodiments, the method optionally includes meshing a gear portion of the tool convex surface with a gear portion of the base convex surface. The preload applied can optionally be such that the gear portion of the tool convex surface and the gear portion of the base convex surface have a gear engagement of between about 40 percent and about 60 percent.

[1038] As used herein, the term “about” when used in connection with a referenced numeric indication means the referenced numeric indication plus or minus up to 10% of that referenced numeric indication. For example, the language “about 50” covers the range of 45 to 55.

[1039] As used in this specification and the appended claims, the term “meso-scale” indicates a part or assembly having an outer diameter size that is between that which is considered a micro-scale part and that which is considered a macro-scale part. And as used in this specification and the appended claims, a part or assembly having an outer diameter of between about 100 microns and about 5 mm is considered meso-scale. Accordingly, a part or assembly having an outer diameter of between about 1 mm and about 5 mm can be considered meso-scale. Use of meso-scale surgical instruments benefits patients by reducing required incision size and associated trauma during minimally invasive surgery. In some instances a meso-scale surgical instrument may be sufficiently small to eliminate the need for a cannula as it passes through the patient’s body wall.

[1040] The term “flexible” in association with a part, such as a mechanical structure, component, or component assembly, should be broadly construed. In essence, the term means the part can be repeatedly bent and restored to an original shape without harm to the part. Many “rigid” objects have a slight inherent resilient “bendiness” due to material properties, although such objects are not considered “flexible” as the term is used herein. A flexible part may have infinite degrees of freedom (DOF’s). Examples of such parts include closed, bendable tubes (made from, e.g., NITINOL, polymer, soft rubber, and the like), helical coil springs, etc. that can be bent into various simple or compound curves, often without significant cross-sectional deformation. Other flexible parts may approximate such an infinite-DOF part by using a series of closely spaced components that are similar to a snake-like arrangement of serial “vertebrae.” In such a vertebral arrangement, each component is a short link in a kinematic chain, and movable mechanical constraints (e.g., pin hinge, cup and ball, live hinge, and the like) between each link may allow one (e.g., pitch) or two (e.g., pitch and yaw) DOFs of relative movement between the links. A short, flexible part may serve as, and be modeled as, a single mechanical constraint (a joint) that provides one or more DOF’s between two links in a kinematic chain, even though the flexible part itself may be a kinematic chain made of several coupled links.

[1041] As used in this specification and the appended claims, the words “proximal” and “distal” refer to direction closer to and away from, respectively, an operator (or controller) of the surgical device. Thus, for example, the end of an a joint assembly that is farthest away from the user (and that is closest to the target tissue) would be the distal end of the joint assembly, while the end opposite the distal end (i.e., the end manipulated by the user or coupled to the actuation shaft) would be the proximal end of the joint assembly.

[1042] Further, specific words chosen to describe one or more embodiments and optional elements or features are not intended to limit the invention. For example, spatially relative terms—such as “beneath”, “below”, “lower”, “above”, “upper”, “proximal”, “distal”, and the like—may be used to describe the relationship of one element or feature to another element or feature as illustrated in the figures. These spatially relative terms are intended to encompass different positions (i.e., translational placements) and orientations (i.e., rotational placements) of a device in use or operation in addition to the position and orientation shown in the figures. For example, if a device in the figures is turned over, elements described as “below” or “beneath” other elements or features would then be “above” or “over” the other elements or features. Thus, the term “below” can encompass both positions and orientations of above and below. A device may be otherwise oriented (e.g., rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly. Likewise, descriptions of movement along (translation) and around (rotation) various axes includes various spatial device positions and orientations. The combination of a body’s position and orientation define the body’s pose.

[1043] Similarly, geometric terms, such as “parallel”, “perpendicular”, “round”, or “square”, are not intended to require absolute mathematical precision, unless the context indicates otherwise. Instead, such geometric terms allow for variations due to manufacturing or equivalent functions. For example, if an element is described as “round” or “generally round”, a component that is not precisely circular (e.g., one that is slightly oblong or is a many-sided polygon) is still encompassed by this description.

[1044] In addition, the singular forms “a”, “an”, and “the” are intended to include the plural forms as well, unless the context indicates otherwise. The terms “comprises”, “includes”, “has”, and the like specify the presence of stated features, steps, operations, elements, components, etc. but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, or groups.

[1045] Unless indicated otherwise, the terms apparatus, joint mechanism, joint assembly, and variants thereof, can be interchangeably used.

[1046] Aspects of the invention are described primarily in terms of an implementation using a *da Vinci*® Surgical System, commercialized by Intuitive Surgical, Inc. of Sunnyvale, California. Examples of such surgical systems are the *da Vinci*® Xi™ Surgical System (Model IS4000) and the *da Vinci*® Si™ HD™ Surgical System (Model IS3000). Knowledgeable persons will understand, however, that inventive aspects disclosed herein may be embodied and implemented in various ways, including computer-assisted, non-computer-assisted, and hybrid combinations of manual and computer-assisted embodiments and implementations. Implementations on *da Vinci*® Surgical Systems (*e.g.*, the Model IS4000, the Model IS3000, the Model IS2000, the Model IS1200) are merely presented as examples, and they are not to be considered as limiting the scope of the inventive aspects disclosed herein. As applicable, inventive aspects may be embodied and implemented in both relatively smaller, hand-held, hand-operated devices and relatively larger systems that have additional mechanical support.

[1047] FIG. 2 is a schematic illustration of a joint assembly 100, according to an embodiment. The joint assembly 200 includes a first tool member 130, a second tool member 140, a base 110, and an actuator assembly 160. The joint assembly 100, and any of the joint assemblies described herein, can be used in any suitable surgical device or system as described herein. For example, the first tool member 130 and the second tool member 140 are optionally parts of an end effector, such as a gripper, shears, or the like. The base 110 can be coupled to the distal end of a surgical instrument shaft (not shown), either directly or via a wrist assembly that allows the end effector to change orientation (*e.g.*, one or more of roll, pitch, and yaw) with reference to the shaft. Example wrist mechanisms suitable for use with all aspects illustrated by the embodiments herein are illustrated in U.S. Patents No. 6,817,974 (filed Jun. 28, 2002) and 8,887,595 (filed Dec 22, 2009); International Patent Application Publication No. WO 2015/127250 (filed Feb. 20, 2015); and U.S. Patent Applications No. 14/806,331 (filed Jul. 22, 2015) and 14/831,699 (filed Aug. 20, 2015), all of which are incorporated by reference in their entirety.

[1048] The first tool member 130 includes a first convex surface 131. Similarly, the second tool member 140 includes a second convex surface 141. The first convex surface 131, the second convex surface 141, and any of the other convex surfaces (outer faces)

described herein can follow any suitable shape and/or contour. For example, in some embodiments, the first convex surface 131, the second convex surface 141, and any of the other convex surfaces described herein follow a cylindrical arc. Similarly stated, the first convex surface 131, the second convex surface 141, and any of the other convex surfaces described herein can follow a contour characterized by a single radius of curvature R_2 (i.e., a circular arc). In other embodiments, however, the first convex surface 131, the second convex surface 141, and any of the other convex surfaces described herein can follow a non-circular arc. For example, in some embodiments, the first convex surface 131, the second convex surface 141, and any of the other convex surfaces described herein can follow an elliptical curve, a parabolic curve, an eccentric cam profile, or the like. Similarly stated, the first convex surface 131, the second convex surface 141, and any of the other convex surfaces described herein can follow a curve and/or contour that cannot be characterized by a single radius of curvature.

[1049] The base 110 includes a base convex surface 112 that has a first portion 113 and a second portion 123 (the first portion 113 and the second portion 123 are delineated by the dashed line in FIG. 2). As shown, the first convex surface 131 is in rolling contact with the first portion 113 and the second convex surface 141 is in rolling contact with the second portion 123. In this manner, the base 110, the first tool member 130 and the second tool member 140 form a rolling element joint assembly. Similarly stated, the first tool member 130 can roll along the first portion 113 of the base convex surface 112 to rotate relative to the base 110, and the second tool member 140 can roll along the second portion 123 of the base convex surface 112 to also rotate relative to the base 110. Additionally, the first tool member 130 can be rotated independently from the second tool member 140. Thus, the tool members are considered as “split in two” to create two distinctly controllable surfaces to which individual jaws, shears, or the like (not shown) can be mounted. This arrangement produces a mechanism that can be characterized as having two mechanical DOFs in two ways. In a first aspect, one DOF is the motion of the first tool member with reference to the base, and the second DOF is the motion of the second tool member with reference to the base. In a second aspect, one DOF is the motion of the two tool members moving in opposite directions to provide a gripping (moving towards one another) or spreading (moving away from one another) effect, and the second DOF is the motions of both tool members moving together to change their mutual orientation (and, e.g., the closed angle orientation of the tool members)

with reference to the base. This second DOF may be optionally termed “yaw” or “pitch” with reference to the base.

[1050] The base convex surface 112 and any of the other base convex surfaces described herein may follow any suitable shape and/or contour. For example, in some embodiments, the base convex surface 112 and any of the other base convex surfaces described herein follow a cylindrical arc. Similarly stated, the base convex surface 112 and any of the other base convex surfaces described herein follow a contour characterized by a single radius of curvature R_1 (i.e., a circular arc). In other embodiments, however, the base convex surface 112 and any of the other base convex surfaces described herein may follow a non-circular arc. For example, in some embodiments, base convex surface 112 and any of the other base convex surfaces described herein follow an elliptical curve, a parabolic curve, an eccentric cam profile, or the like. Similarly stated, base convex surface 112 and any of the other base convex surfaces described herein follow a curve and/or contour that cannot be characterized by a single radius of curvature.

[1051] As shown, the base convex surface 112 is opposite of or opposes the first convex surface 131 and the second convex surface 141. Said another way, the point of contact between the base convex surface 112 and the first convex surface 131 is between the origin of the first radius of curvature R_1 and the origin of the second radius of curvature R_2 . In this manner, when actuated, the first tool member 130 and the second tool member 140 rotate in minimal contact with and about the base member 110, thus reducing friction and parasitic losses.

[1052] Although the first portion 113 and the second portion 123 are shown as having the same curvature or arc, in other embodiments, the first portion 113 of the base convex surface 112 may optionally have a different contour than the second portion 123 of the base convex surface 112. Similarly stated, in some embodiments, the axis about which the radius of curvature characterizing the curvature of the first portion 113 of the base convex surface 112 originates is collinear with the axis about which the radius of curvature characterizing the curvature of the second portion 123 of the base convex surface 112. In other embodiments, however, the axis about which the radius of curvature characterizing the curvature of the first portion 113 originates is non-collinear with the axis about which the radius of curvature characterizing the curvature of the second portion 123.

[1053] The actuator assembly 160 is configured to control rotation of the first tool member 130 and the second tool member 140 about the base 110. The actuator assembly 160 includes a first flexible member 161, a second flexible member 162, a third flexible member 163, and a fourth flexible member 164. The flexible members (and any of the flexible members shown and described herein) can be any suitable bendable and/or flexible component, such as, for example, a flexible tendon, a cord, a cable, or the like.

[1054] The first flexible member 161 and the second flexible member 162 are coupled to the first tool member 130. As shown, a tension force F1 can be applied to first tool member 130 via the end portion 165 of the first flexible member 161, and a tension force F2 can be applied to the first tool member 130 via the end portion 166 of the second flexible member 162. As described herein, when the force F1 is different from the force F2, the first tool member 130 rotates relative to the base 110. The third flexible member 163 and the fourth flexible member 164 are coupled to the second tool member 140. As shown, a tension force F3 can be applied to second tool member 140 via the third flexible member 163, and a tension force F4 can be applied to the second tool member 140 via the fourth flexible member 164. As described herein, when the force F3 is different from the force F4, the second tool member 140 rotates relative to the base 110.

[1055] The actuator assembly 160 is configured to maintain the first convex surface 131 in rolling contact with the first portion 113 of the base convex surface 112, and to maintain the second convex surface 141 in rolling contact with the second portion 123 of the base convex surface 112. Similarly stated, the actuator assembly 160 applies a preload tension to the first tool member 130 and the second tool member 140 to maintain the desired rolling contact between the mating parts. In this manner, the joint assembly 100 maintains its desired assembly integrity during use. This use of preload tension also eliminates the need for a flexure or other coupling component disposed between the first convex surface 131 and the first portion 113 and/or disposed between the second convex surface 141 and the second portion 123 to maintain the components in the desired coupled rolling relationships, although one or more such coupling components may optionally be used.

[1056] As described in more detail herein, the magnitude of the preload applied by the actuator assembly 160 on the first tool member 130 and/or the second tool member 140 is selected to provide the desired robustness of engagement between the mating surfaces while minimizing the frictional load and/or parasitic losses during operation. Said another way, the

magnitude of preload can impact the likelihood of disengagement of the first tool member 130, the second tool member 140, and the base 110 (e.g., via “tipping,” twist, or the like).

[1057] Although the actuator assembly 160 is shown as including a first flexible member 161 and a second flexible member 162 coupled to the first tool member 130, in other embodiments, the actuator assembly 160 (and any of the actuator assemblies shown and described herein) can include a single flexible member that is coupled to a tool member. For example, in some embodiments, the flexible member can be looped through an opening in the tool member (not shown in FIG. 2) such that a first end portion of the flexible member is disposed on an opposite side of the tool member as a second end portion of the flexible member. Similarly stated, in such embodiments, the base convex surface and/or the tool convex surface can be disposed between the first end portion of the flexible member and the second end portion of the flexible member. And, since a flexible member functions as an actuation member for the distal end effector tool member, a rigid member (e.g., a rod) may similarly function as such an actuation member if suitably coupled to an individual tool member. Therefore, one or more rigid actuation members may be substituted for one or more flexible actuation members as described for all embodiments herein, and the use of one or more rigid actuation members will not be described for each embodiment to avoid needless repetition.

[1058] Although the joint assembly 100 is shown and described as including two independently movable tool members, in other embodiments a joint assembly can include only one movable tool member. For example, FIGS. 3 and 4 show a front view and a side view of a joint assembly 200 embodiment. The joint assembly 200 includes a tool member 230, a base 210, and an actuator assembly 260. The joint assembly 200, and any of the joint assemblies described herein, optionally may be used in any suitable surgical device or system as described herein. For example, the tool member 230 and a portion of the base 210 can include and/or be a part of an end effector, such as a gripper, shears, or the like. Moreover, the base 210 can be coupled to the distal end of a surgical instrument shaft (not shown), either directly or via a wrist mechanism as described above.

[1059] The tool member 230 includes a jaw portion 238 and a tool convex surface 231. The tool convex surface 231 and any of the other convex surfaces described herein can follow any suitable shape and/or contour. For example, in some embodiments, the tool convex surface 231 and any of the other convex surfaces described herein follow a cylindrical

arc. Similarly stated, the tool convex surface 231 follow a contour characterized by a single radius of curvature R_2 (i.e., a circular arc) that originates from an axis of rotation A_{R2} . In other embodiments, however, the tool convex surface 231 and any of the other convex surfaces described herein follow a non-circular arc.

[1060] The jaw portion 238 extends from and/or is opposite the tool convex surface 231. In the depicted aspect, the jaw portion includes an optional engagement surface 251. As described in more detail below, when the tool member 230 rotates relative to the base 210, the engagement surface 251 can move towards and contact a corresponding engagement surface 253 of the base to function as a gripper, cutter, tissue manipulator, or the like. In this manner, the tool member 230 and the base 210 form the joint assembly 200 and an end effector for a surgical instrument.

[1061] The base 210 includes a jaw portion 248, a guide surface 228, and a base convex surface 212. As shown, the tool convex surface 231 is in rolling contact with the base convex surface 212. In this manner, the base 210 and the tool member 230 form a rolling element joint assembly. Similarly stated, the tool member 230 can roll along the base convex surface 212 to rotate relative to the base 210 about an axis of rotation A_{R2} .

[1062] In another aspect, the jaw portions 238,248 each include an optional cutting element, such as a scissors blade. The jaw portions 238,248 are positioned so they pass each other in a shearing action to provide a cutting function between the movable jaw portion 238 and the fixed jaw portion 248.

[1063] The base convex surface 212 and any of the other base convex surfaces described herein can follow any suitable shape and/or contour. For example, in some embodiments, the base convex surface 212 and any of the other base convex surfaces described herein follow a cylindrical arc. Similarly stated, the base convex surface 212 and any of the other base convex surfaces described herein follow a contour characterized by a single radius of curvature R_1 (i.e., a circular arc) originating from an axis A_{R1} . In other embodiments, however, the base convex surface 212 and any of the other base convex surfaces described herein follow a non-circular arc.

[1064] The jaw portion 248 extends from the base 210. The jaw portion 248 is fixed with reference to the base 210 and includes an engagement surface 253(or tip portion). As described above, when the tool member 230 rotates relative to the base 210, the engagement

surface 251 can contact the engagement surface 253 of the base to function as a gripper, cutter, tissue manipulator, or the like. In an optional aspect, the jaw portion 248 is separate from the base 210, but is fixed with reference to the base 210, so that rotation of the movable jaw with reference to the base similarly moves the movable jaw with reference to the fixed jaw.

[1065] As shown, the base convex surface 212 is opposite of or opposes the tool convex surface 231. Said another way, the point of contact between the base convex surface 212 and the tool convex surface 231 is between the axis A_{R2} and the axis A_{R1} . In this manner, when actuated, the tool member 230 rotates in contact with and about the base member 210 with minimal contact, thus reducing friction and parasitic losses. In particular, the tool member rotates about the axis A_{R2} . Moreover, the guide surface 228 of the base 210 is positioned to limit rotation of the tool member 230 relative to the base 210 about a second axis that is different from the axis A_{R2} . This arrangement assists in maintaining contact between the base convex surface 212 and the tool convex surface 231. For example, in some embodiments, the guide surface 228 contacts a portion (e.g., an edge portion 235) of the tool member 230 to limit lateral (sideways) movement of the tool member 230 relative to the base 210. In other embodiments, the guide surface 228 contacts a portion of the tool member 230 to limit “tipping” (or rotation as shown by the arrow BB in FIG. 4). Guide surfaces are discussed in more detail below, and may optionally be included in aspects illustrated by the embodiment shown in Figs. 3 and 4.

[1066] The actuator assembly 260 is configured to actuate and/or initiate rotation of the tool member 230 about the base 210. The actuator assembly 260 includes a flexible member 261 coupled to the first tool member 230. The flexible member 261 is disposed at least partially within and/or through an attachment portion (not shown) of the tool member such that a first end portion 265 of the flexible member 261 is disposed on an opposite side of the tool member 230 as a second end portion 266 of the flexible member 261. Similarly stated, the base convex surface 212 and/or the tool convex surface 231 are disposed between the first end portion 265 of the flexible member 261 and the second end portion 266 of the flexible member 261.

[1067] As shown, a tension force $F1$ can be applied to first tool member 230 via the first end portion 265 and a tension force $F2$ can be applied to the first tool member 230 via the

second end portion 266. As described herein, when the force F_1 is different from the force F_2 , the first tool member 230 rotates relative to the base 210.

[1068] It should be understood that the rolling surfaces described herein are not necessarily smooth, geometric surfaces, and many optional features may be used to provide friction between the surfaces to prevent slipping between the base and tool member. For example, the surfaces may be toothed as described below. Thus, as used herein, the rolling surfaces are not necessarily geometric surfaces, but instead they are outer faces of their associated components. And, as described below, the rolling surfaces may optionally include two or more surface features, such as a combination of smooth to withstand compression load and geared to facilitate engagement and rolling motion.

[1069] The motion of the rolling element joint assemblies disclosed herein can be modeled as two half cylinders—a fixed lower segment and a free upper segment that rolls along the curved (or convex) surface of the lower segment. The geometric range of motion is shown in FIG. 5A, and a schematic illustration of a rolling joint 300 is shown in FIG. 5B. The rolling joint (joint assembly) 300 represents any of the joint assemblies described herein, and the kinematic modeling described with reference to FIGS. 5A and 5B is applicable to any of the joint assemblies described herein.

[1070] As shown the joint assembly 300 includes an upper member (tool member) 330 and a lower member (base) 310. The upper member 330 includes a curved (convex) surface 331 and a jaw portion 338. The upper member 330 includes two actuator mount portions: a first actuator mount portion 339 (at which a force F_1 can be applied to one side of the upper member) and a second actuator mount portion 352 (at which a force F_2 can be applied to an opposite side of the upper member). The jaw portion 338 includes an engagement surface 351 against which a reactive force of gripping or cutting, identified as force F_{out} , is applied. The lower member 310 includes a convex (curved) surface 312.

[1071] The design of the joint assembly 300 is based on a half cylinder surface, or some smaller portion of the circular arc, to reduce the size of the joint. This is shown by the arc of the convex surface 331 and the convex surface 312, as shown in FIG. 5B by the solid lines. In some examples, the arcs of rolling element joint assembly model have the same (or similar) radius of curvature, r_1 , and are (or can be) concentric. The centers of the lower member 310 (e.g., the curved surface 312) and the upper member 330 (e.g., the curved

surface 331) are labeled as O and A, respectively. If using some smaller portion of the circular arc, neither of the centers physically may exist on the rolling element joint assembly, but the centers are still used as reference points because they simplify the derivations of equations of motion and force output. The angle θ_r is used to describe the size of the arc used in the design. For example, if θ_r is equal to 90° , the result may be equivalent to the traditional compliant rolling element (CORE) joint. If θ_r is equal to 45° the resulting mechanism may look similar to the one shown by solid lines in FIG. 5B.

[1072] The parameters of interest in this kinematic analysis are the output force at the jaws, F_{out} , the angle of the jaws with reference to a perpendicular y-axis of the base, θ_j , and the required input forces, F_1 and F_2 . The principle of virtual work is used to determine these input forces for any given values of F_{out} and θ_j . The angle used to describe the point of contact between the upper and lower segments (θ_c) is also used but can be described as a function of the jaw angle by the following relation:

$$\theta_c = \frac{\theta_j}{2}$$

Eq. (1):

[1073] All angles shown in FIG. 5A are defined as positive counter-clockwise from the y-axis, and the origin of the coordinate system is at point O as shown. Another coordinate system, $x'-y'$, is also shown. This system will be used along with a rotation matrix to define the location and direction of the input forces in terms of the x-y coordinate system. The origin of the $x'-y'$ coordinate system is point A.

[1074] For purposes of modeling, an assumption can be made regarding the relationship between the two input forces F_1 and F_2 . If the actuation members (not shown in FIGS. 5A and 5B) that apply the forces attached at the points of F_1 and F_2 are connected to a common actuation spool (not shown, but see the system design in FIG. 12 showing similar actuator spools; a single actuation spool that provides simultaneous equal cable pay-in and pay-out may be used), then as a force is applied to one actuation member, the force in the opposite actuation member goes to zero. Thus, under this assumption, if F_1 equals 2N, then F_2 is zero. In addition to this assumption, FIGS. 5A and 5B show that for any nonzero value of F_{out} , F_1 will also be nonzero, and consequently F_2 will be zero. This is because F_1 is the only force that can balance the system. If considering a multi-jaw joint, the other jaw in the assembly (not shown in FIG. 5B), for any nonzero value of F_{out} , F_2 would be nonzero and F_1 would be

zero. The derivations that follow apply to the case shown in FIGS. 5A and 5B where F_2 is zero. However, the same approach can be used to consider the case for the opposite jaw.

[1075] The method of virtual work can be used to determine the magnitude of F_1 for given values of F_{out} and θ_j . The first step in calculating the virtual work in the system is choosing a generalized coordinate. The jaw angle, θ_j , is a convenient parameter because it is used to describe the position of the jaw, and because the expression for F_1 will be derived as a function of θ_j . Therefore, θ_j will be used as the generalized coordinate. Next, each of the applied forces is written in vector form in terms of the generalized coordinate. The input force in this model is placed at a distance d_f from the corner of the upper segment and points toward a point a distance d_f from the corresponding corner of the lower segment. This assumption is based on the idea that actuation members (not shown) provide the input forces F_1 and F_2 , and route around the lower member before connecting to the control interface. The reason for placing the input force a distance from the corner is to increase the moment arm, and consequently to increase the mechanical advantage. This may be important when the point of rolling contact is near corners of the segments (i.e., as θ_c approaches θ_r). However, in this configuration, it is also important to address any interference that may result from placing the forces and the actuation members at these locations. Using this assumption, the directions of the forces are shown in Eqs. (2) and (3) for F_{out} and F_1 , respectively.

$$\text{Eq. (2):} \quad \mathbf{F}_{out} = F_{out} \left(-\cos \theta_j \hat{\mathbf{i}} - \sin \theta_j \hat{\mathbf{j}} \right)$$

$$\text{Eq. (3):} \quad \mathbf{F}_1 = F_1 \left(\sin \frac{\theta_j}{2} \hat{\mathbf{i}} - \cos \frac{\theta_j}{2} \hat{\mathbf{j}} \right)$$

[1076] Next, position vectors are written from the origin, O, to each of the applied forces. The vector describing F_{out} is fairly simple to describe in terms of θ_j and is given by Eq. (4). The other vector is more complicated because it lies at some point on the arc determined by θ_r , and that point sits somewhere in space determined by θ_j . To simplify the derivation of the position vector F_1 , two vectors can be summed together—one from point O to point A, and the second from point A to the location of force application. This second vector can be described in the x-y coordinate system using a rotation matrix. This results in the following equation for the position of F_1 .

$$\mathbf{Z}_{out} = \left[-2r_1 \sin \frac{\theta_j}{2} - (L_j - r_1 \cos \theta_r) \sin \theta_j \right] \hat{\mathbf{i}} + \left[2r_1 \cos \frac{\theta_j}{2} + (L_j - r_1 \cos \theta_r) \cos \theta_j \right] \hat{\mathbf{j}}$$

Eq.(4):

$$\mathbf{Z}_1 = -2r_1 \sin \frac{\theta_j}{2} \hat{\mathbf{i}} + 2r_1 \cos \frac{\theta_j}{2} \hat{\mathbf{j}} + \begin{bmatrix} \cos \theta_j & -\sin \theta_j \\ \sin \theta_j & \cos \theta_j \end{bmatrix} \begin{bmatrix} r_1 \sin \theta_r \hat{\mathbf{i}} \\ -r_1 \cos \theta_r \hat{\mathbf{j}} \end{bmatrix}$$

Eq. (5):

[1077] Eq. (5) can be expanded to its $\hat{\mathbf{i}}$ and $\hat{\mathbf{j}}$ components and then simplified, which results in Eq. (6).

$$\mathbf{Z}_1 = \left[-2r_1 \sin \frac{\theta_j}{2} + r_1 \sin (\theta_j + \theta_r) \right] \hat{\mathbf{i}} + \left[2r_1 \cos \frac{\theta_j}{2} - r_1 \cos (\theta_j + \theta_r) \right] \hat{\mathbf{j}}$$

Eq. (6):

[1078] The next step is to determine the virtual displacement of each point of force application by calculating the partial derivatives of Eqs. (4) and (6) with respect to the generalized coordinate.

$$\delta \mathbf{Z}_{out} = \left\{ \left[-r_1 \cos \frac{\theta_j}{2} - (L_j - r_1 \cos \theta_r) \cos \theta_j \right] \hat{\mathbf{i}} + \left[-r_1 \sin \frac{\theta_j}{2} - (L_j - r_1 \cos \theta_r) \sin \theta_j \right] \hat{\mathbf{j}} \right\} \delta \theta_j$$

Eq. (7):

$$\delta \mathbf{Z}_1 = \left\{ \left[-r_1 \cos \frac{\theta_j}{2} + r_1 \cos (\theta_j + \theta_r) \right] \hat{\mathbf{i}} + \left[-r_1 \sin \frac{\theta_j}{2} + r_1 \sin (\theta_j + \theta_r) \right] \hat{\mathbf{j}} \right\} \delta \theta_j$$

Eq. (8):

[1079] The virtual work associated with each force is determined by calculating the dot product of each force vector (Eqs. (2) and (3)) and its respective virtual displacement vector (Eqs. (7) and (8)).

$$\delta W_{out} = F_{out} \left(r_1 \cos \frac{\theta_j}{2} - r_1 \cos \theta_r + L_j \right) \delta \theta_j$$

Eq. (9):

$$\delta W_1 = -F_1 r_1 \sin \left(\theta_r + \frac{\theta_j}{2} \right) \delta \theta_j$$

Eq. (10):

[1080] The total virtual work in the system is calculated by summing each component of virtual work from Eqs. (9) and (10). For a system in equilibrium, the principle of virtual work states that the total virtual work is equal to zero. This makes it possible to rearrange the equation to determine F_1 for various values of F_{out} and θ_j .

$$0 = \left[F_{out} \left(r_1 \cos \frac{\theta_j}{2} - r_1 \cos \theta_r + L_j \right) - F_1 r_1 \sin \left(\theta_r + \frac{\theta_j}{2} \right) \right]$$

Eq. (11):

$$F_1 = \frac{F_{out} \left(\cos \frac{\theta_j}{2} - \cos \theta_r + \frac{L_j}{r_1} \right)}{\sin \left(\theta_r + \frac{\theta_j}{2} \right)}$$

Eq. (12):

[1081] It may be desirable in some embodiments to apply a certain amount of preload force to the points of force application (FIG. 5B). This reduces effects (e.g., any effects) of backlash that may occur and ensures higher levels of control over the motion of the mechanism. If an equal preload force is applied to both sides of the mechanism (i.e., equal preload in both actuation members), then the changes to the previous derivations are relatively simple. The input force term F_1 in Eq. (11) is replaced by $(F_1 + F_p)$, where F_p is the preload force. The virtual work derivation would also include the effects of F_p at the location of F_2 . Doing this results in a slightly different expression for F_1 given by:

$$F_1 = \frac{F_{out} \left(\cos \frac{\theta_j}{2} - \cos \theta_r + \frac{L_j}{r_1} \right) - 2F_p r_1 \cos \theta_r \sin \frac{\theta_j}{2}}{\sin \left(\theta_r + \frac{\theta_j}{2} \right)}$$

Eq. (13):

[1082] This new expression for F_1 , which includes a preload force on the system, shows two interesting behaviors that occur. First, by including a preload force on both actuation members, the required input force is reduced when θ_j is between 0° and 90° , but is increased when θ_j is between 0° and -90° . Second, for $\theta_r = 90^\circ$ the preload force has no effect on the required input force and Eq. (13) becomes equivalent to Eq. (12).

[1083] As described in more detail below, the magnitude of the preload applied by the actuator assembly via the actuation members can be such that the convex surface 331 is maintained in rolling contact with the convex surface 312.

[1084] To demonstrate the use of these equations of motion, consider a design where the desired jaw rotation is $\pm 90^\circ$ with a jaw length of 6.25 mm and a desired output force of 2 N. Assume that there is not a preload force applied by the actuation members. To achieve this motion θ_r must be at least 45° . To provide reasonable structural support at the extremes of motion, $\theta_r = 60^\circ$. In this example, the assembly may be designed to fit within a 3 mm circle so that it can be attached to a 3 mm diameter instrument shaft. To do this, the base of Split

CORE joint may be assumed to be square. Therefore, one side of the square is equal to $2r_1 \sin \theta_r$. The diagonal of the square will be equal to the diameter of the desired shaft size (3 mm). Using this information r_1 is calculated as follows:

$$\text{Eq. (14):} \quad (3 \text{ mm})^2 = 2 (2r_1 \sin \theta_r)^2$$

$$\text{Eq. (15):} \quad r_1 = \sqrt{\frac{9}{8 \sin^2 \theta_r}}$$

$$\text{Eq. (16):} \quad r_1 = 1.23 \text{ mm}$$

[1085] The distance from the upper segment to the point of force application (d_f) may also be determined in this design. One option is to define this distance as the point where the force would be applied if θ_r were equal to 90° . Doing this gives the design the same mechanical advantage as a traditional CORE mechanism, but its overall height is reduced because the actual profile is defined by $\theta_r = 60^\circ$. Therefore, calculating d_f is done using the following relation:

$$\text{Eq. (17):} \quad d_f = r_1 - r_1 \sin \theta_r$$

$$\text{Eq. (18):} \quad d_f = 0.165 \text{ mm}$$

[1086] With these values the input force, F_1 , can be determined for any jaw rotation using Eq. (12). In this calculation the value of $\theta_r = 90^\circ$ will be used because that defines the location of force input. For other calculations such as segment height and range of motion, $\theta_r = 60^\circ$ would be used.

[1087] FIG. 6 is a graph depicting the required input force for a range of θ_j from -90° to 90° for the rolling element joint assembly 300 (or any of the joint assemblies shown herein). This plot shows that the required force is symmetric about $\theta_j = 0^\circ$ and ranges between approximately 12 N and 16 N. The locations of greatest force are at the extremes of motion. This is to be expected because it is where the moment arm of force application is minimized.

[1088] FIG. 7 is a graph of the mechanical advantage of the rolling element joint assembly 300 (or any of the joint assemblies shown herein). Also, FIG. 7 illustrates the concept that mechanical advantage is maximum at $\theta_j = 0^\circ$.

[1089] In addition to the force requirements, mechanical advantage also gives some insight into the control and precision of the instrument. Mechanical advantage can be used to describe the relationship between input displacement and output displacement. In this particular design, the input displacement is the amount of motion in the actuation cable. The output displacement corresponds to the displacement of the tip of the jaw where F_{out} is positioned (see FIGS. 5A and 5B). For the example design given, this means that when $\theta_j = 0^\circ$ (where M.A. = 0.164), a 1 mm displacement of the actuation member 120 would result in an output displacement of approximately 6.10 mm. This is based on the following relationship:

$$Eq. (19): \quad MA = \frac{\text{input displacement}}{\text{output displacement}}$$

[1090] There are a few different ways to maximize precision and control of the distal end of the tool member (i.e., the instrument tip). One way is to increase the mechanical advantage of the system. This can be done by increasing the radius of curvature in the upper and lower segments (r_1). Another way to accomplish improved control is to reduce the diameter of the actuation spool that is used to actuate the actuation member. With a smaller diameter actuation spool, a given rotational input will result in a smaller cable displacement than would occur with the same rotational input on a larger spool. This method does not change the required input force (or mechanical advantage), but it does improve the control of the motion at the jaw tip.

[1091] The critical stresses experienced by the rolling element joint assemblies described herein can be determined using Hertzian Contact Stress Theory. The stress calculations are described with reference to FIGS. 8A and 8B, which show schematic illustrations of a rolling joint 300'. The rolling joint (joint assembly) 300' is similar to any of the joint assemblies described herein, and the stress modeling described with reference to FIGS. 8A and 8B is applicable to any of the joint assemblies described herein.

[1092] As shown, the joint assembly 300' includes an upper member (tool member) 330' and a lower member (base) 310'. The upper member 330' includes a curved (convex) surface

331'. The lower member 310' includes a curved (convex) surface 312'. Contact stress theory is used to model the interfacial stresses between two mating solids. In the case of two cylindrical surfaces, the area of contact forms a rectangle of width $2b$ and length l . The length, l , is simply the total length of the flat regions carrying the compressive loads. Using the parameters shown in FIG. 8, the half width of the stress area, b , is given by the following equation:

$$\text{Eq. (20):} \quad b = \sqrt{\frac{4r_1 F' (1 - \nu^2)}{\pi l E}}$$

[1093] The parameter F is the input force F_1 or F_2 , depending on which case is being considered, ν is Poisson's ratio, and E is the modulus of elasticity for the material being used. Eq. (20) assumes that the radius of curvature for upper and lower segments is equal, and that both are of the same material. The contact area creates an elliptical pressure distribution with its maximum at the center. FIGS. 8A and 8B illustrate the geometry depicting the parameters used to determine the stress states cause by the contact between the upper and lower segments of the joint assembly 300'. Also, the distribution is shown in FIG. 8B. The maximum pressure is defined as:

$$\text{Eq. (21):} \quad P_{max} = \frac{2F}{\pi bl}$$

[1094] Subsequently, the stress states along each of the three axes can be expressed in terms of the distance away from the point of contact (the depth into the material). This depth is denoted as y , as it corresponds to the y axis (FIG. 8A). These expressions are given by the following three equations.

$$\text{Eq. (22):} \quad \sigma_x = -P_{max} \left(\frac{1 + 2 \left(\frac{y}{b} \right)^2}{\sqrt{1 + \left(\frac{y}{b} \right)^2}} - \left| \frac{y}{b} \right| \right)$$

$$\text{Eq. (23):} \quad \sigma_y = \frac{-P_{max}}{\sqrt{1 + \left(\frac{y}{b} \right)^2}}$$

$$\text{Eq. (24):} \quad \sigma_z = -2\nu P_{max} \left(\sqrt{1 + \left(\frac{y}{b} \right)^2} + \left| \frac{y}{b} \right| \right)$$

[1095] The parameters used in the previous example will be used here to determine the stress states at the contact point of the mechanism. For this design example, the material being used is titanium (Ti-6Al-4V) with an elastic modulus of 114 GPa, compressive yield

strength of 1070 MPa, and Poisson's ratio of 0.34. The non-gear portion (or smooth portion) of the contact surface may be one third of the total length of the joint, where the length of the joint is equal to $2r_1$, or 2.12 mm, so that it fits on a 3 mm diameter instrument shaft. The remaining portions of the surfaces are comprised of gear teeth, which only transmit loads associated with motion. From this information, the length l is calculated to be approximately 0.7 mm, and the contact width b is calculated using Eq. (20). These calculations are based on the position at which θ_j is zero, which corresponds to $F_1 = 12.2$ N. However, this same approach can be used to determine the contact stresses at any angle of rotation.

$$b = \sqrt{\frac{4 (0.00123) (12.2) (1 - 0.34^2)}{\pi (0.0007) (114 \times 10^9)}}$$

Eq. (25):

$$b = 0.015 \text{ mm}$$

Eq. (26):

[1096] These values are substituted into Eq. (21) to calculate the contact pressure, which gives a value of $P_{\max} = 742$ MPa. Lastly, these values are substituted into Eqs. (22)-(24) to determine each of the stress states.

[1097] FIG. 9 is a graph plotting the stress states at the contact point when the example design is in the vertical position ($\theta_j = 0$) according to an aspect. The maximum stress in each of the three directions occurs at the outer surface where contact is made. The maximum stresses for σ_x , σ_y , and σ_z at this location are 742 MPa, 742 MPa, and 504 MPa, respectively. This results in a maximum Von Mises stress of $\sigma' = 638$ MPa. The location of the maximum Von Mises stress is approximately 0.011 mm from the contact surface ($z \approx 0.74b$). This gives a minimum safety factor of 1.68.

[1098] The motion of the joint assembly 300', and any of the other joint assemblies described herein, is based on the kinematic modeling described above. Given a desired rotation angle and output force, the required input forces can be calculated. Also, because the jaw segments roll, rather than slide, along the surface of the lower segment the effects of friction are minimal. The critical stresses in the system are due to compressive contact and occur at rolling contact between upper and lower segments. These stresses can also be predicted for a particular rotation angle and output force.

[1099] As referenced above, in some embodiments, a joint assembly can include mating geared portions to reduce the slip and/or enhance the control of the movement of a tool member relative to a base. For example, FIGS. 10 and 11 are perspective views of a joint assembly 400, according to an embodiment. The joint assembly 400 includes a first tool member 430, a second tool member 440, a base 410, and an actuator assembly 460 (see FIG. 12). The joint assembly 400, and any of the joint assemblies described herein, can be used in any suitable surgical device or system as described herein. For example, in one aspect the first tool member 430 and the second tool member 440 are a surgical end effector 402, such as a gripper, shears, or the like. The base 410 is optionally coupled to a shaft 406 of a surgical instrument (see FIG. 12), as described above.

[1100] The first tool member 430 includes a jaw portion 438, a platform 436, and a first convex surface 431. The jaw portion 438 extends from the platform 436 opposite the first convex surface 431. The jaw portion 438 includes an engagement surface 451 (or tip portion). In this manner, when the first tool member 430 rotates relative to the base 410, the engagement surface 451 can cooperate with the corresponding engagement surface 453 to function as a shearing (cutting) tool. In some aspects, the jaw portion 438 may optionally include an engagement surface 451 that functions as a gripper, tissue manipulator, or the like. In this manner, the first tool member 430 and the second tool member form the joint assembly 400 and the end effector 402 for a surgical instrument.

[1101] The platform 436 of the first tool member 430 includes a surface opposite to the first convex surface 431 from which the jaw portion 438 extends. In some embodiments, the platform 436 can include a planar surface (e.g., the platform 436 can define a surface plane having a width and length). In some embodiments, the platform 436 can have a uniform width along its entire length. In other embodiments, the platform 436 can include a curved, non-planar surface or a planar surface having a non-rectangular shape. In yet other embodiments, the platform 436 includes projections or extensions that extend away from its surface (e.g., portions to which the jaw portion 438 is coupled). In some embodiments, a recess, hole, or cavity is defined in platform 436, within which the jaw portion 438 is coupled. Therefore tool member 430 may be a single monolithic piece, or it may be made of two or more separate pieces joined together.

[1102] The first convex surface 431 can have any suitable contour as described herein. For example, in some embodiments, the first convex surface 431 follows a cylindrical arc.

The first convex surface 431 includes two compression portions 434 and a geared portion 432 between the two compression portions. The compression portions 434 are bounded by the edges of the first tool member 430 and contact and/or interface with the corresponding compression portions 415 of the base 410. In use the compression portions 434 support the compressive loads associated with the motion of the first tool member 430 and the preload of the actuator assembly 460 that maintains the first convex surface 431 in rolling contact with the base 410, as described below. The non-geared, compression portions 434 are included so that the compressive loads are transferred away from the geared portion 432, which would otherwise experience higher stresses because of the inherently smaller cross-sections and stress concentrations.

[1103] The geared portion 432 includes a set of recesses and gear teeth that are disposed within a row over the first convex surface 431. The geared portion 432 can have any type of gear profile structure (e.g., various pitches, tooth heights, tooth widths, straight cut, helical cut, etc.). As shown, the geared portion 432 of the first tool member 430 meshes with (engages) with the corresponding gear portion 414 of the base 410. In some embodiments, the geared portion 432 and the gear portion 414 define a gear clearance. Said another way, the teeth of the geared portion 432 do not contact the bottoms of the recesses associated with the teeth of the gear portion 414. The gear clearance can be defined as the whole gear depth less two times the addendum. In some embodiments, the gear clearance is between about 30% and about 70%. In other embodiments, the gear clearance is between about 40% and about 60%. In yet other embodiments, the gear clearance is about 50%. In some embodiments, as described in more detail below, the compression portions 434 and the corresponding compression portions 415 of the base 410 can be designed to maintain the desired spacing between the geared portions in view of any preload tension applied by the actuator assembly 460.

[1104] The second tool member 440 includes a jaw portion 448, a platform 446, and a second convex surface 441. The jaw portion 448 extends from the platform 446 opposite the second convex surface 441. The jaw portion 448 includes an engagement surface 453 (or tip portion). In this manner, when the second tool member 440 rotates relative to the base 410, the engagement surface 453 can cooperate with the corresponding engagement surface 451 to function as a shearing (cutting) tool. In some aspects, the jaw portion 448 may optionally include an engagement surface 453 that functions as a gripper, tissue manipulator, or the like.

In this manner, the first tool member 430 and the second tool member 440 form the joint assembly 400 and the end effector 402 for a surgical instrument.

[1105] The platform 446 of the second tool member 440 includes a surface opposite to the second convex surface 441 from which the jaw portion 448 extends. In some embodiments, the platform 446 can include a planar surface (e.g., the platform 446 can define a surface plane having a width and length). In some embodiments, the platform 446 can have a uniform width along its entire length. In other embodiments, the platform 446 can include a curved, non-planar surface or a planar surface having a non-rectangular shape. In yet other embodiments, the platform 446 includes projections or extensions that extend away from its surface (e.g., portions to which the jaw portion 438 is coupled). In some embodiments, a recess, hole, or cavity is defined in platform 436, within which the jaw portion 448 is coupled.

[1106] The second convex surface 441 can have any suitable contour as described herein. For example, in some embodiments, the second convex surface 441 follows a cylindrical arc. The second convex surface 441 includes two compression portions 444 and a geared portion 442 between the compression portions. The compression portions 434 are bounded by the edges 445 of the second tool member 440 and contact and/or interface with the corresponding compression portions 425 of the base 410. In use the compression portions 444 support the compressive loads associated with the motion of the second tool member 440 and the preload of the actuator assembly 460 that maintains the second convex surface 441 in rolling contact with the base 410, as described below. The non-geared, compression portions 444 are included so that the compressive loads are transferred away from the geared portion 442, which would otherwise experience higher stresses because of the inherently smaller cross-sections and stress concentrations.

[1107] The geared portion 442 includes a set of recesses and gear teeth that are disposed within a row over the second convex surface 441. The geared portion 442 can have any type of gear profile structure (e.g., various pitches, tooth heights, tooth widths, straight cut, helical cut, etc.). As shown, the geared portion 442 of the second tool member 440 meshes (engages) with the gear portion 424 of the base 410. In some embodiments, the geared portion 442 and the gear portion 424 define a gear clearance. Said another way, the teeth of the geared portion 442 do not contact the bottoms of the recesses associated with the teeth of the gear portion 424. In some embodiments, the gear clearance is between about 30% and

about 70%. In other embodiments, the gear clearance is between about 40% and about 60%. In yet other embodiments, the gear clearance is about 50%. In some embodiments, as described in more detail below, the compression portions 444 and the corresponding compression portions 425 of the base 410 are designed to maintain the desired spacing between the geared portions in view of any preload and/or tension applied by the actuator assembly 460.

[1108] The base 410 includes a platform 417 and a base convex surface 412. The platform 417 includes a surface opposite to the base convex surface 412 to which the shaft 406 (see e.g., FIG. 12) can be coupled. In some embodiments, the platform 417 can include a planar surface (e.g., the platform 417 can define a surface plane having a width and length). In other embodiments, the platform 417 can include a curved, non-planar surface or a flat planar surface having a non-rectangular shape. In yet other embodiments, the platform 417 includes projections or extensions that extend away from its surface (e.g., portions to which the shaft 406 is coupled). In some embodiments, a recess, hole, or cavity is defined in platform 417, within which a portion of the shaft 406 is coupled, or a portion of a wrist mechanism (not shown) is coupled.

[1109] The base convex surface 412 can follow any suitable shape and/or contour, as described herein. For example, in some embodiments, the base convex surface 412 and any of the other base convex surfaces described herein follow a cylindrical arc. The base convex surface 412 has a first portion 413 and a second portion 423. The first portion 413 includes a gear portion 414 and two compression portions 415. The compression portions 415 are bounded by the edges of the base 410 and contact and/or interface with the corresponding compression portions 434 of the first tool member 430. In use, the compression portions 415 support the compressive loads associated with the motion of the first tool member 430 and the preload of the actuator assembly 460 that maintains the first convex surface 431 in rolling contact with the base 410, as described above.

[1110] The gear portion 414 includes a set of recesses and gear teeth that are disposed within a row over the base convex surface 412. The geared portion 414 can have any type of gear profile structure (e.g., various pitches, tooth heights, tooth widths, straight cut, helical cut, etc.). As shown, the geared portion 432 of the first tool member 430 meshes with and/or engages with the gear portion 414. In some embodiments, the geared portion 432 and the gear portion 414 define a gear clearance, as described above.

[1111] The second portion 423 includes a gear portion 424 and two compression portions 425. The compression portions 425 are bounded by the edges of the base 410, and contact and/or interface with the corresponding compression portions 444 of the second tool member 440. In use, the compression portions 415 support the compressive loads associated with the motion of the second tool member 440 and the preload of the actuator assembly 460 that maintains the second convex surface 441 in rolling contact with the base 410, as described above.

[1112] The gear portion 424 includes a set of recesses and gear teeth that are disposed within a row over the base convex surface 412. The geared portion 424 can have any type of gear profile structure (e.g., various pitches, tooth heights, tooth widths, straight cut, helical cut, etc.). As shown, the geared portion 442 of the second tool member 440 meshes with (engages) with the gear portion 424. In some embodiments, the geared portion 442 and the gear portion 424 define a gear clearance, as described above.

[1113] As shown, the first convex surface 431 is in rolling contact with the first portion 413 and the second convex surface 441 is in rolling contact with the second portion 423. In this manner, the base 410, the first tool member 430 and the second tool member 440 form a rolling element joint assembly. Similarly stated, the first tool member 430 can roll along the first portion 413 of the base convex surface 412 to rotate relative to the base 410, and the second tool member 440 can roll along the second portion 423 of the base convex surface 412 to rotate relative to the base 410. Additionally, the first tool member 430 can be rotated independently from the second tool member 440. Thus, the tool members are considered as “split in two” to create two distinctly controllable components to which individual jaws, scissors blades, or the like (not shown) can be made integral or mounted. This arrangement produces a two-degree-of-freedom mechanism as described above.

[1114] Referring to FIG. 12, the actuator assembly 460 includes a first flexible member 461, a second flexible member 462, and four spools 468. In one illustrative use, the spools are controlled and driven by motors in a teleoperated surgical instrument manipulator (not shown) that supports the entire embodiment shown in Fig. 12. In another illustrative use, each spool 468 is driven and controlled by a corresponding motor 467 that is in the same actuator assembly 460 as the spools, such as in a hand-held surgical instrument. The flexible members (and any of the flexible members shown and described herein) can be any suitable bendable and/or flexible component, such as, for example, a flexible tendon, a cord, a cable, a

cable and hypotube combination, or the like. The first flexible member 461 is coupled to the first tool member 430 and a first actuation spool 468. The second flexible member 462 is coupled to the second tool member 440 and a second actuation spool 468. The actuation spools 468 are operated via a motor as described, which places input forces on the first tool member 430 and the second tool member 440 to open and close the end effector 402 as well as rotate the end effector 402 with respect to the shaft 406.

[1115] As described herein, when the force on one end of a flexible member is different from the force on another end of the flexible member, the associated tool member rotates relative to the base 410. In some embodiments, two opposing flexible members are attached to one actuation spool 468 such that when the actuation spool 468 rotates in one direction, the actuation spool 468 applies tension to one flexible member and slackens or optionally pushes the opposing flexible member. Each actuation spool 468 may control one of the degrees of freedom, so only two actuation spools 468 depicted in FIG. 12 are used for the two degrees of freedom of the split core wrist mechanism. However, additional actuation spools 468 may be incorporated into the device (e.g., the two activation spools 468 on the left side of FIG. 12) for other degrees of freedom. And as described above, a single spool may control both cable pay-in and pay-out, so that two flexible members are controlled by a single spool, with the flexible members being under preload tension.

[1116] The actuator assembly 460 is configured to maintain the first convex surface 431 in rolling contact with the first portion 413 of the base convex surface 412, and to maintain the second convex surface 441 in rolling contact with the second portion 423 of the base convex surface 412. Similarly stated, the actuator assembly 460 applies a preload tension to the first tool member 430 and the second tool member 440 to maintain the desired rolling contact between the mating parts. In this manner, the joint assembly 400 can maintain its desired assembly during use. This arrangement further obviates the need for a flexure or other component disposed between the first convex surface 431 and the first portion 413 and/or disposed between the second convex surface 441 and the second portion 423 to maintain the components in the desired coupled relationship. But as described above, such a coupling component that mechanically couples the components, such as a tension spring between the centers of the tool member and the base, may be used to hold the joint components together.

[1117] The magnitude of the preload applied by the actuator assembly 460 on the first tool member 430 and/or the second tool member 440 can be selected to provide the desired robustness of engagement between the mating surfaces while minimizing the frictional load and/or parasitic losses during operation. Said another way, the magnitude of preload can impact the likelihood of disengagement of the first tool member 430, the second tool member 440, and the base 410 (e.g., via “tipping” (angular displacement of the tool member orthogonal to the rotation direction), twist (angular rotation around the tool member’s long axis), combinations, or the like). For example, in some embodiments, the amount of preload applied by the actuator assembly 460, in conjunction with the size and/or material properties of the mating compression portions 434 and 415, and 444 and 425, are such that the corresponding gear clearance is between about 30% and about 70%. In other embodiments, the gear clearance is between about 40% and about 60%. In other embodiments, the gear clearance is between about 30% and about 50%. In yet other embodiments, the gear clearance is about 50%. In some embodiments, the compression portions 434 and the corresponding compression portions 415 of the base 410 are designed to maintain the desired spacing between the geared portions in view of any preload and/or tension applied by the actuator assembly 460. More particularly, the amount of preload can be determined in conjunction with the size and/or stiffness of the mating surfaces of the base 410 and the tool members.

[1118] For example, FIG. 13 shows a half cylinder 410' discretized into sections, each section having its own spring constant. The half cylinder 410' of FIGS. 13 and 14 are models of any of the joint assembly components described herein, such as the base 410, the first tool member 430, and the second tool member 440. These sections can be treated as springs in series and evaluated to estimate the stiffness (e.g., entire stiffness) K_j of the joint assembly (e.g., the joint assembly 400). As the height of each cross-section dy is decreased, the summation of the spring constants can be evaluated in the form of an integral. This can yield a joint stiffness of $K_j = \frac{4lE}{\pi}$ where l is the length of the rolling contact areas (as viewed into the page), and E is the modulus of the material.

[1119] FIG. 14 illustrates how the spring constant can be used to construct a series of springs representative of the joint assembly (e.g., the joint assembly 400). The two half cylinders (K_j) can function as springs in series while the flexible members (K_e) can

function as springs in parallel. The value of K_c was obtained through testing of the tungsten cabling used in the actuation assembly for certain prototype parts. The cables and joint assembly can function as springs in series, because for a given force they may not undergo the same deflection.

[1120] In some embodiments, the equivalent spring constant modeling of the joint assembly for 50% engagement. The tensioning force on the cables (identified as F_c) before F_a is applied, can initially cause the joint to compress. Thus, the force F_a is the force to first release the compression in the joint and stretch the cables (or flexible members), for example, 0.04 mm (half the distance from the contact surface to the tip of the gear teeth). Subsequently, calculating F_a is, for example:

$$\text{Eq. (26):} \quad F_a = 2K_c(\delta_j + \delta_{50}) = 3.9 \text{ N}$$

where $2K_c$ is the equivalent spring constant of the two cables, $\delta_j = \frac{4F_c}{K_j}$ is the original deflection of the joint and δ_{50} is the distance from the rolling contact surface to, for example, 50% gear tooth engagement. For the geometry of the example, the resulting force $F_a = 3.9 \text{ N}$.

[1121] The preload applied by the actuator assembly, such as the actuator assembly 460, can further maintain the engagement of the joint assembly when lateral forces are applied to the first tool member 430 and/or the second tool member 440.

[1122] In addition to the preload applied by the actuator assembly, in some embodiments a joint assembly, such as the joint assembly 400, can include one or more guide surfaces positioned to limit lateral movement of a first tool member and/or a second tool member relative to a base. Similarly stated, in some embodiments, a joint assembly can include one or more guide surfaces (either on a tool member, on a base, or both) configured to limit rotation of the tool member about an axis other than the intended axis of rotation. Such an arrangement can, for example, limit the likelihood of tipping or twisting of the tool member relative to the base.

[1123] For example, FIGS. 15A–15D show portions of a base convex surface, each according to an embodiment. FIG. 15A shows a portion of the base 410 for purposes of

comparison with the embodiments shown in FIGS. 15B - 15D. FIG. 15B shows a portion of a base 510 according to an embodiment. The base 510 can be used in conjunction with any of the joint assemblies described herein, such as with the joint assembly 400. The base 510 includes a base convex surface 512, a first guide member 526, and a second guide member 527. The convex surface 512 has a first portion 513 and a second portion 523. The first portion 513 includes a gear portion 514 and two compression portions 515. The second portion 523 includes a gear portion 524 and two compression portions 525. The compression portions 515, 525 are bounded by the first guide member 526 and the second guide member 527. In use, the compression portions support the compressive loads associated with the motion of a first tool member (not shown, similar to the first tool member 430) and a second tool member (not shown, similar to the second tool member 440). Moreover, the first guide member 526 can contact and/or engage a portion of the first tool member to limit lateral movement, prevent tipping and/or prevent torsional twisting during use. Similarly, the second guide member 527 can contact and/or engage a portion of the second tool member to limit lateral movement, prevent tipping and/or prevent torsional twisting during use.

[1124] FIG. 15C shows a portion of a base 510' according to an embodiment. The base 510' can be used in conjunction with any of the joint assemblies described herein, such as with the joint assembly 400. The base 510' includes a base convex surface 512', a first guide member 526', a second guide member 527', and a third (central; intermediate) guide member 528'. The convex surface 512' has a first portion 513' and a second portion 523'. The first portion 513' includes a gear portion 514' and two compression portions 515'. The second portion 523' includes a gear portion 524' and two compression portions 525'. The compression portions 515' are bounded by the first guide member 526' and the third (central; intermediate) guide member 528'. The compression portions 525' are bounded by the second guide member 527' and the third (central; intermediate) guide member 528'. In use, the compression portions support the compressive loads associated with the motion of a first tool member (not shown, similar to the first tool member 430) and a second tool member (not shown, similar to the second tool member 440). Moreover, the first guide member 526' and the third guide member 528' can contact and/or engage a portion of the first tool member to limit lateral movement, prevent tipping, and prevent torsional twisting during use. Similarly, the second guide member 527' and the third guide member 528' can contact and/or engage a portion of the second tool member to limit lateral movement, prevent tipping, and prevent torsional twisting during use.

[1125] FIG. 15D shows a portion of a base 510'' according to an embodiment. The base 510'' can be used in conjunction with any of the joint assemblies described herein, such as with the joint assembly 400. The base 510'' is similar to the base 510' in that it includes a first guide member 526'', a second guide member 527'', and a third (central; intermediate) guide member 528''. The guide members of the base 510'', however, are longer and/or have a higher profile than the guide members of the base 510'. This arrangement provides a greater amount of contact such that the first guide member 526'' and the third guide member 528'' limit lateral movement, prevent tipping, and prevent torsional twisting of the first tool member during use. Similarly, the second guide member 527'' and the third guide member 528'' can contact and/or engage a portion of the second tool member to limit lateral movement, prevent tipping, and prevent torsional twisting during use.

[1126] FIGS. 16A and 16B provide geometric information for a joint assembly 600 with which the likelihood of undesirable tipping can be evaluated. The joint assembly 600 can be similar to any of the joint assemblies shown and described, and the stress modeling described with reference to FIGS. 16A and 16B is applicable to any of the joint assemblies described herein. As shown, F_{tip} represents the output force applied when the engagement surface of the tool member grasps and/or manipulates tissue or other items. The force of the actuator assembly (e.g., the actuator assembly 460 having the flexible member 461) is represented by F_{cables} . In some embodiments, the moments resulting from F_{tip} and F_{cables} are balanced around point O , as shown. The modeling of tipping was calculated for three different joint configurations: (1) the joint assembly 600 shown and described above; (2) the joint assembly 400, but in conjunction with a base including guide members, such as those shown in FIGS. 15B–15D, and (3) the joint assembly 600 with the inclusion of a frictional force imposed by the preload applied by the actuator assembly (e.g., the actuator assembly 460). Specifically, the friction force is represented by $F_{friction} = 2F_{cables}\mu$ where μ is the coefficient of friction, was added to the moment balance equation for the third scenario. The dynamic coefficient of friction for steel on steel was used in place of the static coefficient as a conservative approximation. The equations for the three scenarios are as follows:

Eq. (27):
$$F_{tip1} = \frac{2F_{cables}x_c}{l_{jaw}}$$

$$\text{Eq. (28):} \quad F_{tip2} = \frac{2F_{cables}x_c}{l_{jaw} - y_w}$$

$$\text{Eq. (29):} \quad F_{tip3} = \frac{x_c = \mu y_w}{l_{jaw} - y_w}$$

[1127] The results for these calculations are provided in Table 1, below:

Table 1: TIPPING FORCE FOR 3 SCENARIOS

Scenario	Load (N)
1	2.0
2	2.4
3	5.3

[1128] FIG. 17 provides geometric information for the joint assembly 600 with which the likelihood of undesirable disengagement from torque applied about a longitudinal axis A_L can be evaluated. The joint assembly 600 can be similar to any of the joint assemblies shown and described, and the stress modeling described with reference to FIG. 17 is applicable to any of the joint assemblies described herein. To evaluate the resistance of the joint assembly to such engagement, testing was completed at five times scale (3 mm diameter design scaled up to 15 mm for testing) for four variants: (1) the the joint assembly 600 shown and described above; (2) the joint assembly 600 including the base 510; (3) the joint assembly 600 including the base 510; and (4) the joint assembly 600 including the base 510".

[1129] The testing was completed on the test fixture shown in FIGS. 18A-18D. Specifically, as shown, the subject joint assembly was held in compression with a cord to mimic the loading in the final assembly (e.g, the actuator pre-load). The cable tension was scaled up, as an example, four times (44.5 N; 10 lb) to approximate the scale of the mechanism. Custom printed joints (identified as joint 700, see, e.g., FIG. 18B) included a moment arm where additional weights were attached to simulate an applied torque along the axis of the instrument (FIG. 18D). The cables attaching the weights to the joint were routed over a low friction pulley to ensure the load was transferred to the joint with negligible frictional losses. The torque was increased by, for example, 9.5 N·mm by adding 100 g increments until the joint derailed or the parts failed. This was repeated five times for each of the four design types in a random order to help normalize operator error and bias.

[1130] The results for these calculations are provided in Table 2 below, and they show that any mechanical features (e.g., guide members or surfaces) constraining the parts in torsion add considerable stability to the design. In some implementations, the high three-walled design (the base 510" shown in FIG. 15C) provides the largest improvement with, for example, a 23.5% increase in load capacity. However, the outer walled (base 510 shown in FIG. 15A) and low three-walled (base 510' shown in FIG. 15B) variations can provide (e.g., can unexpectedly provide) similar increases in stability at, for example, 15.3% and 14.2%, respectively. Because the outer walled design was tested with one jaw in place, in some implementations with both jaws engaged the performance can be improved even further. The second jaw adds increased resistance to torsion on the first jaw.

[1131] The second and fourth design also exhibited relatively less variation in their performance. Table 2 lists the average torque value before failure for each design variation. Additionally, Table 2 lists the standard deviation for the sample set. Designs 1 and 3 both, for example, had $\sigma = 0.71$ while designs 2 and 4, for example, had $\sigma = 0.10$ and 0.27 respectively.

Table 2: Torque to Failure and Standard Deviation for Four Design Variants

Variant	Torque to Failure (N · m)	σ
1	0.24	0.71
2	0.29	0.10
3	0.28	0.71
4	0.32	0.27

[1132] In some optional embodiments, a surgical instrument employs a pull-pull actuation system where a single DoF is controlled with a pair of complimentary cables (flexible members). This can be executed by attaching both cables to the same spool. In such cable-length conservative mechanisms the pair of cables can extend or retract the same amount. If the mechanism is non-length-conservative, then the actuating cable can retract less than its companion can extend (or vice versa), resulting in slack and loss of tension on the mechanism. Non-conservative cable length mechanisms also result in increased forces in one of an actuation cable pair because it can stretch to accommodate the difference in length.

[1133] In some embodiments, a kinematic model can show that cable length is not conservative in the rolling element joints described herein (such as the joint assembly 400). The jaws were displaced by, for example, 15-degree increments from 0 degrees to 75 degrees, and the distances between the cable holes were measured at each increment on both sides of the mechanism. The sum of cable extension and retraction was then plotted as a function of the angular displacement, as shown in FIG. 19. Length conservative cables would exhibit a horizontal line through the origin.

[1134] In the case where the mechanism geometry interrupts the path of the cable, multiple line segments were used to define the length of the cable. The distance from the cable holes in the tool member to these points on the gear tooth were measured in addition to the line segment extending between the points of interruption. These segments were then summed to estimate the entire relevant cable length.

[1135] FIG. 19 shows that the joint assembly cables may not be length conservative, but they vary by less than, for example, 0.51 mm (0.02 in). Using the force-displacement relationship of the cables, the force to stretch—and artificially achieve length conservation—can be evaluated. In this case, a force of, for example, 6.7 N (1.5 lb) is all that may be needed. It may also be that 0.51 mm (0.02 in) is sufficiently small to make the non-length-conservative nature of the cables negligible. In another aspect, this problem is solved by using a separate actuator for each cable or by running the cables over a mirrored mechanism before attaching to the actuators. Control inputs to each cable actuator are made based on modelled or observed non-length-conservation information, as well as tool member position information (represented, e.g., by sensed motor position) so as to maintain the required minimum forces on the cables.

[1136] In some embodiments, a tool member can be designed to maintain its structural integrity in view of the applied forces, the actuator preload, the anticipated forces during use, and the like. Moreover, because the rolling element joints described herein include tool members in which the contact portion (where the output force is applied) is offset from the spatial location where the input (e.g., actuator) force is applied, such designs can be subject to bending stress and/or buckling. In some embodiments, the size and/or shape of a tool member can be configured to withstand the applied stresses. For example, FIGS. 20A, 20B, 21A, and 21B show views of a tool member 630. The tool member 630 can be similar to any of the joint assemblies shown and described (e.g., tool member 430), and the modeling

described with reference to FIGS. 20A, 20B, 21A, and 21B is applicable to any of the joint assemblies described herein. As shown, the two smallest cross sectional areas located the farthest away from the applied load were identified and analyzed. These cross sections are located distances y_1 and y_2 from the platform (see FIG. 20B). The applied load acts through a moment arm $l_i = l_{jaw} - y_i$. The stress due to bending, as well as the torsional stress resulting from the eccentric loading, were calculated using the equations $\sigma = \frac{Mc}{I}$ and $\tau = \frac{Tc}{J}$, where $M = FL_i$ and $T = F_b e$.

[1137] In some implementations, the maximum stress in the jaw occurs at point A on cross section b (FIG. 21B). The Von Mises stress is, for example, 306.1 MPa, which represents a factor of safety of, for example, 3.5.

[1138] FIG. 22 shows the parameters related to a finite element (FE) model, as well as a simplified analytical model that were evaluated to determine the likelihood of buckling due to the cable preload and applied axial load. The FE model was constrained, for example, in the x and y directions by limiting the movement of the center gear tooth and similarly constrained in the z direction by fixing the translation of the rolling contact surface. Additionally, the preload forces from the cables ($F_{cables} = 11.1\text{ N}$) were applied on either end of the through hole in the tool member.

[1139] Under these conditions, with an axial force of, for example, $F_{buckling} = 133.4\text{ N}$. The minimum factor of safety was, for example, 1.94x.

Fabrication

[1140] Traditional surgical instrument fabrication methods could be at the edge of their limits to create the features at the scale and definition required for smooth engagement and performance. As a result, a micro Metal Laser Sintering (MLS) method can be used, for example, to fabricate illustrative 3 mm diameter scale embodiments.

[1141] In some implementations, fine metal powders with an average particle size distribution of, for example, $< 5\mu\text{m}$ D90 (at least 90% of the particles can be less than, for example, $5\mu\text{m}$ in diameter) can be used. This allows the build to achieve tolerances on the order of, for example, $\pm 5\mu\text{m}$ and features as small as, for example, $25\mu\text{m}$. These

capabilities represent a great improvement over traditional machining or Metal Injection Molding (MIM) methods that typically have difficulty accurately defining features much smaller than, for example, $100\mu\text{m}$.

[1142] A working configuration of a joint assembly according to an embodiment is shown in FIG. 23C. FIG. 23A illustrates a device having a nominal shaft diameter of 8.4 mm. FIG. 23B illustrates a device having a nominal shaft diameter of 5.5 mm. The surgical instruments shown in FIGS. 23A and 23B are used with da Vinci® Surgical Systems. FIG. 23C illustrates a device having a nominal shaft diameter of 4.1 mm with an embodiment of the joint assembly mounted at the end and the flexible actuator members routed proximally through the shaft. The metal used is, for example, 316L Stainless Steel, with a demonstrated tensile strength of, for example, 694 MPa.

[1143] FIG. 24 shows on the right a medical device having an assembled configuration in accordance with inventive aspects in the process of suturing next to a 8.4 mm instrument on the left, as an example. The instrument on the right is being controlled by a person operating a computer-assisted and teleoperated surgical system (e.g., a da Vinci® Surgical System). During testing, the embodiment shown demonstrated the dexterity and strength to repeatedly drive the suture through the foam and pass the suture back and forth between the adjacent instrument.

[1144] In some implementations, a physical configuration is, for example, 4.1 mm in diameter with, for example, 3 DoF at the distal end (see Fig. 23C—a wrist provides an arbitrarily-labelled end effector pitch DOF, motion of the end effector tool members together provides an arbitrarily-labelled end effector yaw DOF, and motion of the end effector tool members opposite one another provides a grip and spread DOF). Additionally the wrist can be, for example, 5.4 mm long. These dimensions represent, for example, a 25.5% reduction in instrument diameter and, for example, a 74.1% reduction in joint length over commercially available alternatives. The reduction in joint length in addition to, for example, well-contained centers of rotation, results in a reduced swept volume. In some implementations, the volume for the instrument to operate is reduced and the instrument can therefore operate in cavities previously too small or restricting for existing instruments.

[1145] FIG. 25 is a flow chart of a method of assembling an instrument 10, according to an embodiment. The method 10 can be performed using any of the devices, joint

assemblies, or components thereof described herein. The method 10 includes coupling an actuator assembly to a tool member, at 12. The actuation assembly includes at least one flexible member, such as for example, the flexible member 461 described above. The tool member has a tool convex surface, such as, for example, the tool convex surface 431 described above.

[1146] The tool convex surface is placed into rolling contact with a base convex surface of a base such that when the actuator assembly applies an actuation force to the tool member the tool member rotates relative to the base, at 14. In some embodiments, the placing includes disposing the base convex surface between a first end portion of the flexible member and a second end portion of the flexible member. In some embodiments, the placing includes meshing a gear portion of the tool convex surface with a gear portion of the base convex surface. A preload force is applied to the flexible member to maintain the tool convex surface in contact with the base convex surface, at 16.

[1147] In some embodiments, the method 10 optionally includes coupling the base to a shaft of a surgical system, at 18.

[1148] While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Where methods and/or schematics described above indicate certain events and/or flow patterns occurring in certain order, the ordering of certain events and/or operations may be modified. While the embodiments have been particularly shown and described, it will be understood that various changes in form and details may be made.

[1149] For example, although the tool convex surface 231 is shown following the same cylindrical arc (i.e., being characterized by the same radius of curvature) as the second convex surface 241, in other embodiments, the tool convex surface 231 and the second convex surface 241 can have different profiles. Moreover, any of the convex and/or curved surfaces described herein can have any suitable profile that can be different from that of another part (e.g., tool member or base) of the joint assembly.

[1150] Although various embodiments have been described as having particular features and/or combinations of components, other embodiments are possible having a combination of any features and/or components from any of embodiments as discussed above. Aspects have been described in the general context of medical devices, and more specifically

surgical instruments, but inventive aspects are not necessarily limited to use in medical devices.

What is claimed is:

1. An apparatus, comprising:
 - a first tool member having a first convex surface;
 - a second tool member having a second convex surface;
 - a base having a base convex surface, the first tool member configured to rotate relative to the base, the second tool member configured to rotate relative to the base; and
 - an actuator assembly configured to maintain the first convex surface in rolling contact with a first portion of the base convex surface, the actuator assembly configured to maintain the second convex surface in rolling contact with a second portion of the base convex surface.
2. The apparatus of claim 1, wherein the actuator assembly includes a flexible member coupled to the first tool member, the base convex surface disposed between a first end portion of the flexible member and a second end portion of the flexible member.
3. The apparatus of claim 1, wherein the actuator assembly includes a flexible member coupled to the first tool member, a first end portion of the flexible member configured to exert a first force on the first tool member, a second end portion of the flexible member configured to exert a second force on the first tool member, the first force different from the second force such that the first tool member rotates relative to the base.
4. The apparatus of claim 1, wherein the actuator assembly includes a flexible member spaced apart from at least one of the first convex surface or the base convex surface.
5. The apparatus of claim 1, wherein:
 - the first convex surface includes a gear portion meshed with a gear portion of the first portion of the base convex surface; and
 - the actuator assembly includes a flexible member configured to exert a force against the first tool member to maintain a gear engagement of between about 40 percent and about 60 percent.

6. The apparatus of claim 1, wherein:
the first portion of the base convex surface is characterized by a first radius of curvature about a first axis; and
the second portion of the base convex surface is characterized by a second radius of curvature about a second axis, the second axis collinear with the first axis.
7. The apparatus of claim 1, wherein the base convex surface follows a cylindrical arc.

Side wall configuration

8. The apparatus of claim 1, wherein the base includes a guide surface positioned to engage a side portion of the first tool member to limit lateral movement of the first tool member relative to the base.
9. The apparatus of claim 1, wherein the first tool member includes a guide surface configured to engage a side portion of the base to limit lateral movement of the first tool member relative to the base.
10. The apparatus of claim 1, wherein the base includes a first guide surface and a second guide surface, the base convex surface disposed between the first guide surface and the second guide surface.
11. An apparatus, comprising:
a tool member having a tool convex surface;
a base having a base convex surface, the tool member configured to rotate relative to the base; and
an actuator assembly configured to maintain the tool convex surface in rolling contact with the base convex surface, the actuator assembly including a flexible member coupled to the tool member, the base convex surface disposed between a first end portion of the flexible member and a second end portion of the flexible member.
12. The apparatus of claim 11, wherein the first end portion of the flexible member is configured to exert a first force on the tool member, a second end portion of the flexible member is configured to exert a second force on the tool member, the first force different from the second force such that the tool member rotates relative to the base.

13. The apparatus of claim 11, wherein:
the tool convex surface includes a gear portion meshed with a gear portion of the base convex surface; and
the flexible member is configured to exert a force against the tool member to maintain a gear engagement of between about 40 percent and about 60 percent.
14. The apparatus of claim 11, wherein:
the first portion of the base convex surface is characterized by a first radius of curvature about a first axis; and
the second portion of the base convex surface is characterized by a second radius of curvature about a second axis, the second axis collinear with the first axis.
15. The apparatus of claim 11, wherein the base includes a guide surface configured to engage a side portion of the tool member to limit lateral movement of the tool member relative to the base.
16. The apparatus of claim 11, wherein the base includes a first guide surface and a second guide surface, the base convex surface disposed between the first guide surface and the second guide surface.
17. An apparatus, comprising:
a tool member having a tool convex surface and a jaw portion; and
a base having a base convex surface and jaw portion, the base convex surface in rolling contact with the tool convex surface such that jaw portion of tool member rotates relative to the base about a first axis to contact the jaw portion of the base, the base having a guide surface positioned to limit movement of the tool member relative to the base about a second axis, the second axis nonparallel to the first axis.
18. The apparatus of claim 17, further comprising:
an actuator assembly engaged with the tool member and configured to exert an actuation force to rotate the tool member relative to the base about the first axis, the actuator assembly exerting a preload force to maintain the tool convex surface in rolling contact with the base convex surface.

19. The apparatus of claim 17, wherein the tool convex surface includes a gear portion meshed with a gear portion of the base convex surface, the apparatus further comprising:
a flexible member configured to exert a force against the tool member to maintain a gear engagement of between about 40 percent and about 60 percent.
20. The apparatus of claim 17, wherein the base convex surface follows a cylindrical arc of at least about 90 degrees.
21. An apparatus, comprising:
a tool member having a tool convex surface; and
a base having a base convex surface, the tool member coupled to the base such that the tool convex surface is in rolling contact with the base convex surface to rotate the tool member relative to the base about a first axis; and
at least one of the tool member or the base including a guide surface configured to limit movement of the tool member relative to the base about a second axis, the second axis nonparallel to the first axis.
22. The apparatus of claim 21, wherein the guide surface is a first guide surface, the base including a second guide surface, the base convex surface disposed between the first guide surface and the second guide surface.
23. The apparatus of claim 21, wherein the tool convex surface includes a gear portion meshed with a gear portion of the base convex surface, the apparatus further comprising:
an actuator assembly configured to rotate the tool member relative to the base about the first axis, the actuator assembly configured to exert a force against the first tool member to maintain a gear engagement of between about 40 percent and about 60 percent.
24. The apparatus of claim 21, further comprising:
an the actuator assembly configured to maintain the tool convex surface in rolling contact with the base convex surface.

25. A method, comprising:
- coupling an actuator assembly to a tool member, the actuation assembly including at least one flexible member, the tool member having a tool convex surface;
 - placing the tool convex surface into rolling contact with a base convex surface of a base such that when the actuator assembly applies an actuation force to the tool member the tool member rotates relative to the base; and
 - applying a preload force to the flexible member to maintain the tool convex surface in contact with the base convex surface.
26. The method of claim 25, wherein the placing includes disposing the base convex surface between a first end portion of the flexible member and a second end portion of the flexible member.
27. The method of claim 25, wherein the placing includes meshing a gear portion of the tool convex surface with a gear portion of the base convex surface.
28. The method of claim E3, wherein the applying the preload is performed such the gear portion of the tool convex surface and the gear portion of the base convex surface have a gear engagement of between about 40 percent and about 60 percent.
29. The method of claim 25, wherein the tool member is fabricated using a metal laser sintering (MLS) process.
30. The method of claim 25, further comprising:
- coupling the base to a shaft of a surgical system.

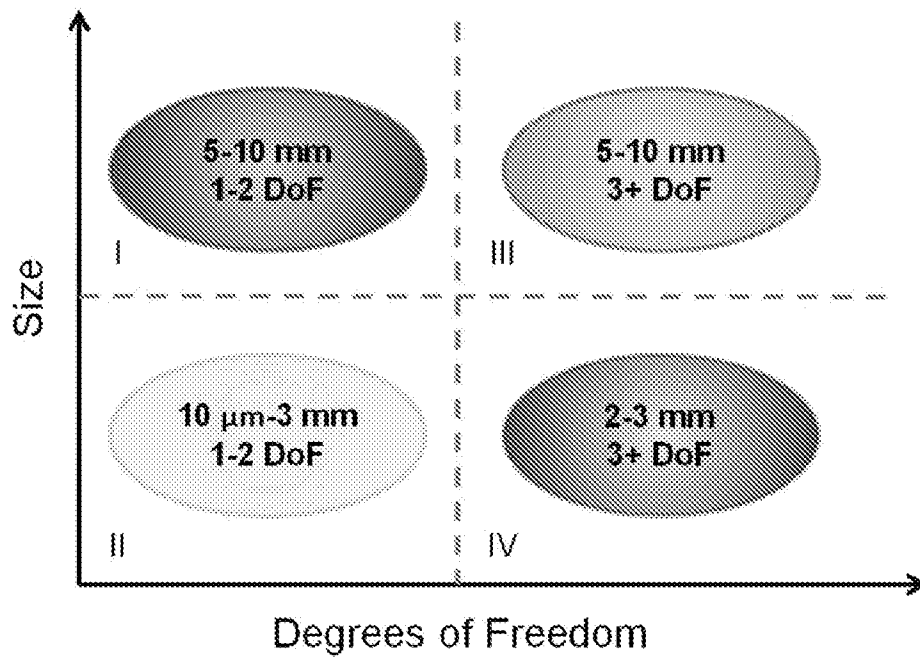


FIG. 1

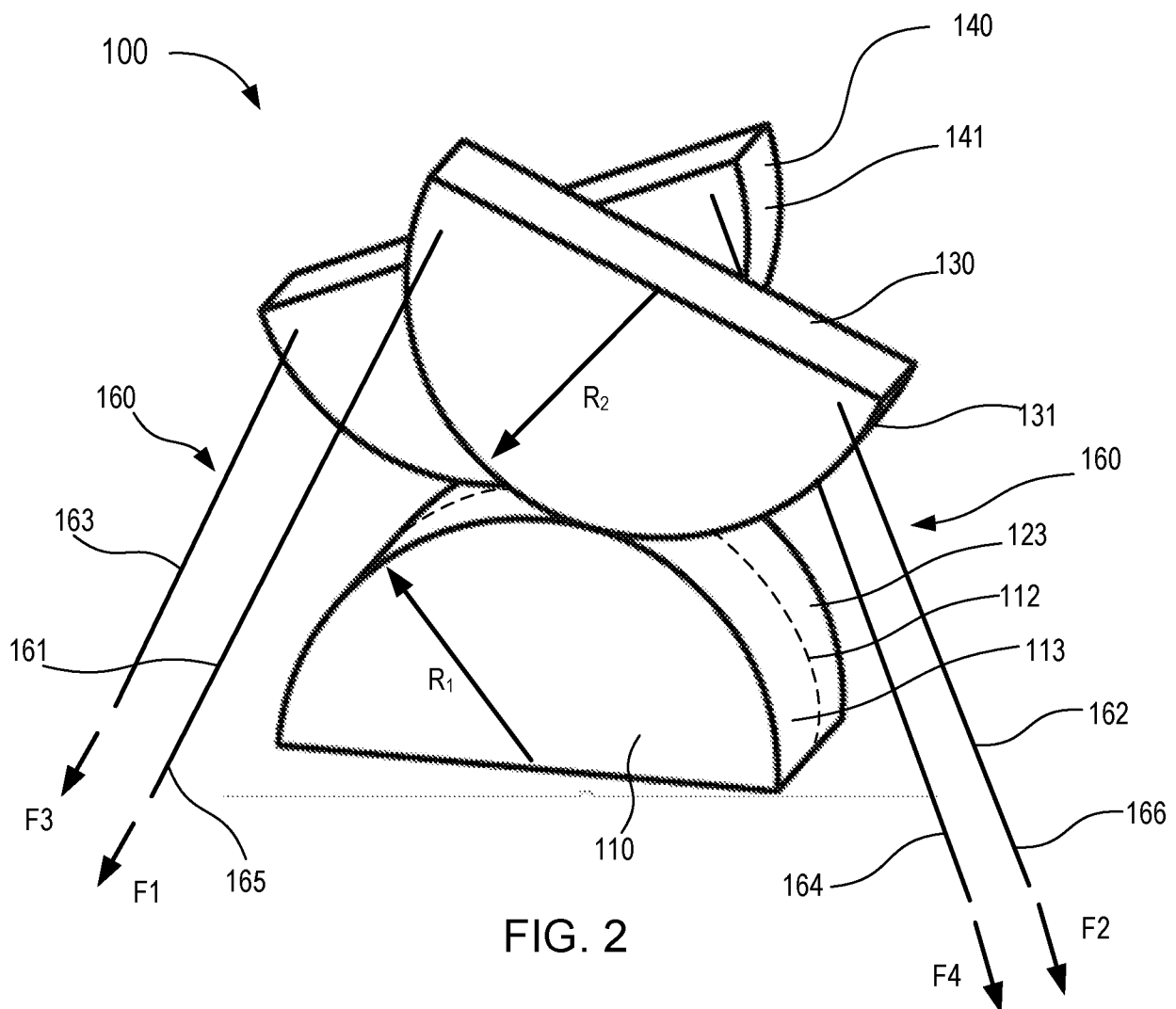


FIG. 2

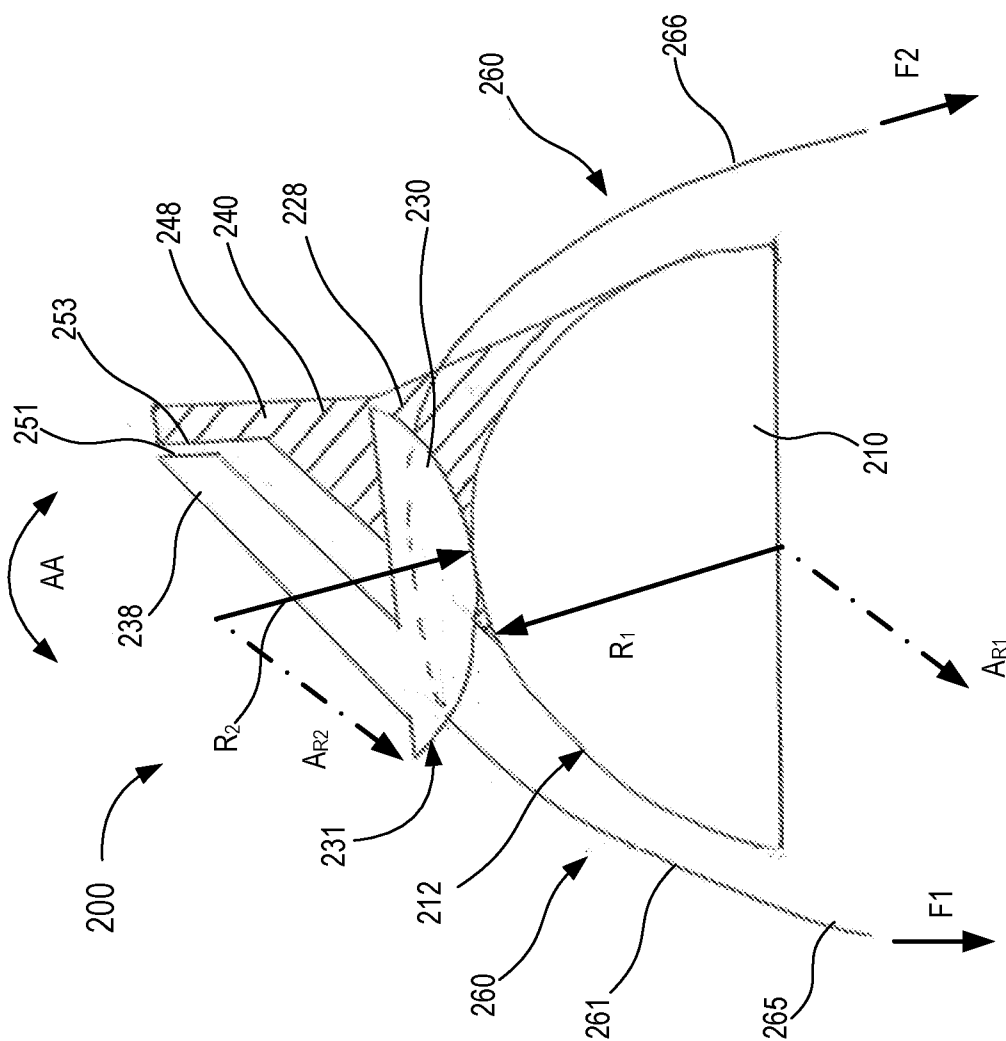


FIG. 3

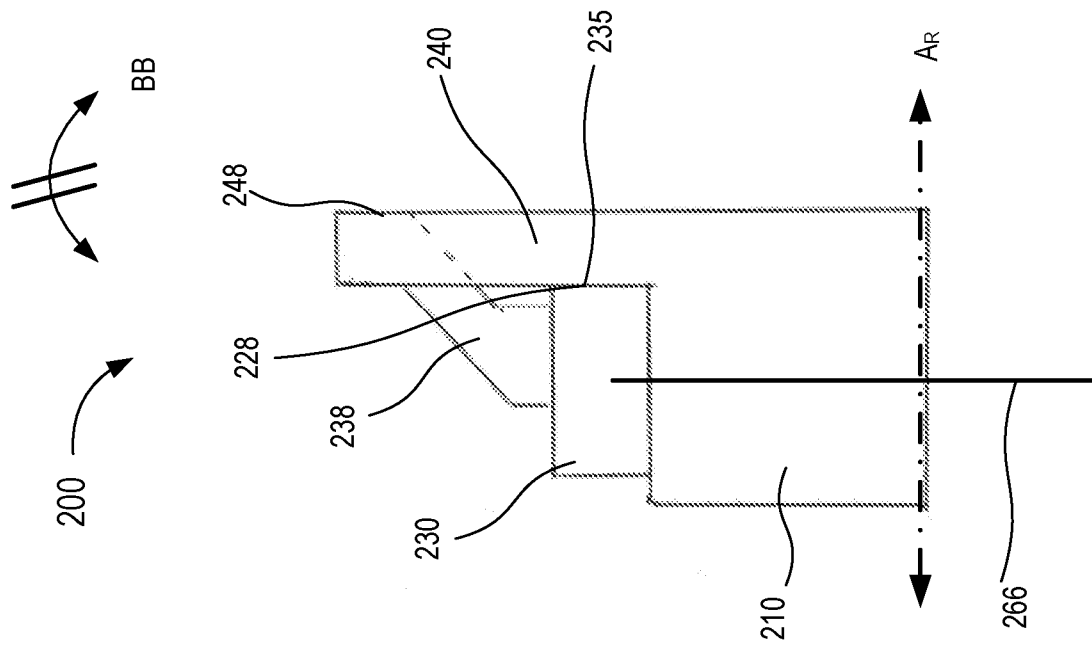


FIG. 4

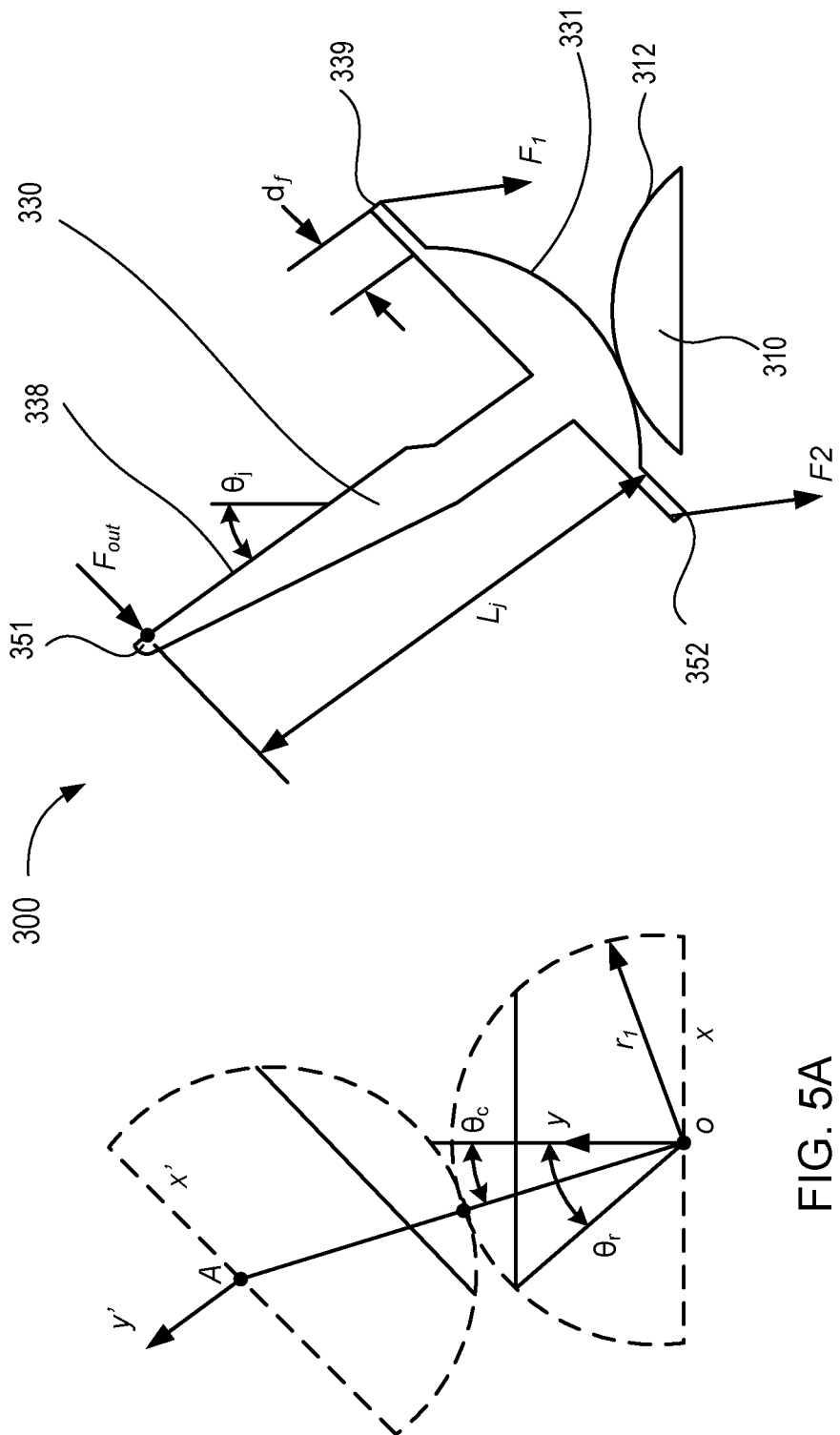


FIG. 5B

FIG. 5A

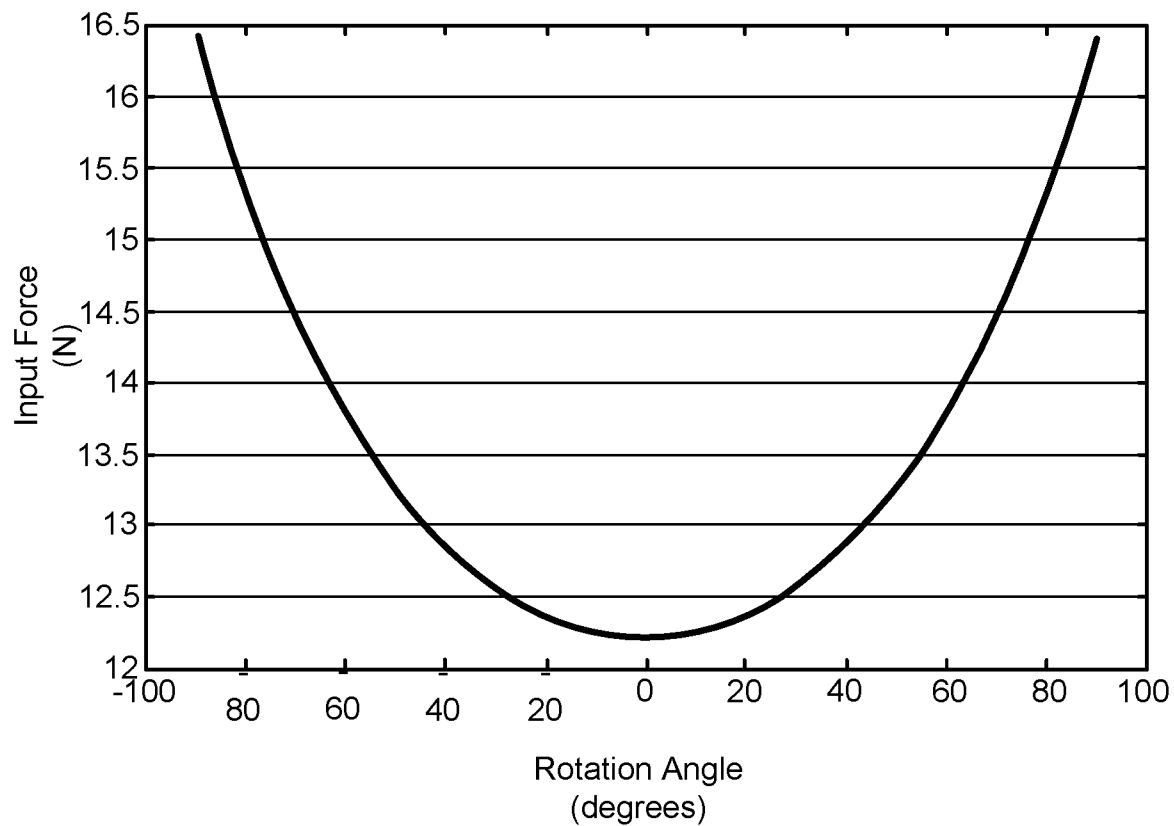


FIG. 6

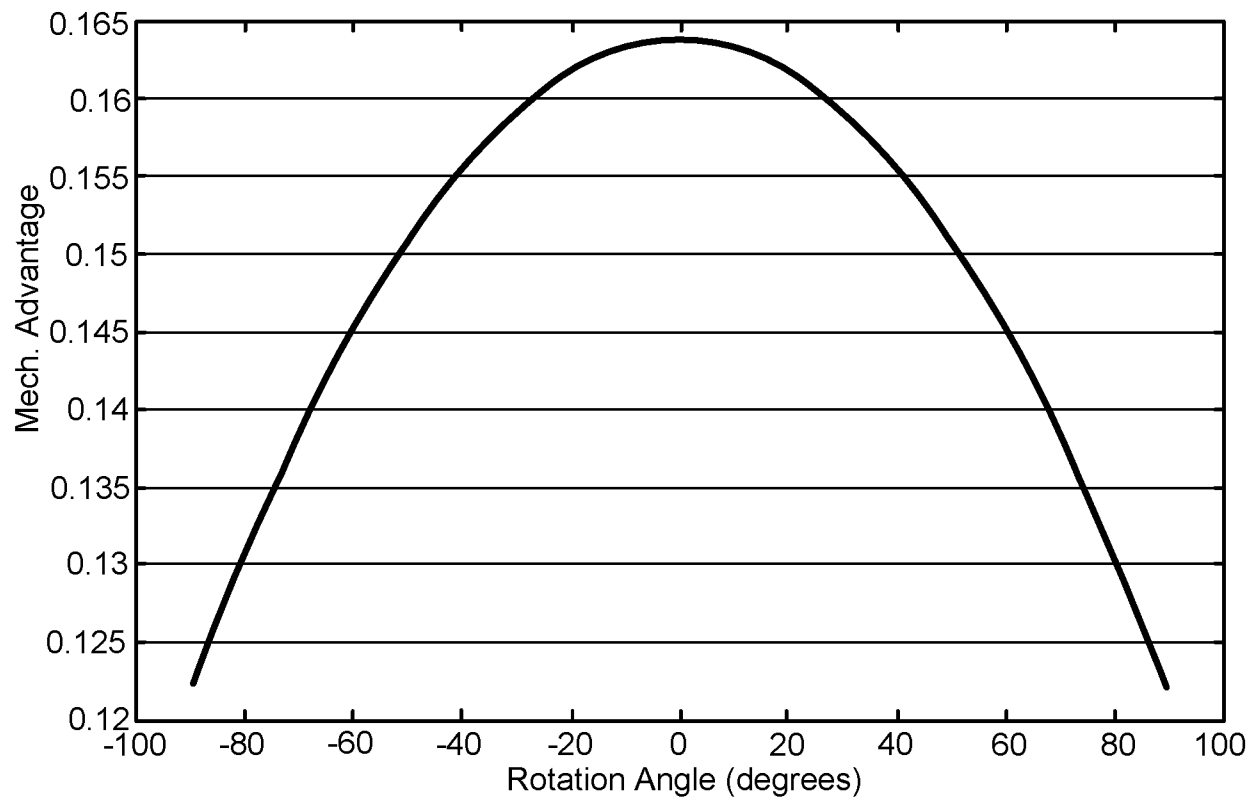


FIG. 7

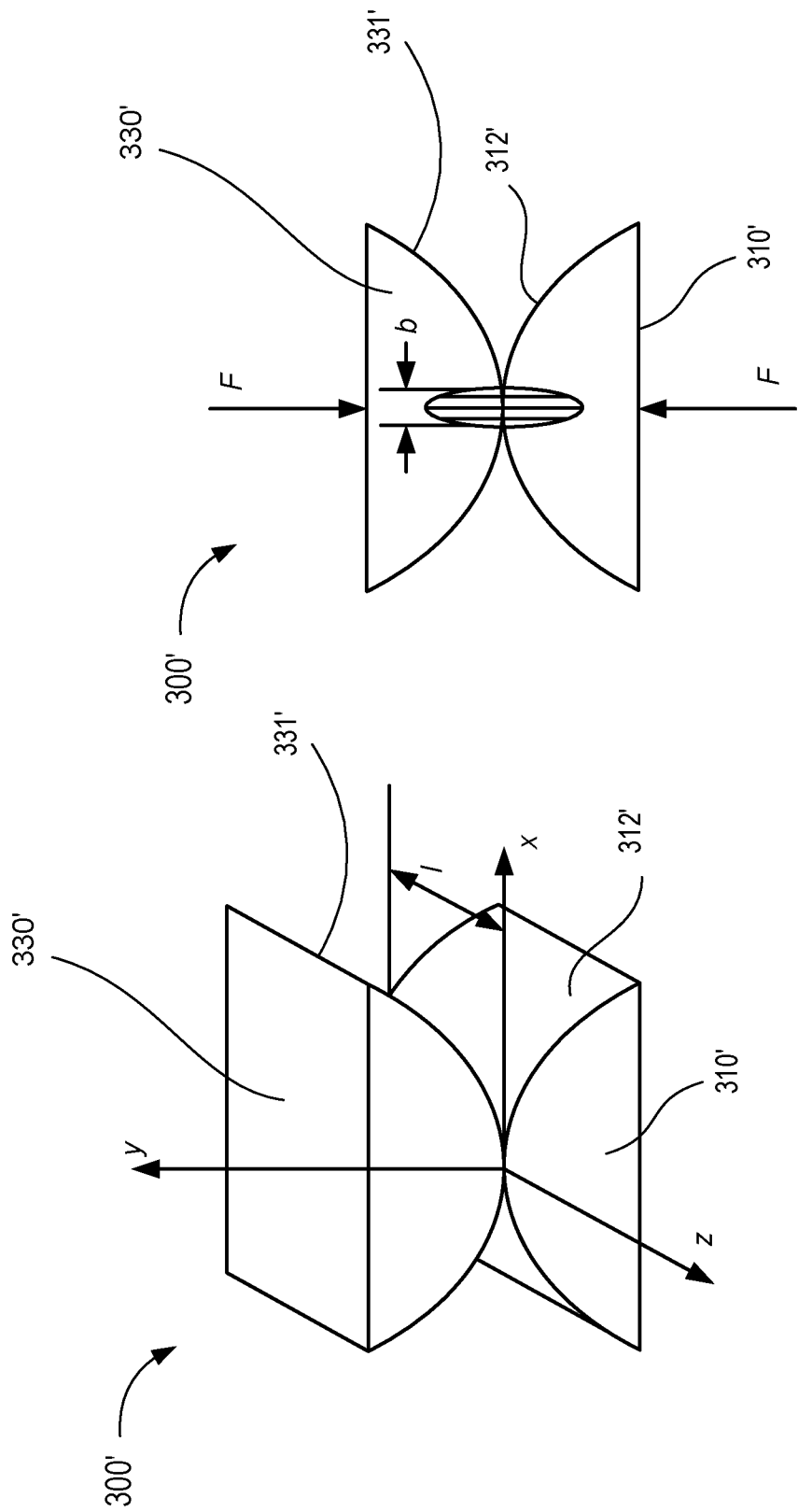


FIG. 8B

FIG. 8A

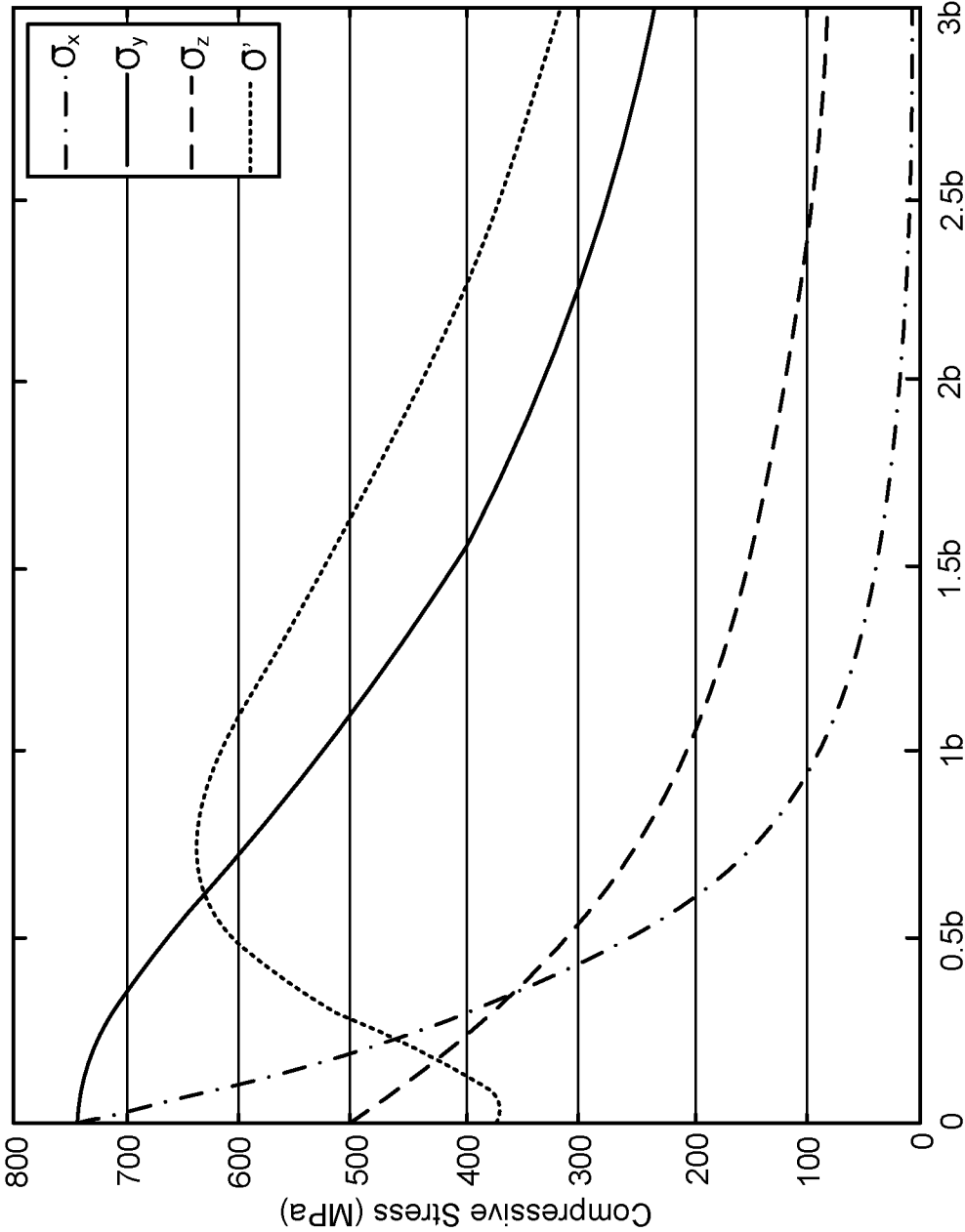


FIG. 9

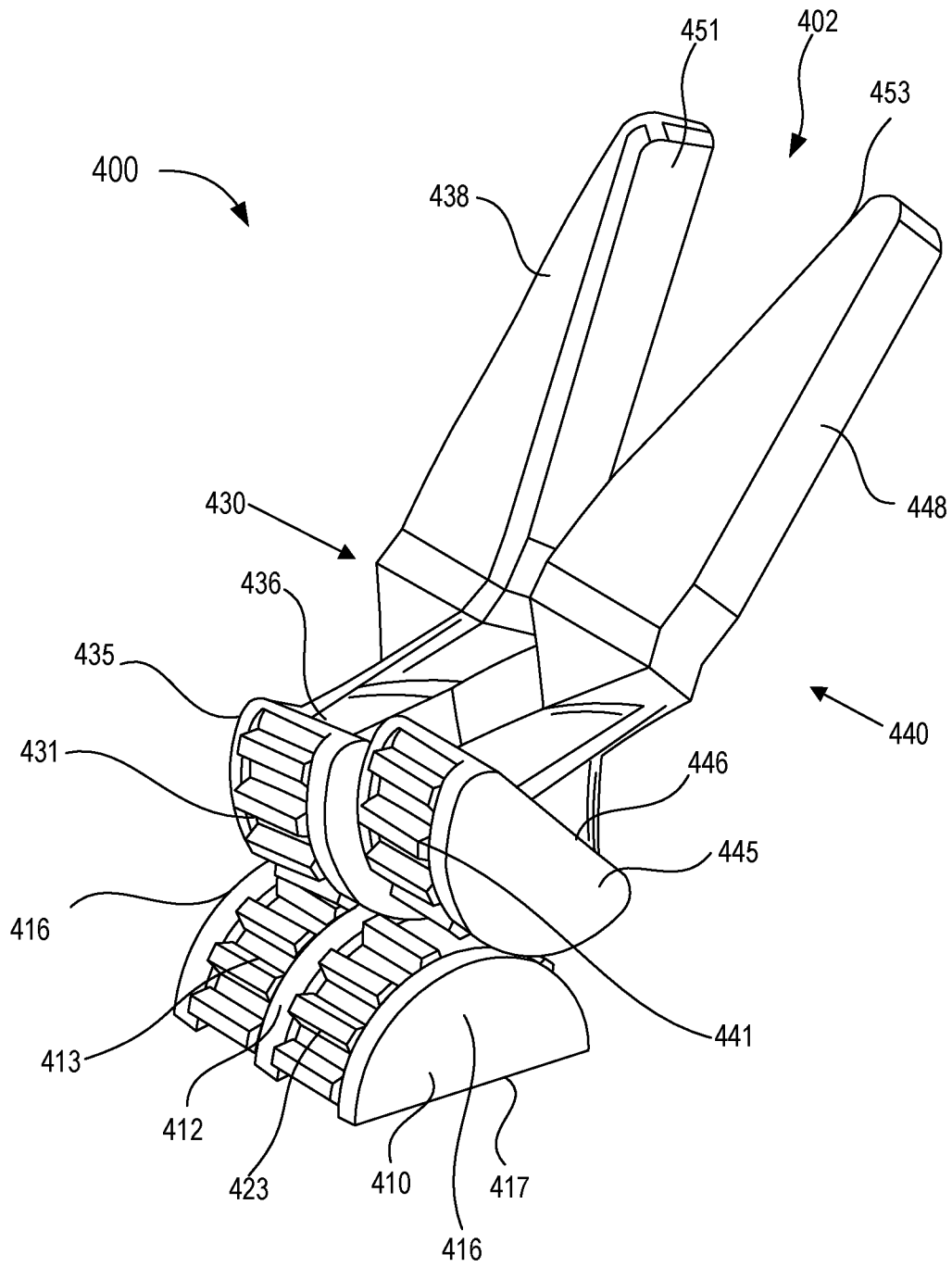


FIG. 10

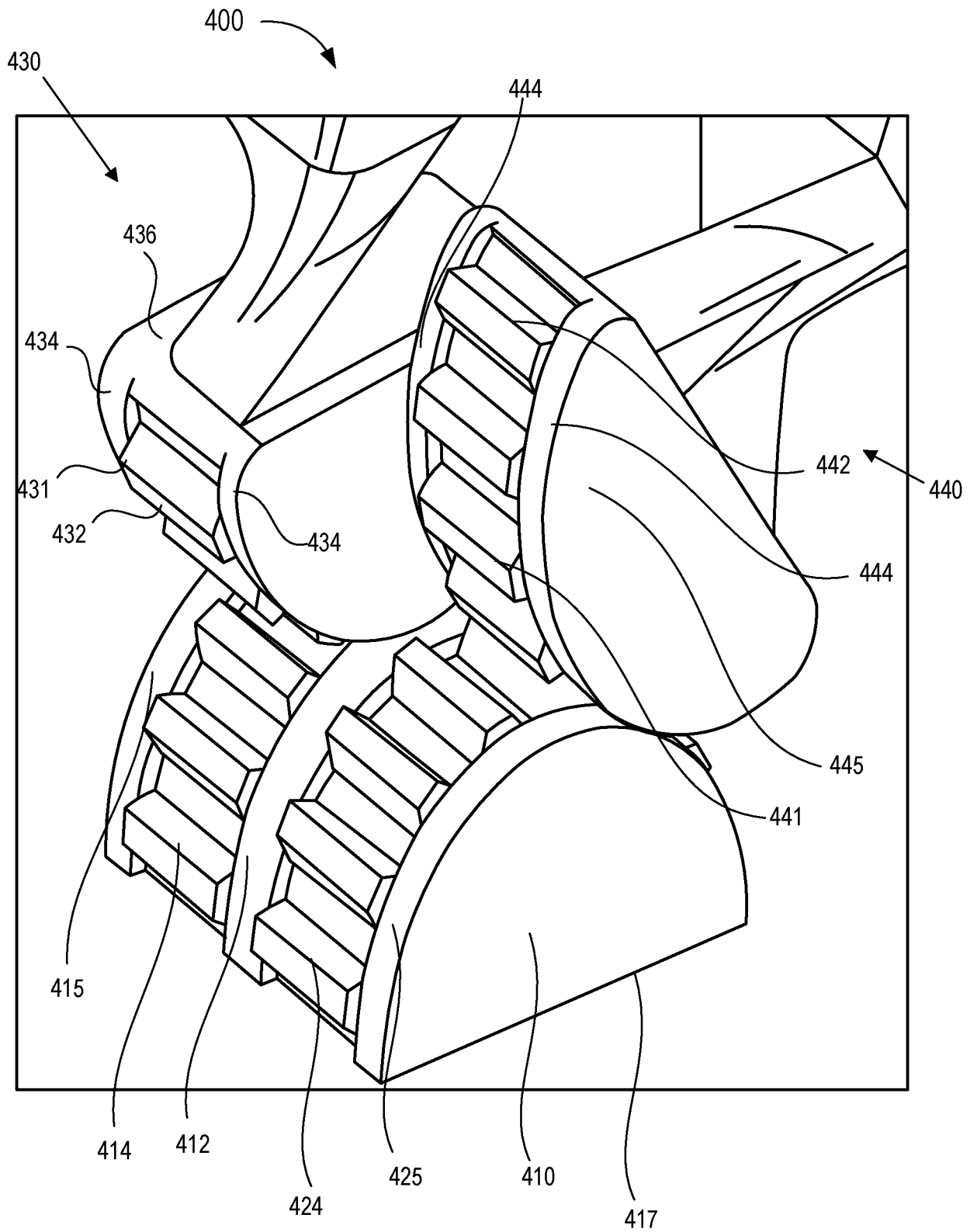


FIG. 11

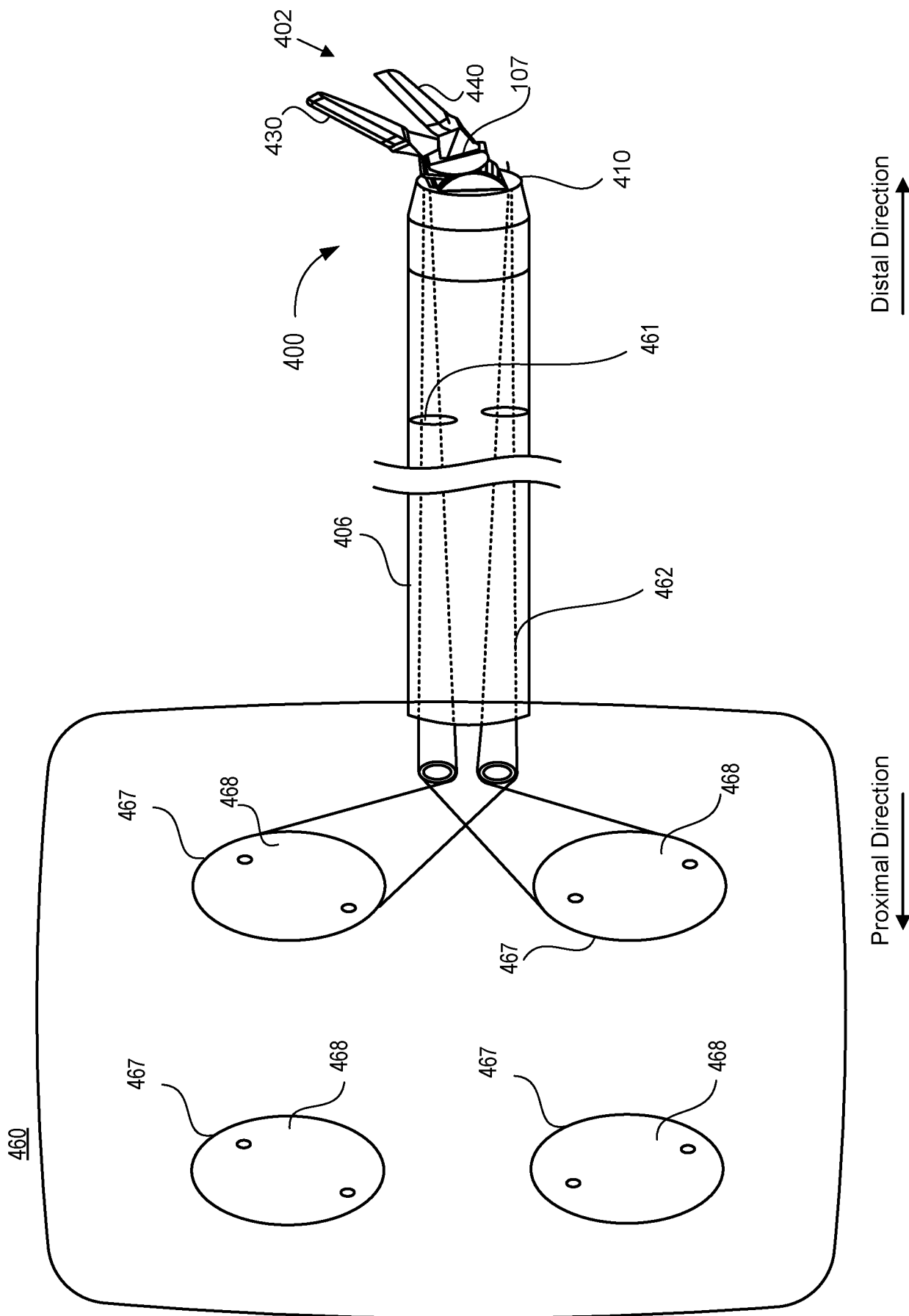


FIG. 12

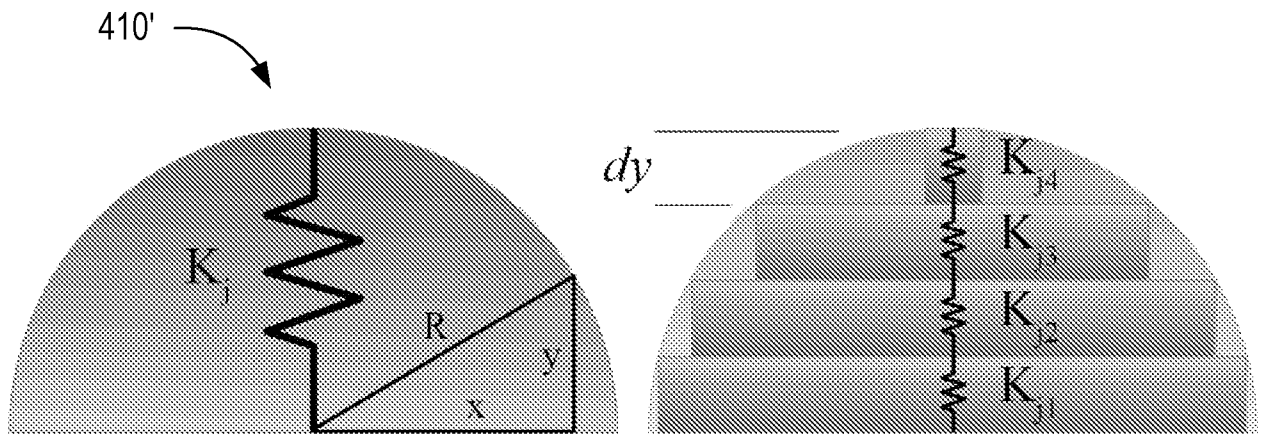


FIG. 13

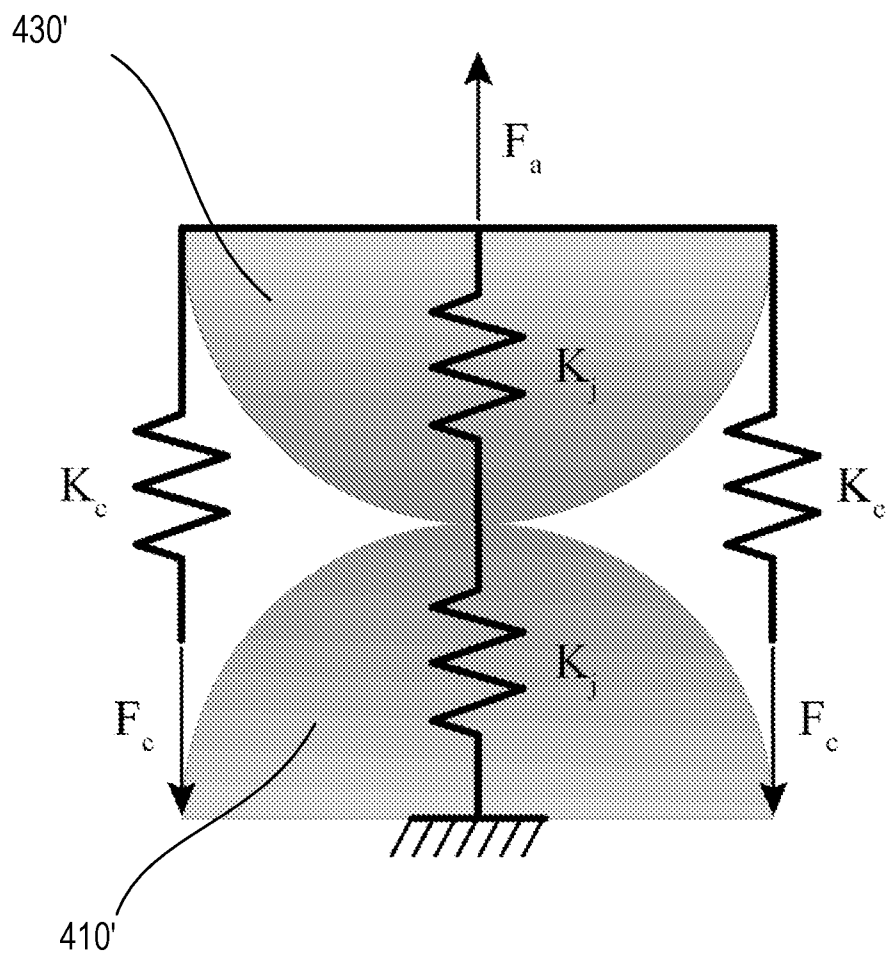


FIG. 14

410

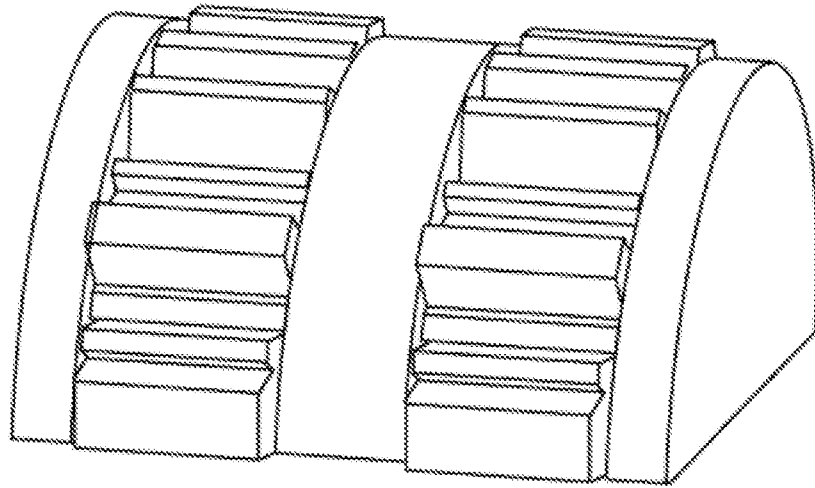



FIG. 15A

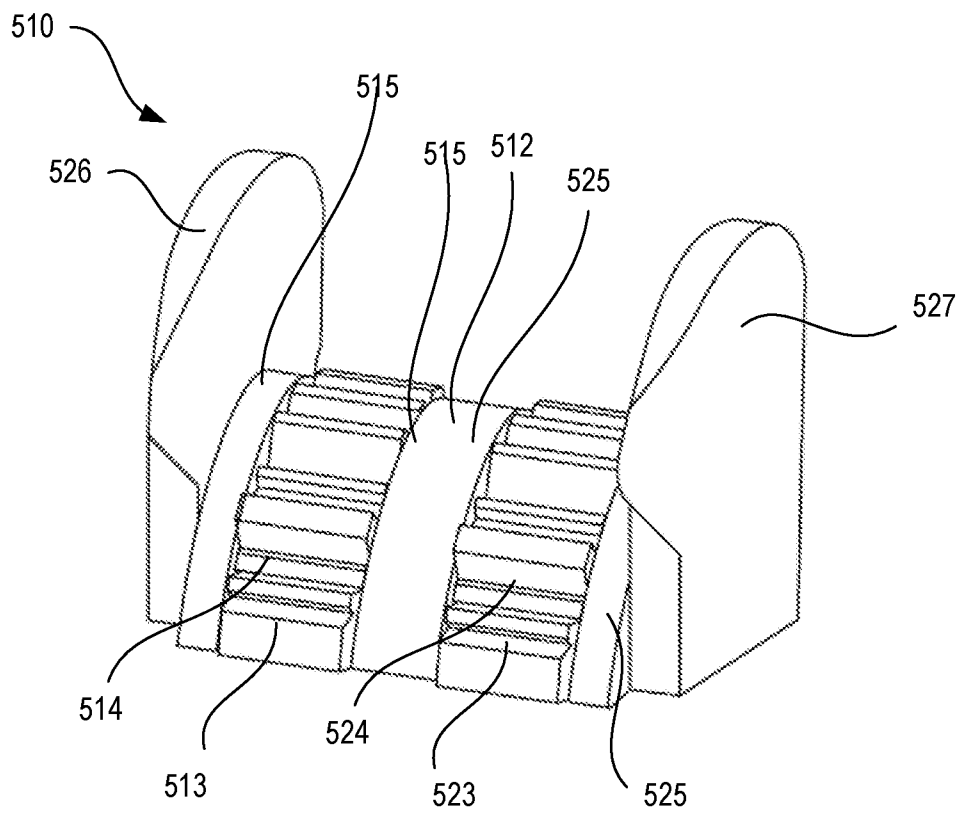


FIG. 15B

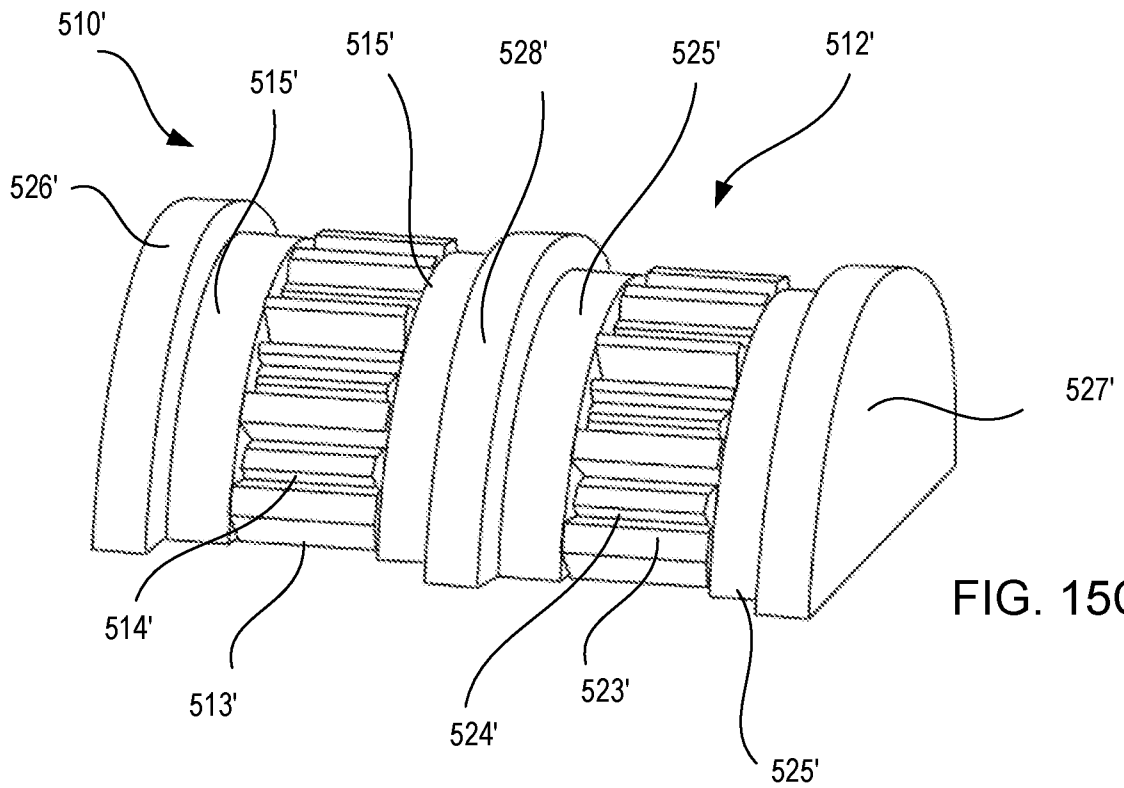


FIG. 15C

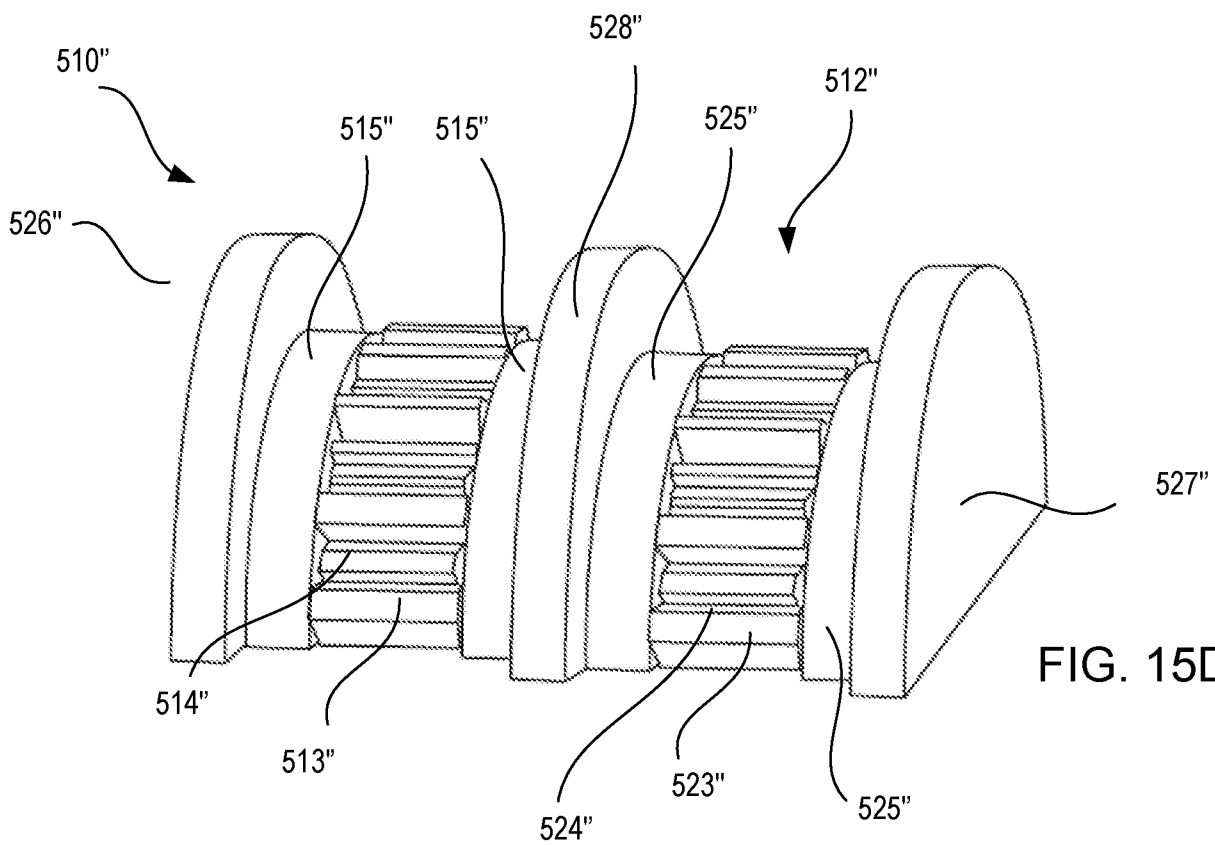


FIG. 15D

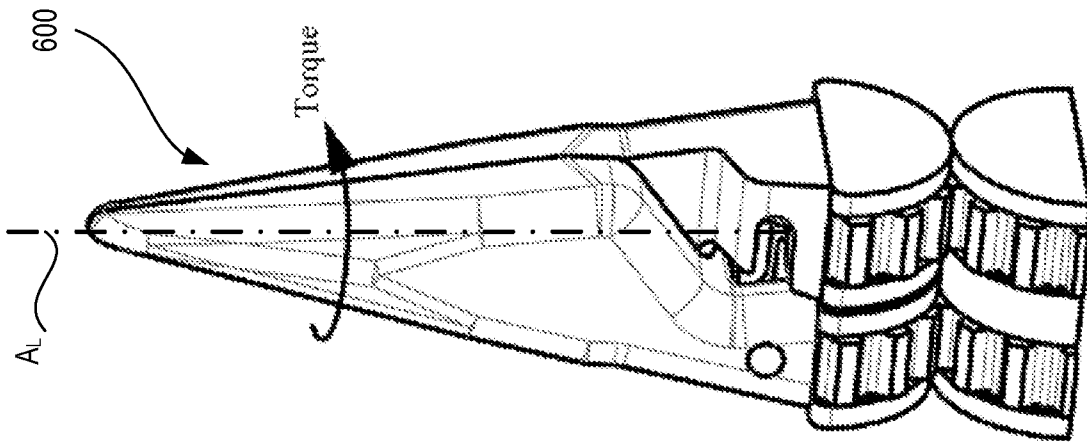


FIG. 17

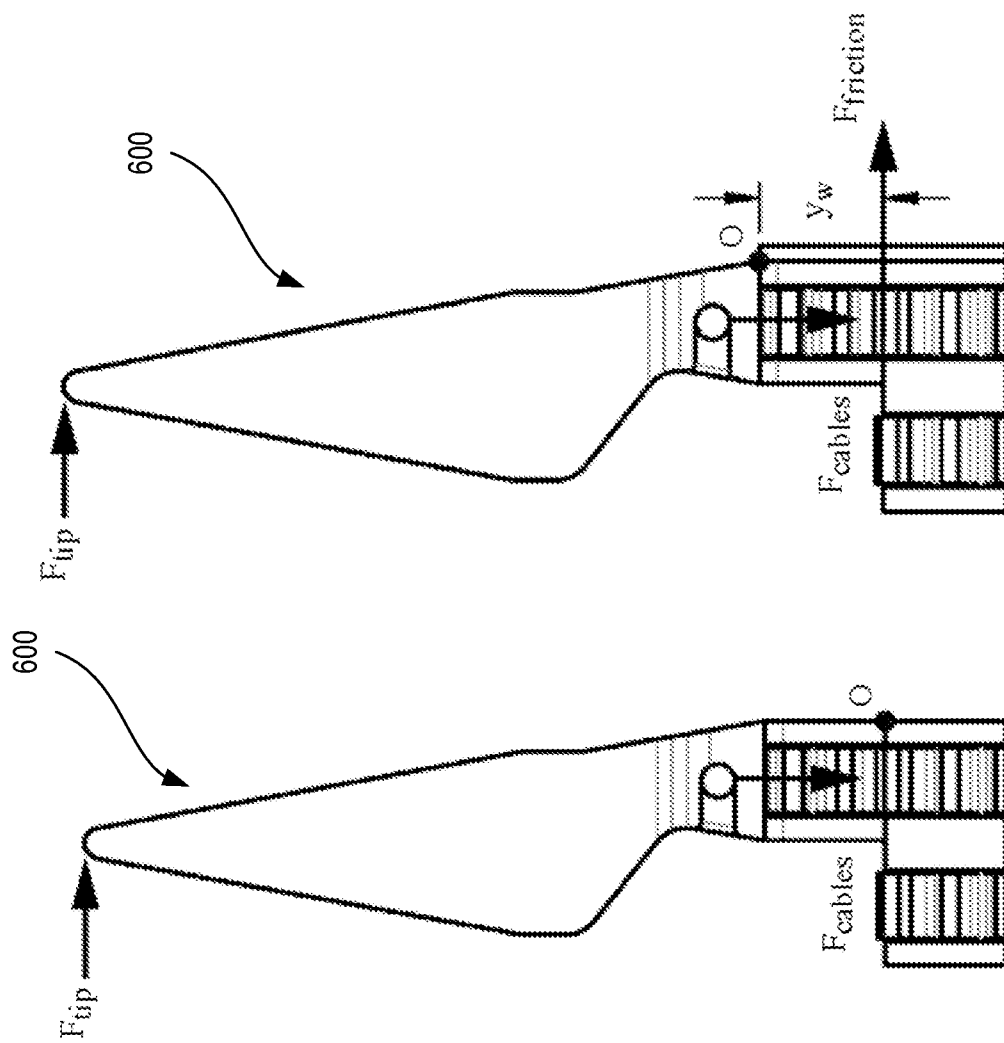


FIG. 16B

FIG. 16A

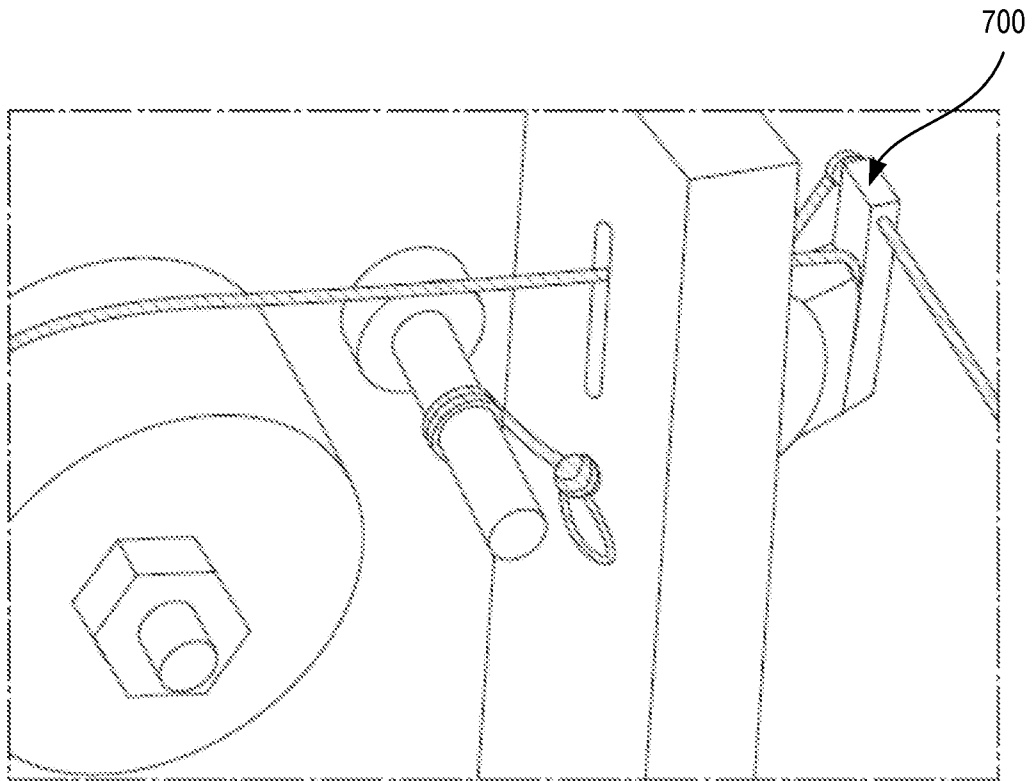


FIG. 18A

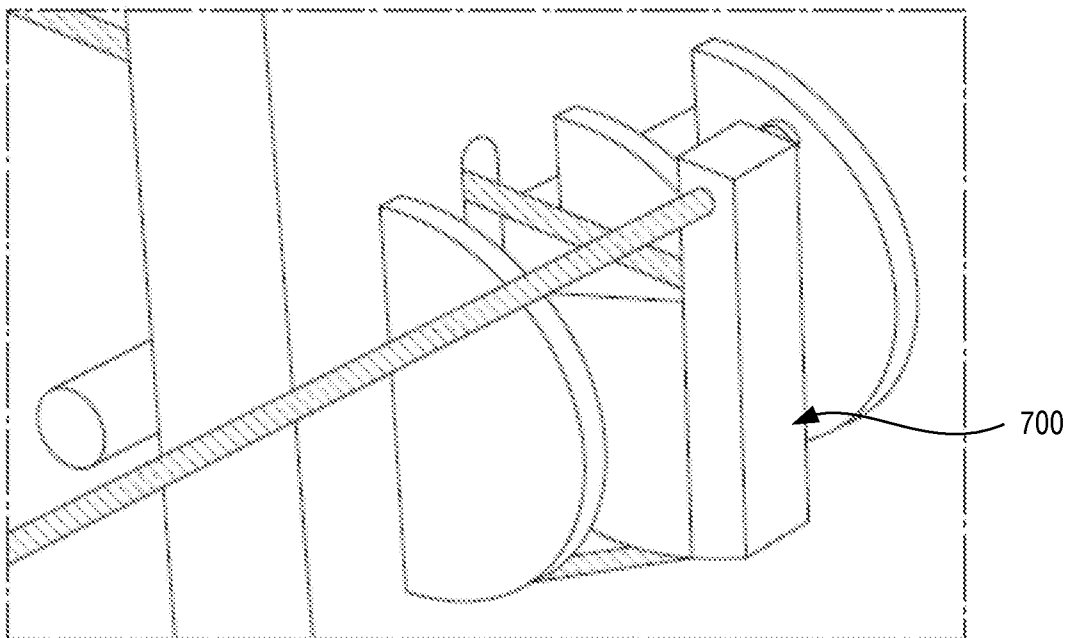


FIG. 18B

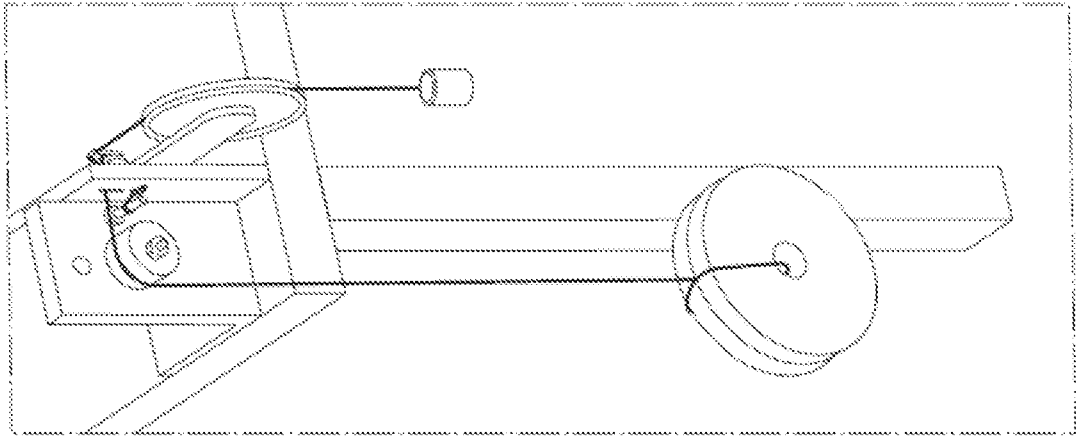


FIG. 18D

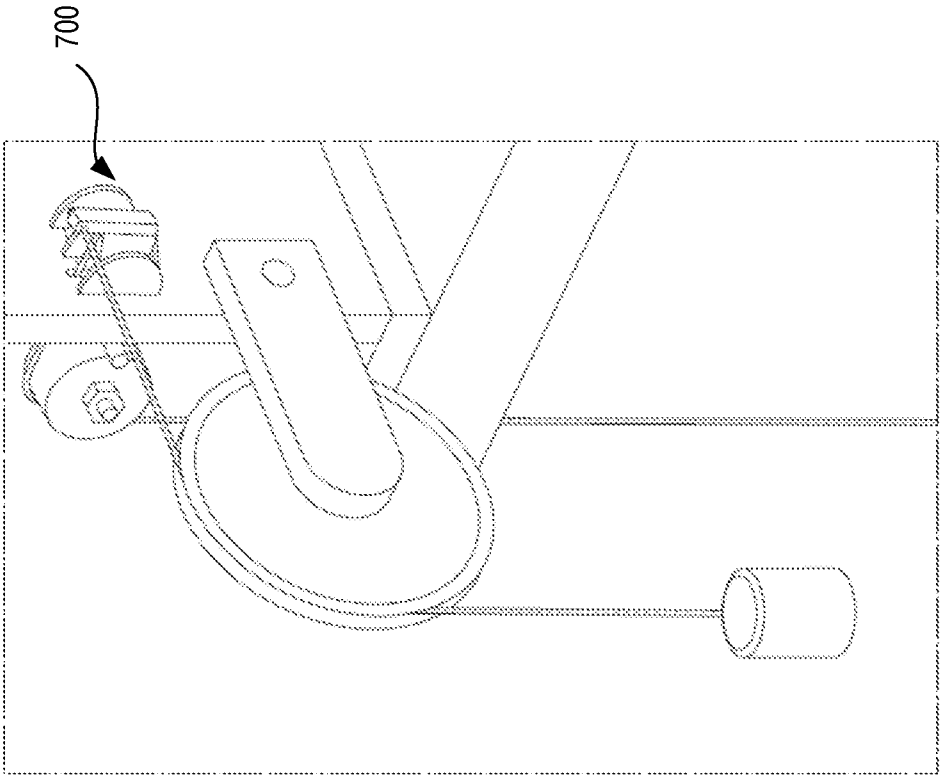


FIG. 18C

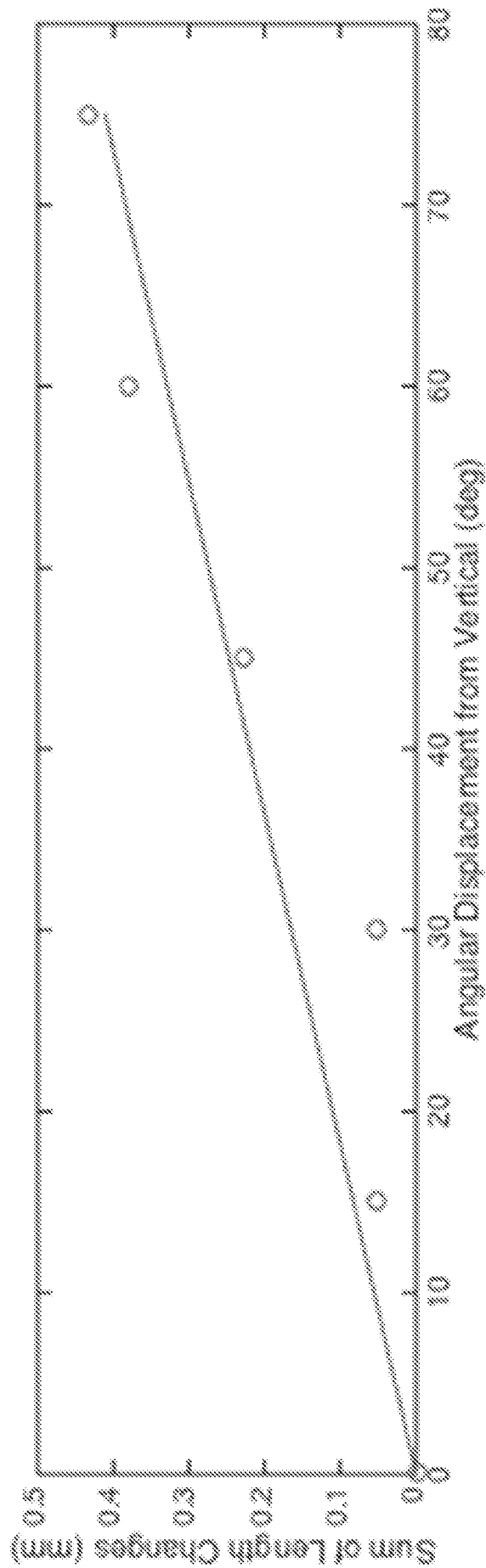


FIG. 19

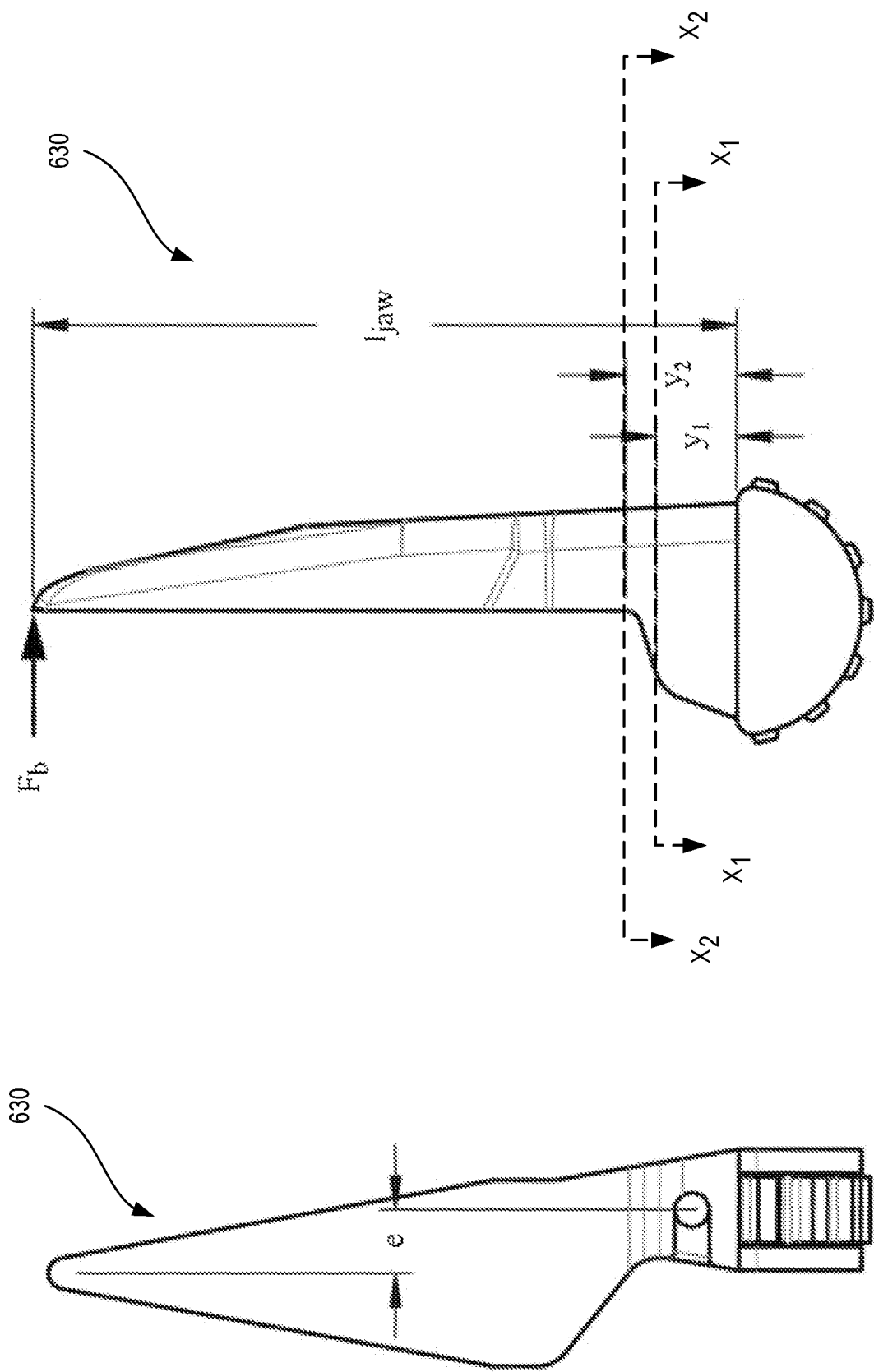


FIG. 20A

FIG. 20B

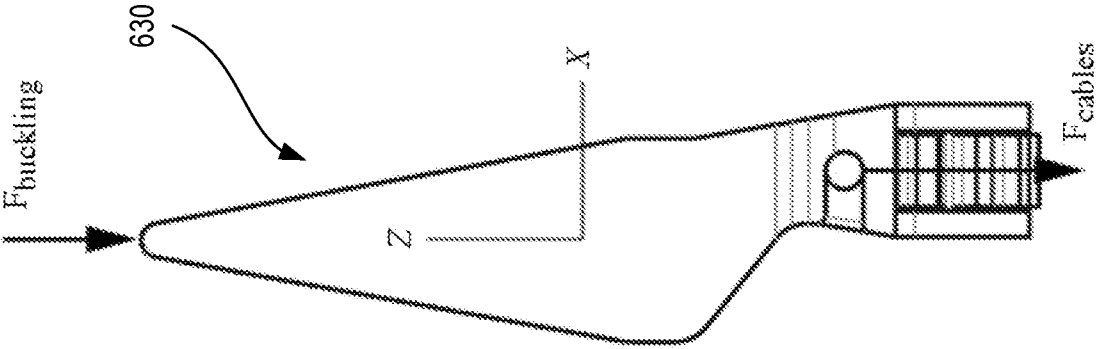


FIG. 22

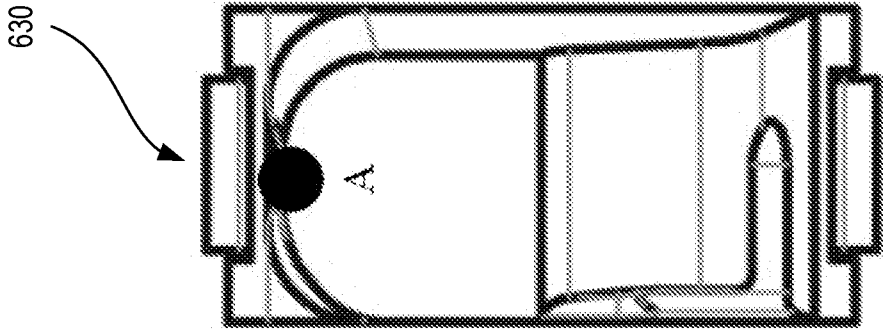


FIG. 21B

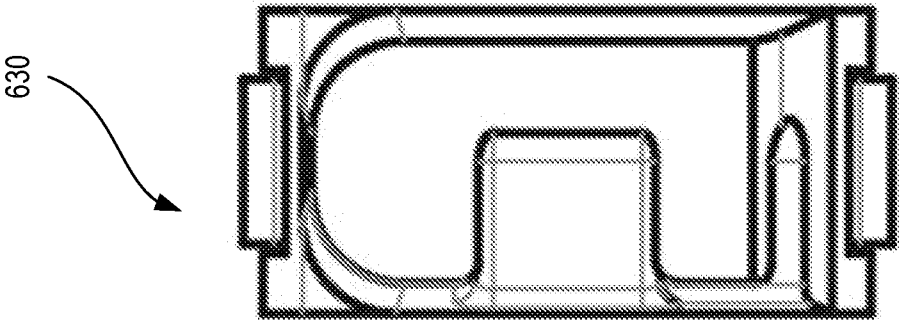
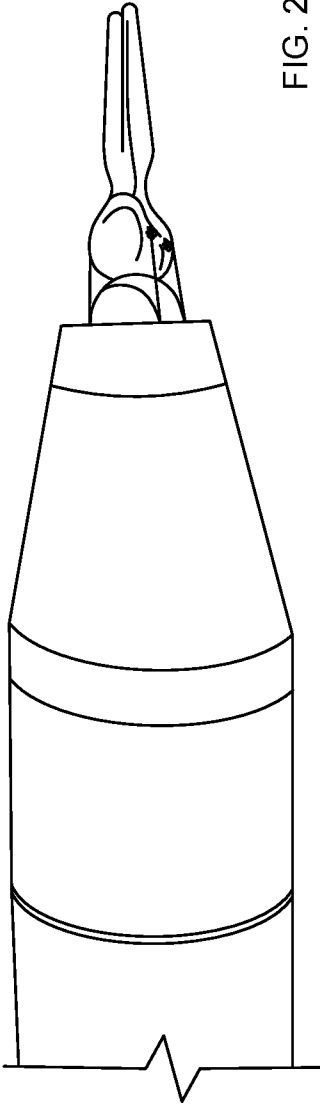
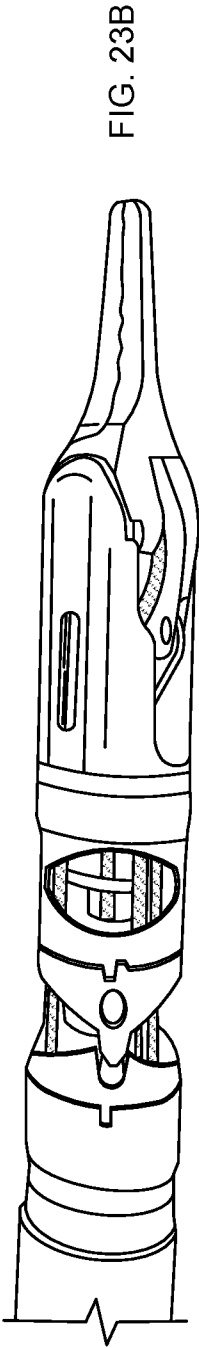
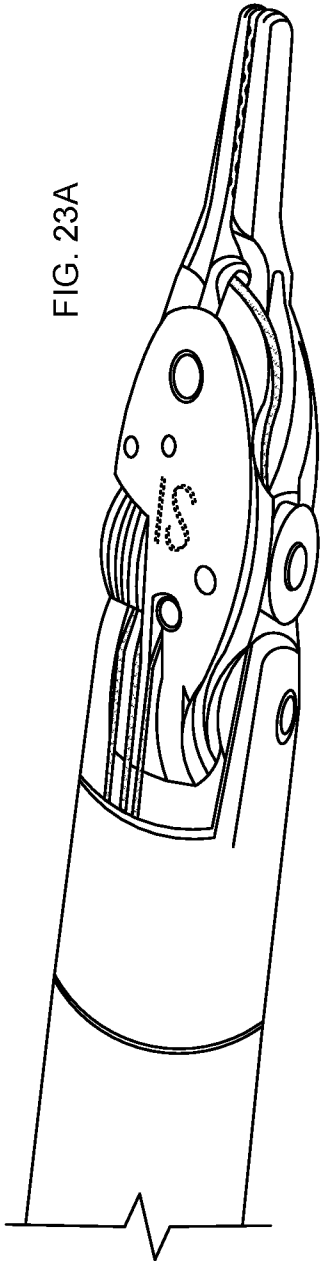


FIG. 21A



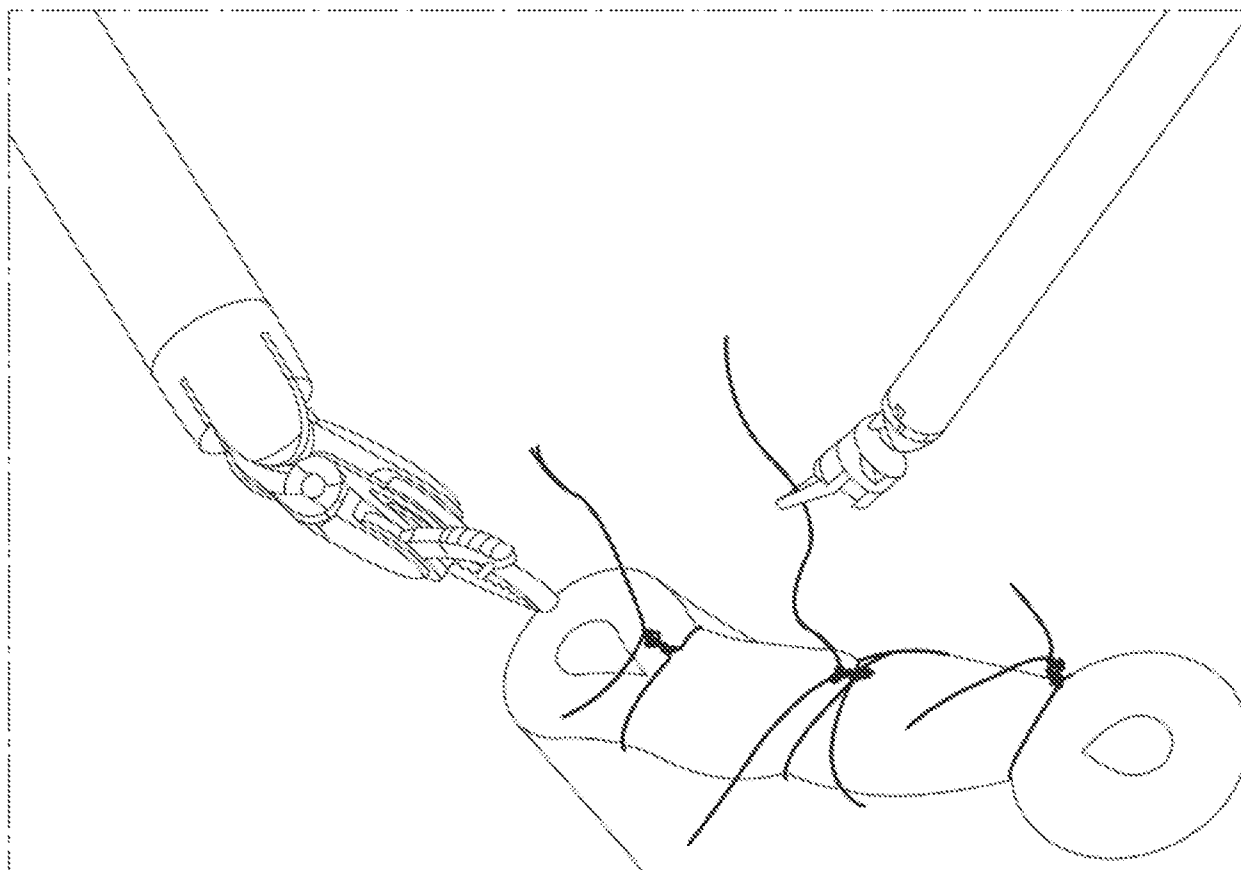


FIG. 24

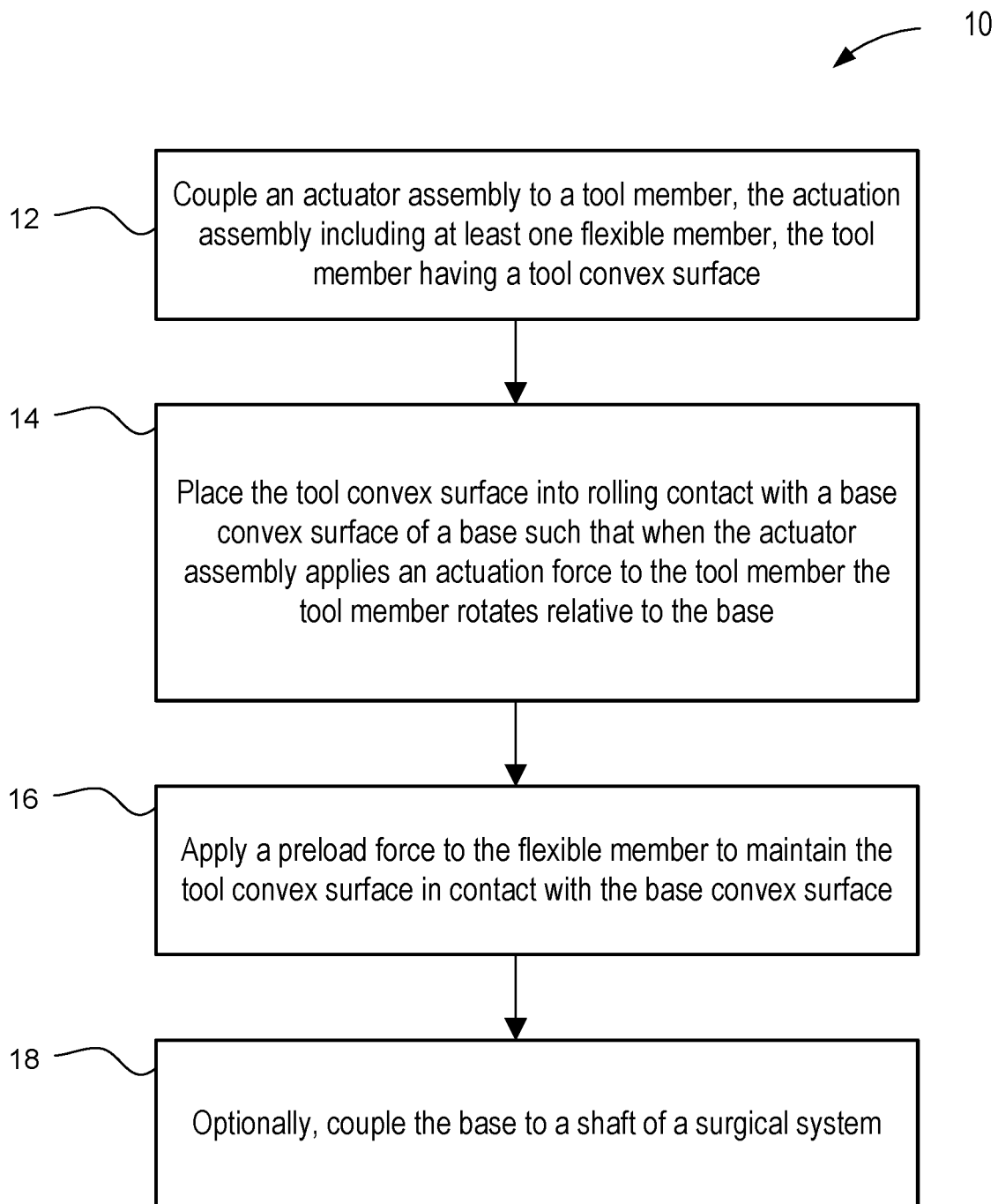


FIG. 25